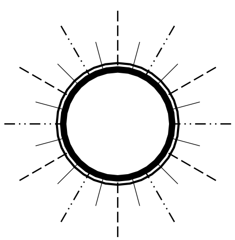
高エネルギー現象で探る宇宙の多様性I
2021 October 18(Mon)-19(Tue)
Institute for Cosmic Ray Research, the University of Tokyo (Kashiwa/On-line)

磁気再結合における粒子加速の理解を目指して：太陽フレア観測衛星 PhoENiX計画

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



Noriyuki Narukage (NAOJ)

Mitsuo Oka, Yasushi Fukazawa, Keiichi Matsuzaki, Shin Watanabe, Taro Sakao, Kouichi Hagino, Ikuyuki Mitsuishi, Tsunefumi Mizuno, Iku Shinohara, Masumi Shimojo, Shinsuke Takasao, Tomoko Kawate, Takafumi Kaneko, Seiji Zenitani, Hiroshi Tanabe, Munetaka Ueno, Tadayuki Takahashi, Takeshi Takashima, Masayuki Ohta and PhoENiX WG member

Science Goal

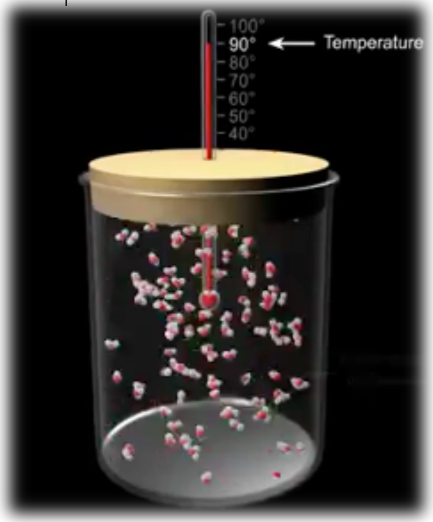
Understanding of particle acceleration during magnetic reconnection

- **Science Objectives**

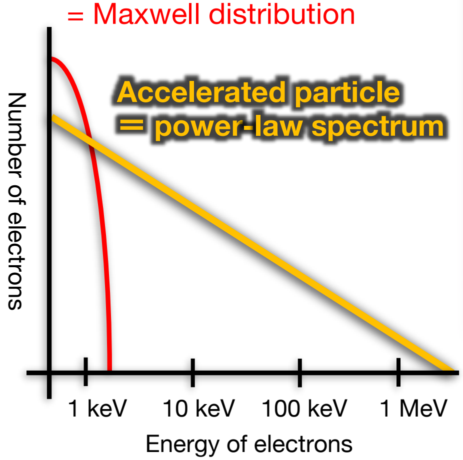
1. To identify
   particle acceleration sites
   in reconnection-associated structures in solar flares
2. To investigate
   the timing of particle acceleration
   during reconnection-associated phenomena in solar flares
3. To characterize
   the properties of accelerated particle populations in solar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

Particle acceleration

Accelerated particles are deviated from equilibrium.



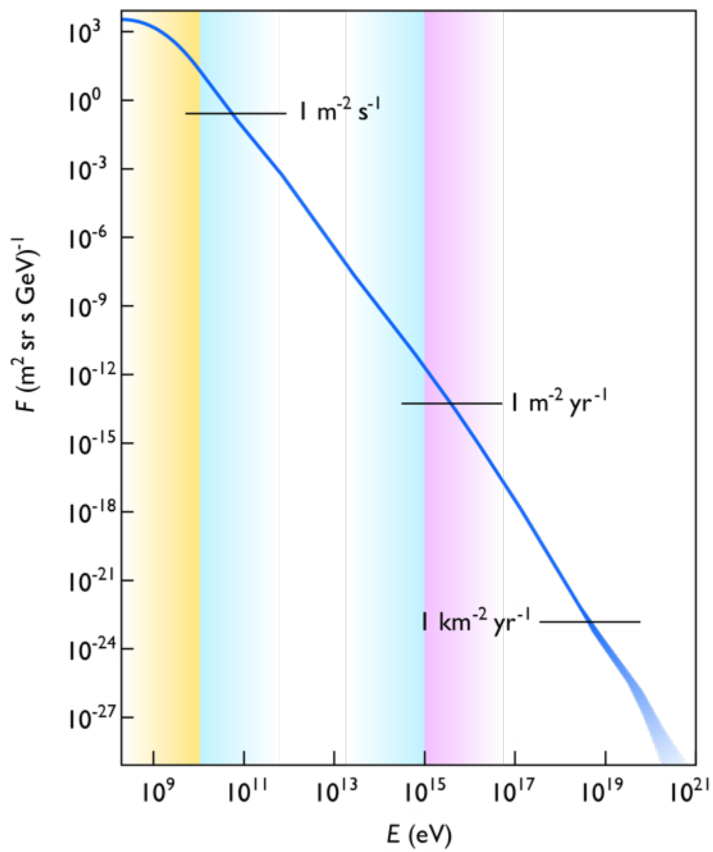
Thermal equilibrium
= Maxwell distribution

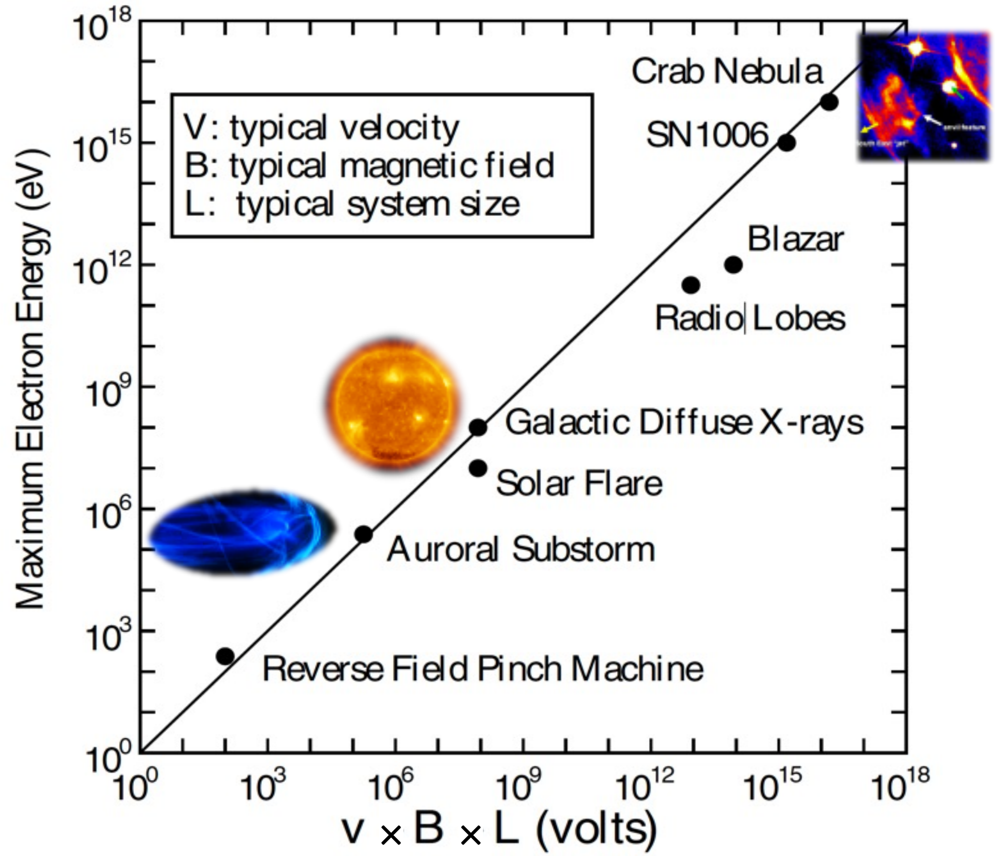


Particle acceleration

The energy of accelerated particles achieves up to 10^{20} eV.

Accelerated particles are ubiquitously detected in the universe.



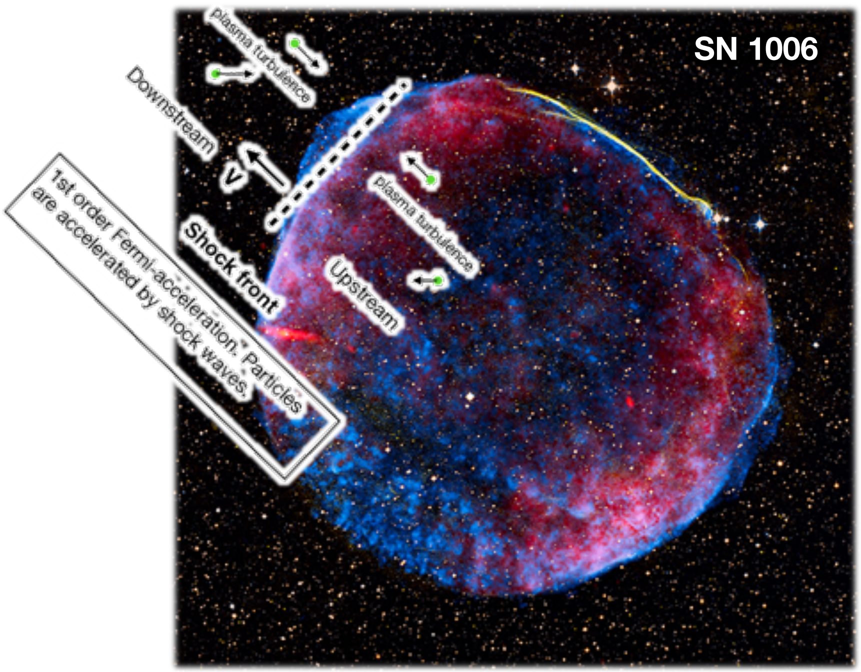


Makishima (1999)

Particle acceleration

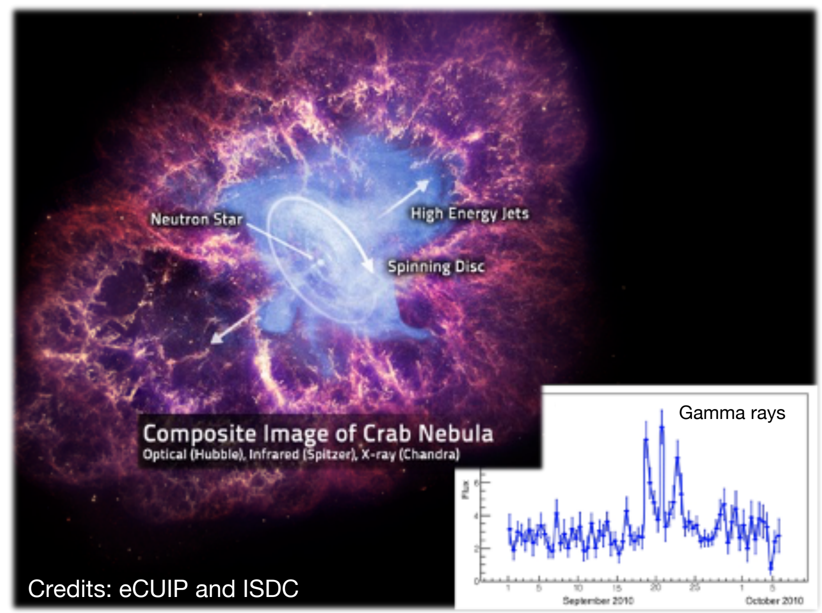
How are particles accelerated? It is not fully understood.

Super Nova Remnant
(long time acceleration)



1st order Fermi-acceleration
Statistical acceleration

Gamma-ray Burst
(short time acceleration)

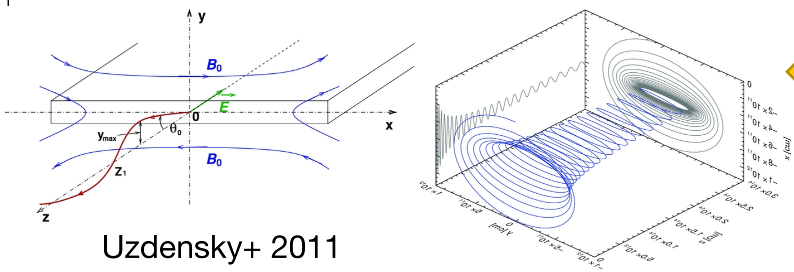


Balbo+ 2011

How are particles accelerated in very short time?

Particle acceleration

Magnetic reconnection is a key.

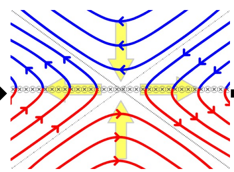


Uzdensky+ 2011

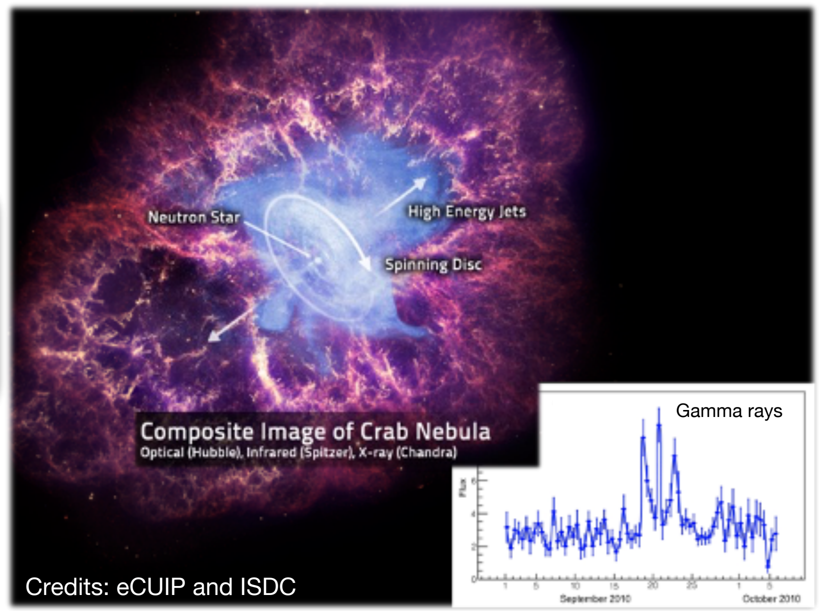
Gamma-ray Burst
(short time acceleration)

Magnetic reconnection

Magnetic energy ➔



➔ Kinetic energy
Thermal energy



Balbo+ 2011

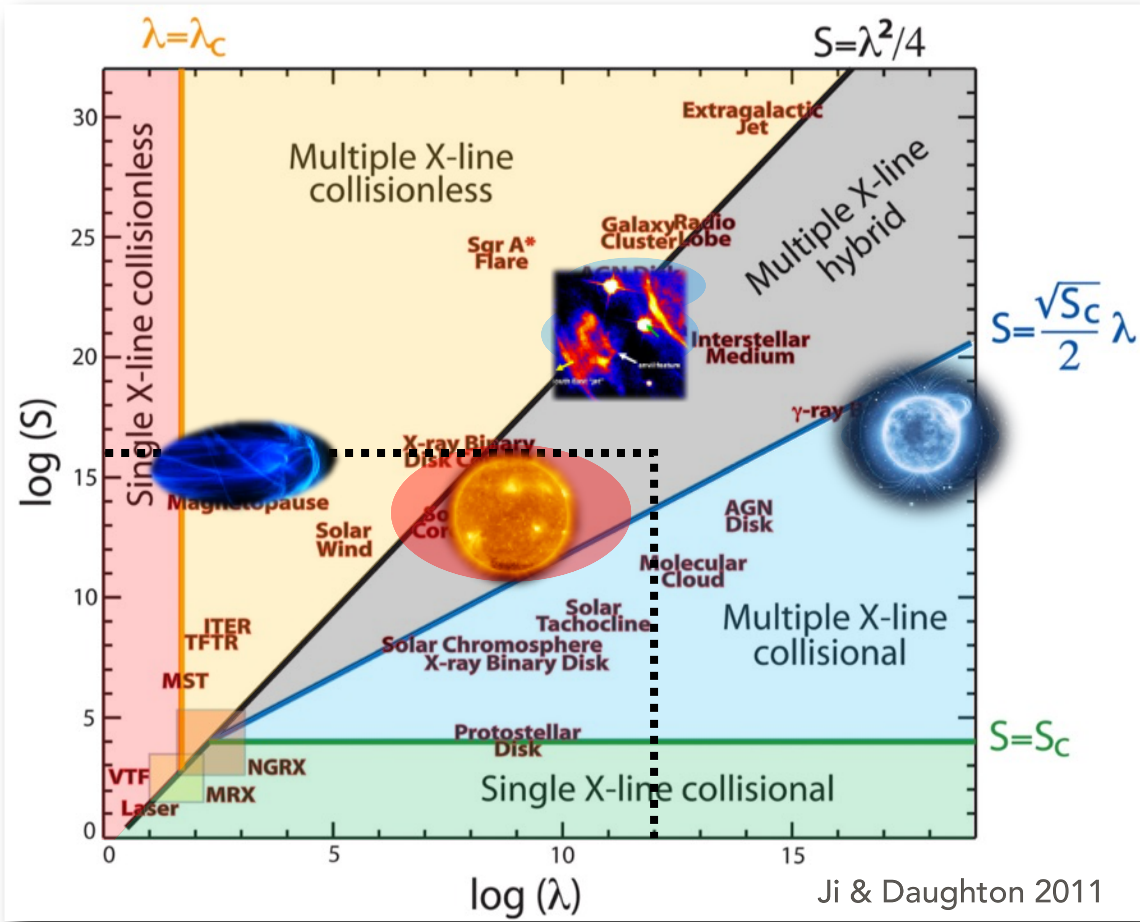
How are particles accelerated
in very short time?

Magnetic Reconnection

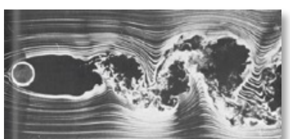
MR is fundamental plasma process and ubiquitously occurs in the universe.

Lundquist number

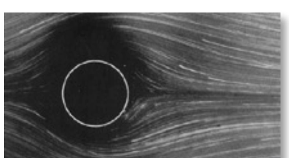
$$S \equiv \frac{\mu_0 V_A L_{CS}}{\eta}$$



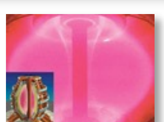
Cf. Reynolds number



$R_e = 10^4$



$R_e = 1.54$



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

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**

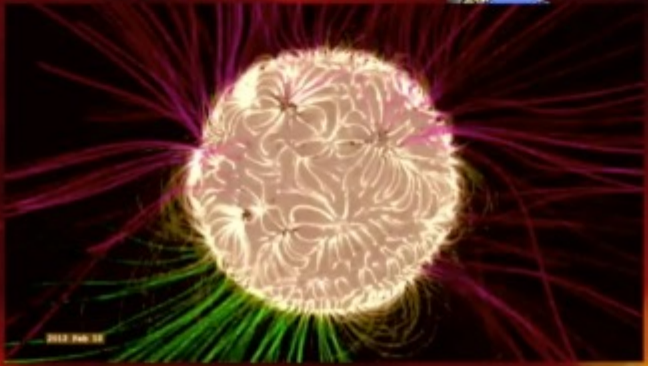
[Impacts on the Earth and social environments]

The mother of the Earth

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

[As a star]

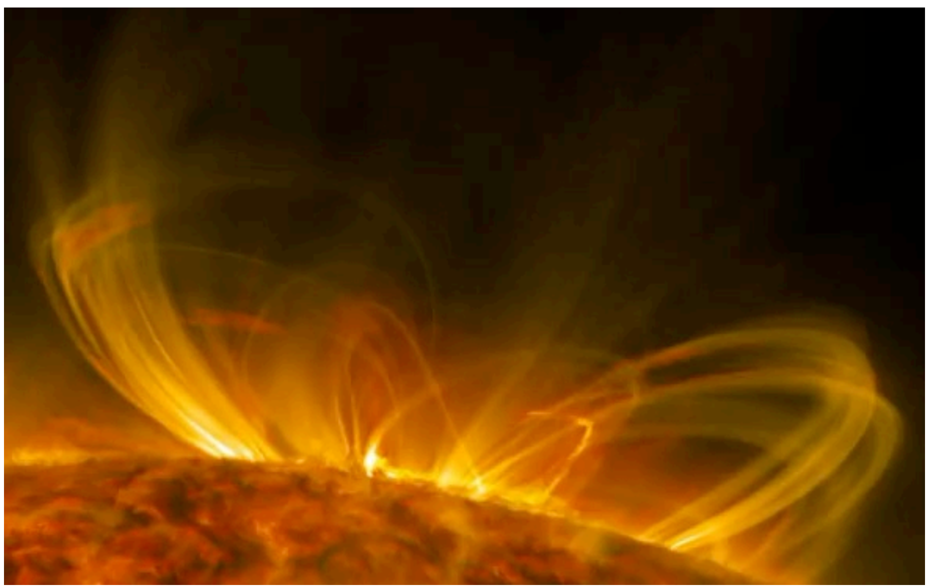
- **Reference of other astrophysical objects**



2011−09−12 05:34:16 UT

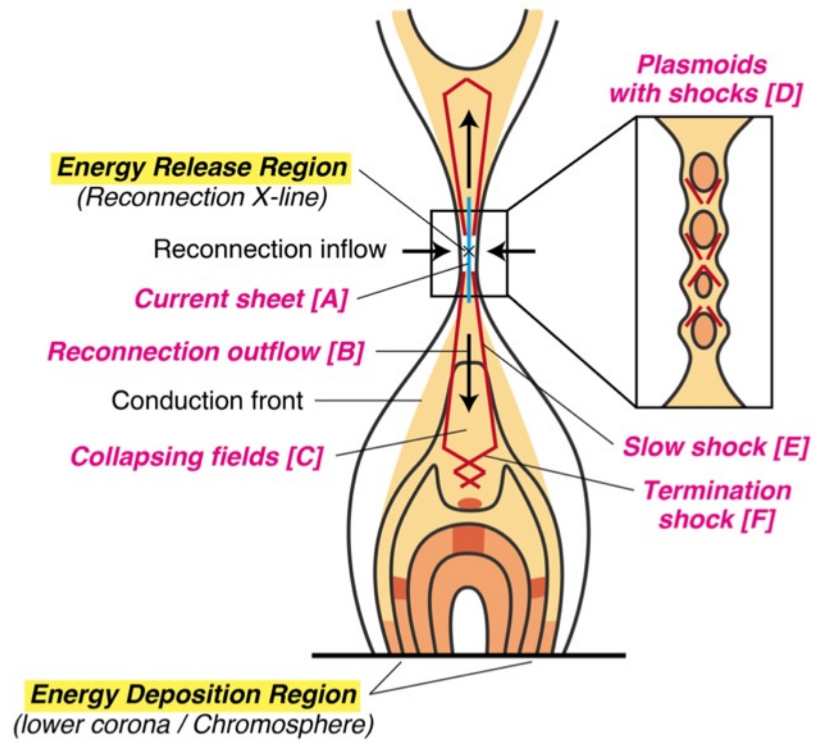
Magnetic Reconnection Picture in Solar Flare
has been established by both observation and theory.

Observation



SDO Spots X8.2-Class Solar Flare,
Sep 10, 2017

Model



Magnetic Reconnection Picture in Solar Flare
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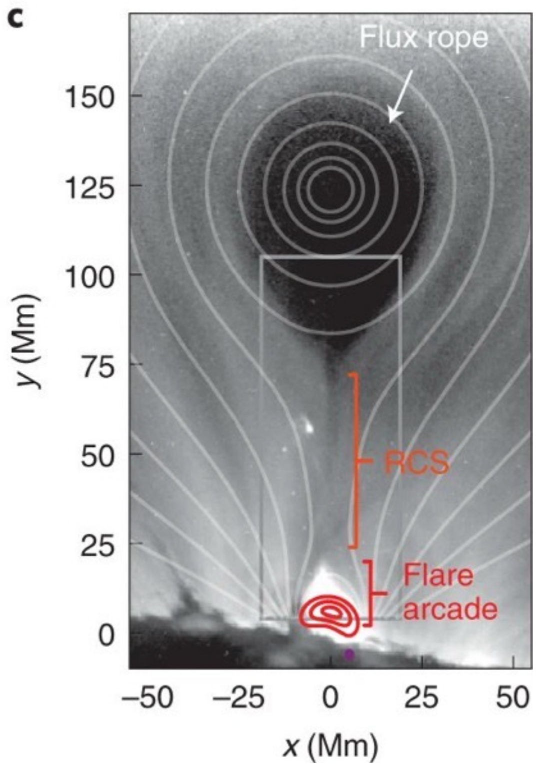
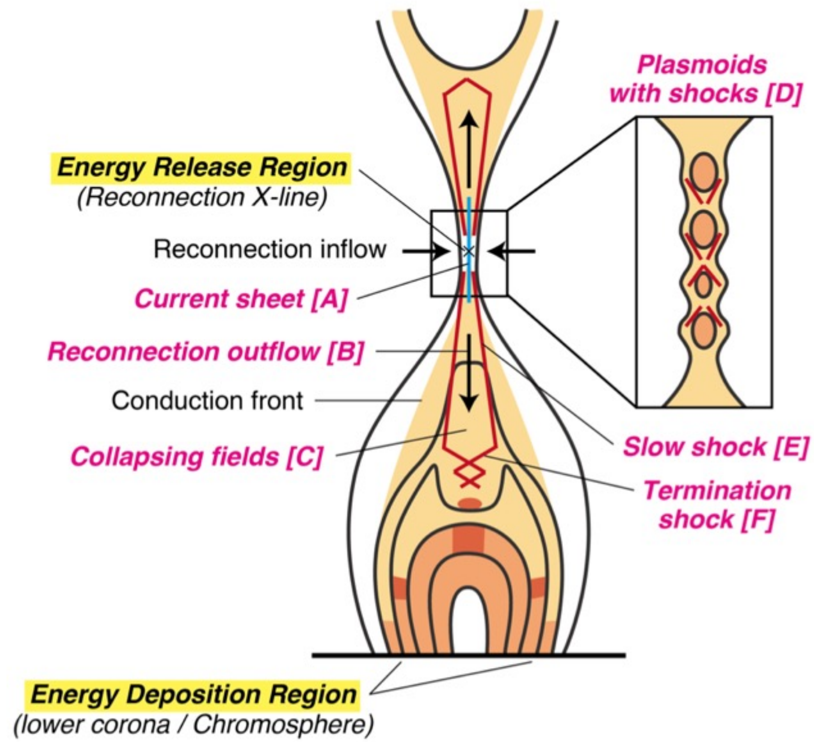
Observation



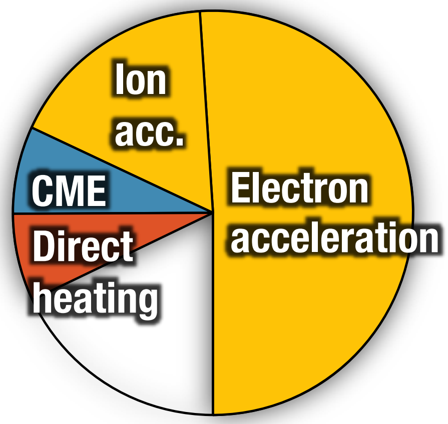
Model



Magnetic reconnection & Particle acceleration in solar flare

1. A solar flare is an efficient accelerator.

Aschwanden et al. (2017)

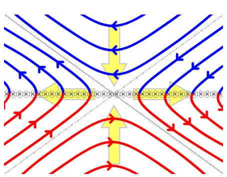


Elec/magnetic energy = 0.51+0.17
Ions/magnetic energy = 0.17+0.17
CME/magnetic energy = 0.07+0.14
direct/magnetic energy= 0.07+0.17

ENERGY CLOSURE :
Sum/magnetic energy = 0.87+0.18

Magnetic Energy

Magnetic reconnection



Kinetic Energy (Bulk motion)

Thermal Energy

Particle Acceleration

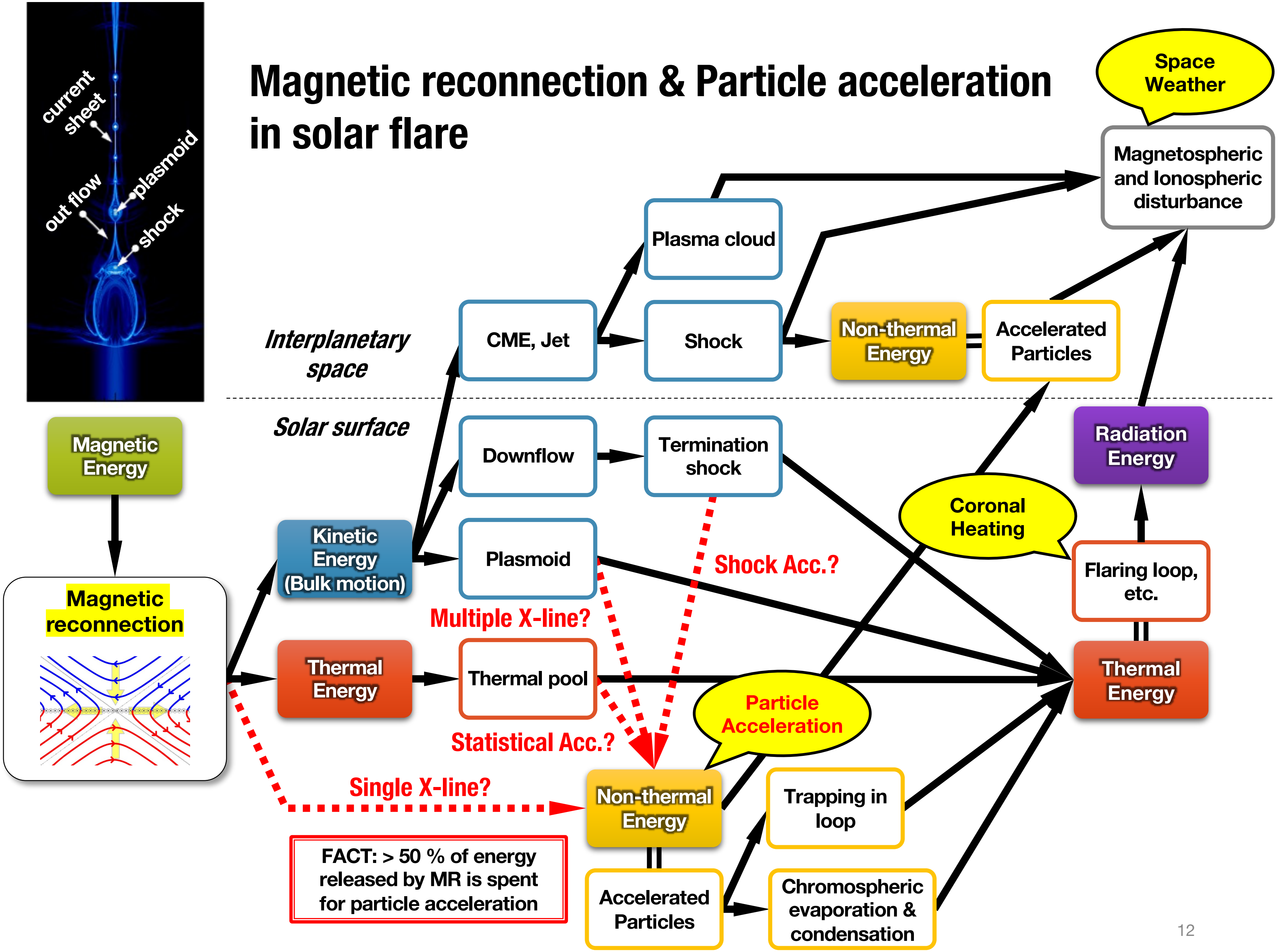
Non-thermal Energy

Accelerated Particles

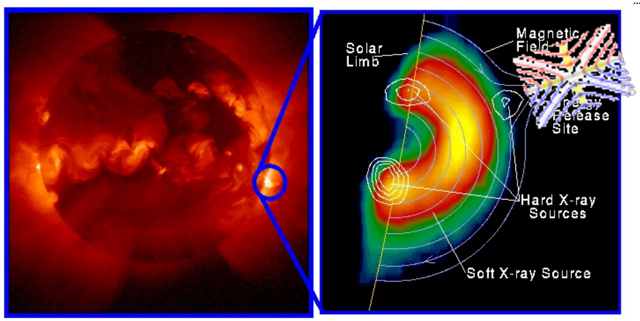
FACT: > 50 % of energy released by MR is spent for particle acceleration

2. The particle acceleration is a key to energy release and conversion in solar flares.

Magnetic reconnection & Particle acceleration in solar flare



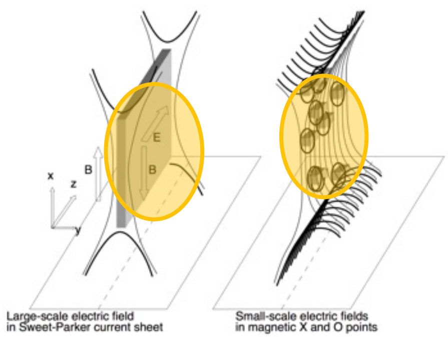
Particle Acceleration is one of the long-standing major puzzles in solar physics



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

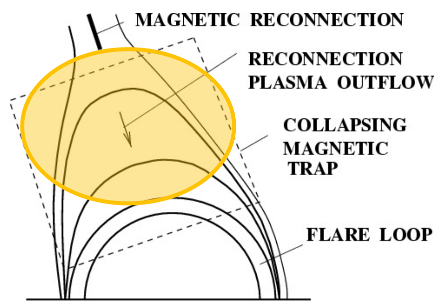
[Reason 1] Poor observations, especially for the energy release region (around the X-point)

DC acceleration?



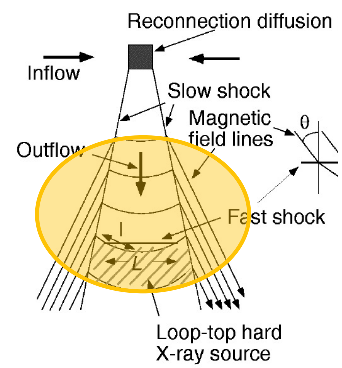
Aschwanden (2002)

Collapsing magnetic traps?



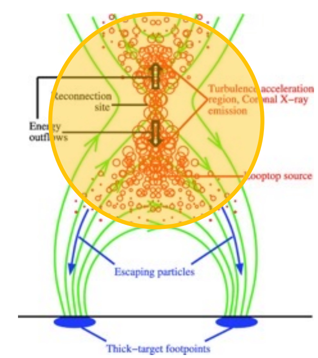
Karlicky & Kosugi (2004)

Shocks?



Tsuneta & Naito (1998),
Takasao & Shibata (2016)

Turbulence?



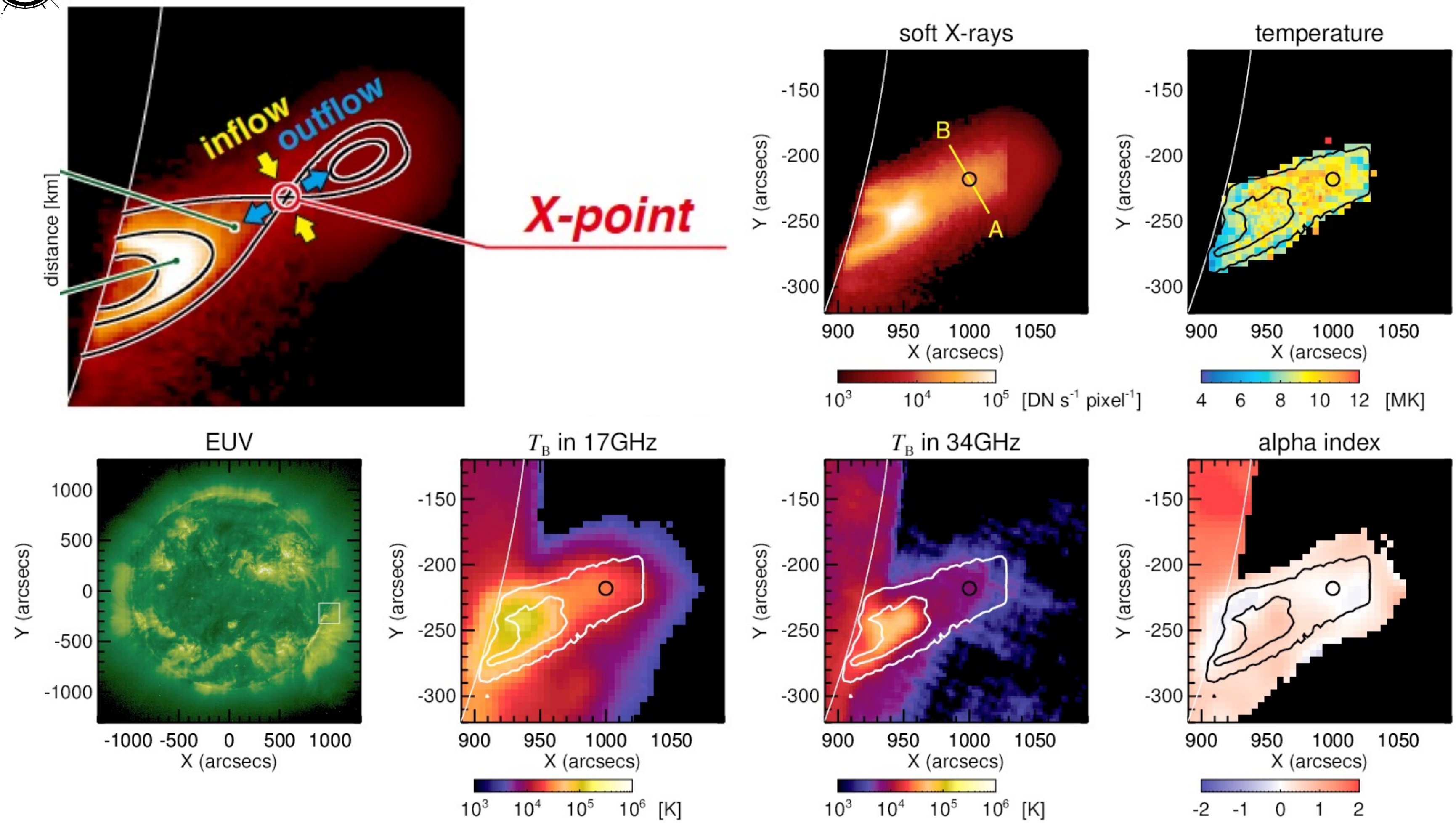
Liu et al. (2008),
Petrosian, (2012)

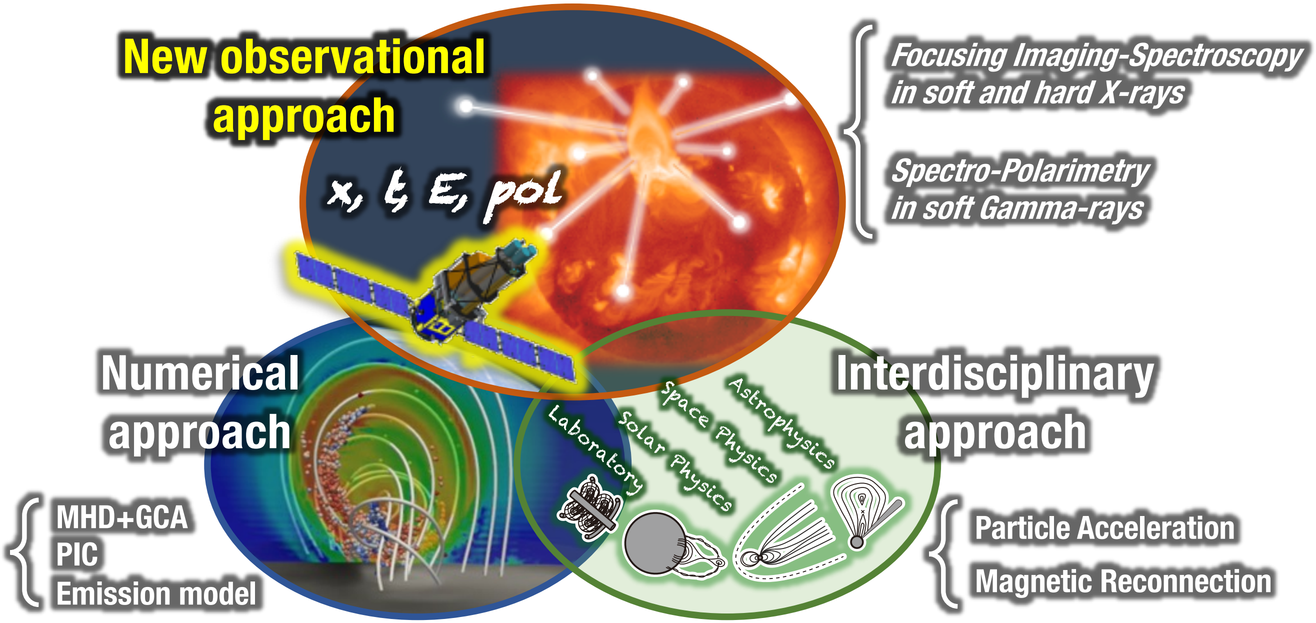
Accelerator	MHD scale	~ 10^7 - 10^{10} cm (Size of plasma structures)	~ 10 sec (Alfven time)
Accelerated Particles	Particle scale	~ 10^0 - 10^2 cm (Electron - Ion Larmor radius)	<< 1 sec

⇕ *[Reason 2] Huge scale gap in both space and time!!*

Non-thermal component around X-point

Narukage et al. (2014) ApJ, 787, 125





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')

Why X-rays and Gamma-rays?

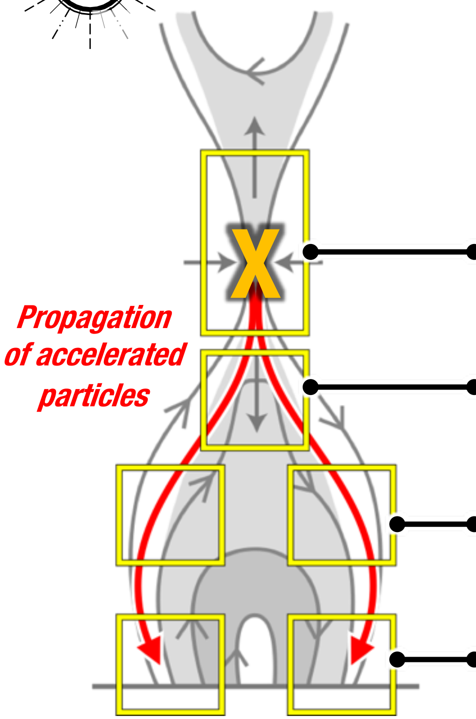
– comparison with spectroscopy in other wavelengths

Significant	New by PhoENiX	Collaboration

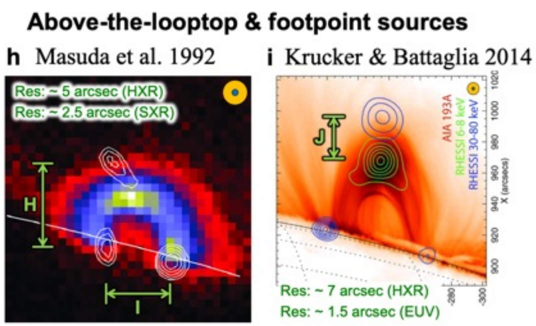
Wavelength	EUV	Soft X-rays	Hard X-rays	Gamma-rays	Radio
Energy	< 0.1 keV	0.1 – 10 keV	10 – 100 keV	0.1 – 1 MeV	0.1 – 1 MeV
Common properties					
Dynamic range	✅✅	✅✅✅	✅✅✅		✓
Field of view	✅✅	✅✅✅	✅✅✅		✅✅✅
Spatial sampling	✅✅✅	✅✅	✅✅		✓
Temporal sampling	✅✅	✅✅✅	✅✅✅	✅✅✅	✅✅✅
For investigation of thermal plasmas (possible agents of particle acceleration)					
Temperature diagnostic capability	✅✅✅	✅✅✅	✅✅		
Response speed to temperature change	✓	✅✅✅	✅✅✅		
Velocity measurement of bulk plasma	✅✅✅	✅✅	✅✅		✓
For investigation of non-thermal plasmas (particle acceleration)					
Accelerat<u>ing</u> electrons	(✓)	✅✅✅	✓		
Accelerat<u>ed</u> electrons	(✓)	✓	✅✅✅	✅✅✅	✅✅✅
Low energy cutoff		✅✅	✓		
Maximum energy				✅✅	
Electron anisotropy				✅✅	✓
Magnetic field measurement					
Magnetic field measurement					✓

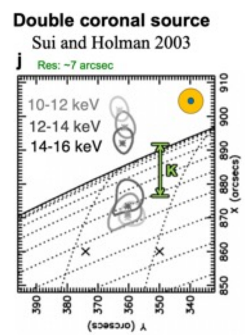
Required measurements to trace the accelerated particles in MHD-scale solar flare system

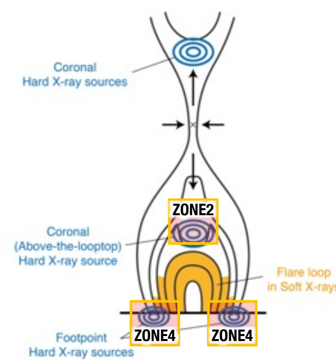
(Update from past or existing observations)

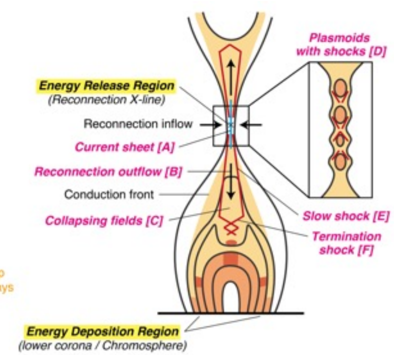


ZONE	Structural characteristic	Property in particle acceleration point of view	Observational capability: Past or existing obs.	Observational capability: Requirements for new obs.
ZONE1	Around reconnection site	• Energy release region ➔ Possible acceleration site	Few samples in X-ray obs.	Plasma diagnostic capability for both thermal and non-thermal plasmas in all the ZONEs and capability to track the propagation of accelerated particles
ZONE2	Above-the-loop-top	• Boundary between rare and dense plasmas ➔ Possible acceleration site	Sometimes observed as hard X-ray coronal sources	
ZONE3	Flare loop	• Transit area • Trapping area ➔ Possible acceleration site	Few samples in hard X-ray obs.	
ZONE4	Foot points of the flare loop (Solar surface)	• Energy deposition region • Mirroring region	Observed in many flares as the brightest hard X-ray source	



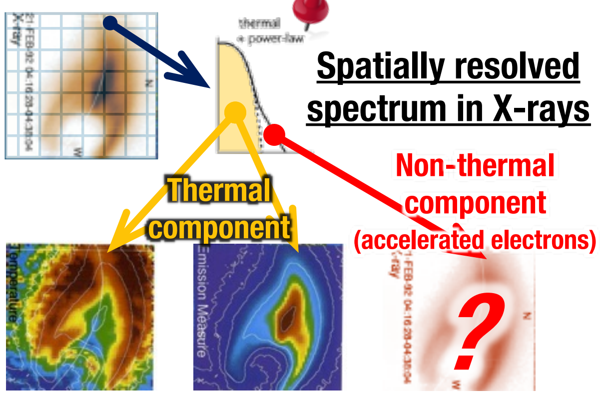




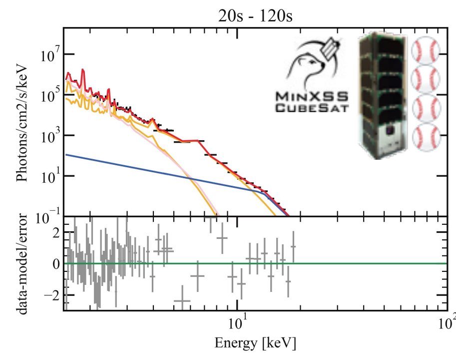


Observational Approach for Scientific Objectives

Spatially resolved spectrum in X-rays

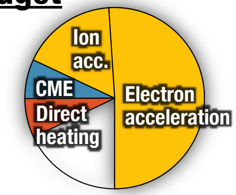


Temporal evolution of spectrum



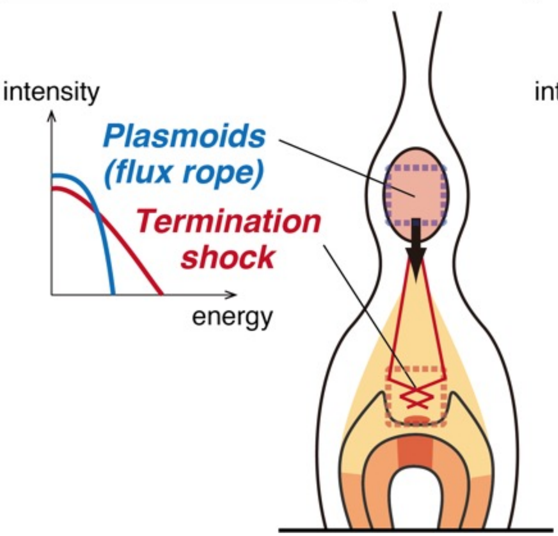
Energy transportation & budget

- Released magnetic energy $= E_{B\_pre\text{-}flare} - E_{B\_post\text{-}flare}$

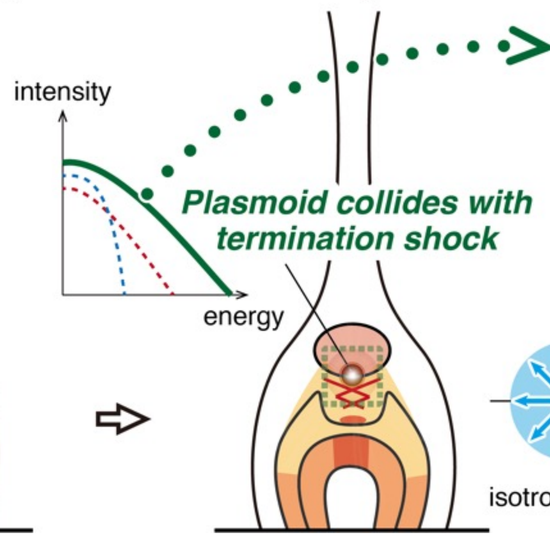


- Kinetic energy of bulk plasma $= 1/2\ N_p\ m_p\ v^2$
- Thermal energy $= \int 3/2\ N\ k_B\ T\ \underline{dT}$
- Energy of accelerated particles $= \int N_{NT}\ E_{NT}\ \underline{dE}$

Scientific Objective 1
where?



Scientific Objective 2
when?



Parameters obtained from spectroscopy

Power-Law Index
Relative Intensity
Lower/Higher Energy Cut-off
Break Energy

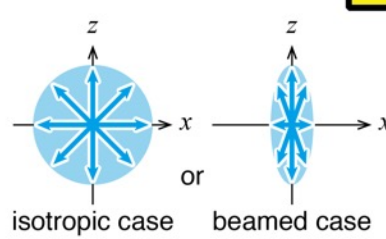
Theory / Model

Numerical Simulation

Laboratory Experiment

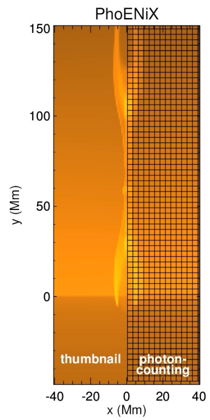
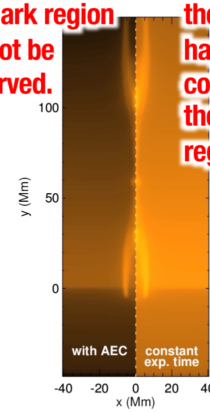
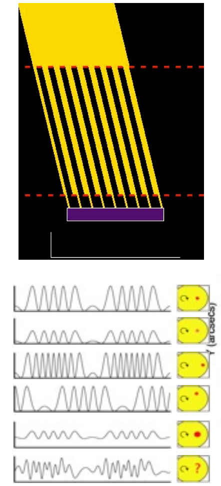
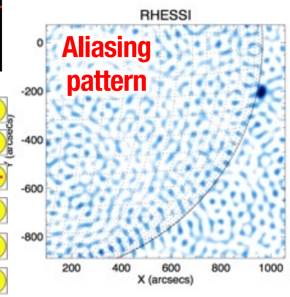
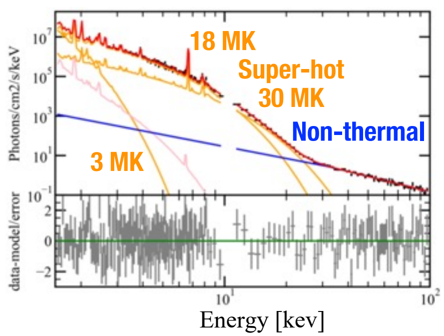
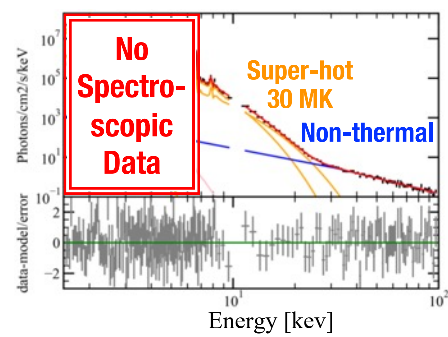
Comparison with other observations than solar

Scientific Objective 3
how?



Parameters obtained from polarimetry

Direction of polarization
Degree of polarization

Capability	PhoENiX	Other (past or existing) X-ray missions
Dynamic Range To observe entire ZONEs	 [SXR & HXR] Focusing optics (mirror) + CMOS or CdTe	In the case of short exposure, the dark region cannot be observed. In the case of long exposure, the blooming happens and contaminates the dark region.  [SXR] Focusing optics (mirror) + CCD  [HXR] with modulation collimator
Imaging Spectroscopy SXR: • Thermal plasma • Accelerating e$^-$ • Low energy cutoff HXR: • Accelerated e$^-$	 [SXR & HXR] Imaging spectroscopy	 [SXR] Mainly Imaging only [HXR] Imaging spectroscopy

<table>
<tr><th>Capability</th><th>PhoENiX</th><th>Other (past or existing) X-ray missions</th></tr>
<tr><td>

<u>Polarization</u>

- **Electron anisotropy** (velocity angle to the guiding magnetic field)
- **High energy cutoff** (highest energy electrons produced by the acceleration conditions: mechanism, spatial extent, and time)

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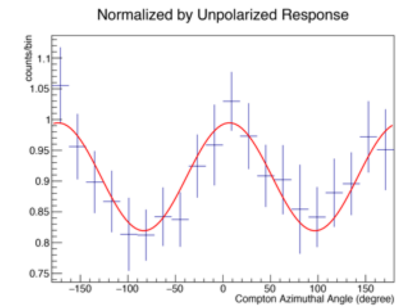
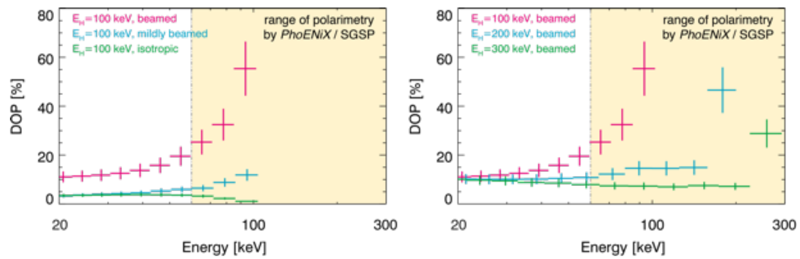


Minimum detectable polarization degree < 10%

🡐 Expected modulation polarization with PhoENiX for 60 – 300 keV in an M3.4 flare. Assumed polarization degree is 20%.



Jeffrey et al. (2020)

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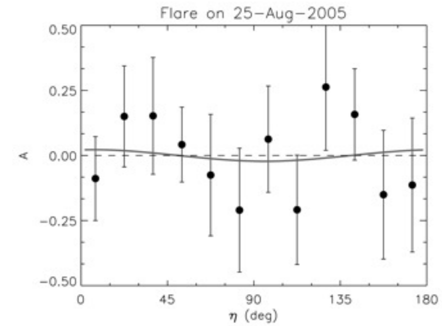
Polarization = 6 ± 25% for 100 – 350 keV in M7 flare



Suarez-Garcia et al. (2006)

There are some studies to estimate the polarization in solar flares with RHESSI. But <u>RHESSI is not designed (calibrated) to derive the polarization.</u>

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Energy Coverage

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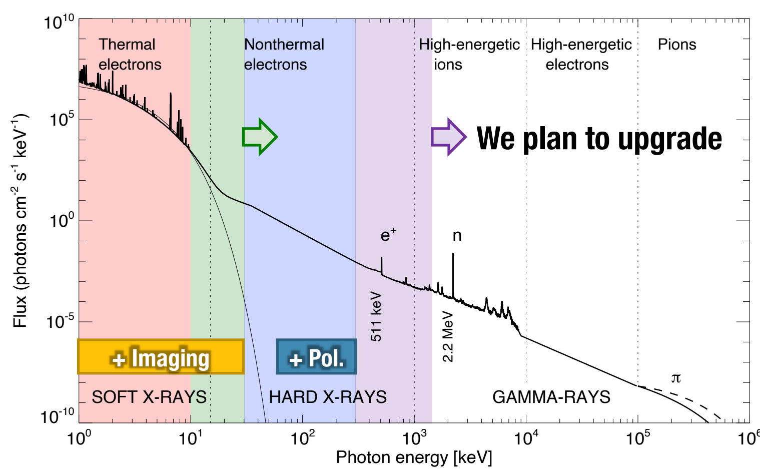

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Specification of the PhoENiX instruments

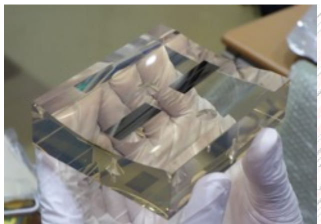
観測能力	要求値	根拠
太陽フレアを観測するために必要な性能（全てのエネルギー帯域の観測に共通の要求）		
視野	> 360×360 arcsec^2	フレア領域全体が視野に収まること
観測時間	> 10 minutes	少なくとも、フレア発生前からフレアピークまでを観測できること
時間分解能	< 10 sec per spectrum < 1 sec per lightcurve	スペクトルに対してはAlfvén時間で規定 ライトカーブに対しては加速電子の伝搬時間で規定
太陽フレアシステムが生み出すプラズマ構造（加速源）と加速中の電子集団を調査するために必要な性能：軟X線集光撮像分光		
エネルギー範囲	0.5 keV – 10 keV	プラズマ構造の温度（熱的スペクトル）と、加速中の電子の情報（熱的分布から乖離していくスペクトル）が取得できること
エネルギー分解能	< 0.2 keV (FWHM)	物理情報を引き出すために、輝線群と連続光成分が分離可能なこと
空間分解能	< 2 arcsec (FWHM)	磁気再結合が生み出す構造にはスケールフリーなものが含まれるため、次の様に設定する。大規模フレア（$\sim 10^5$ km ~ 140”）では各ZONE内を分解し各プラズマ構造が識別できること。小規模なフレア（$\sim 10^4$ km ~ 14”）では少なくともフレア領域をZONE1〜4に分離できること。
ダイナミックレンジ	> 10^4	フレアループが増光しても、全てのZONEをくまなく観測できること
スペクトル毎の光子数	> 1600 photons	温度・密度の測定誤差を10% 以下に収めること
加速された電子集団の検出と、その伝搬を追跡するために必要な性能：硬X線集光撮像分光		
エネルギー範囲	5 keV – 30 keV	加速電子の情報（熱的分布から乖離した冪型スペクトル）の取得のため
エネルギー分解能	< 1 keV (FWHM)	加速状態が異なる成分（冪型スペクトルの折れ曲り）も検出できること
光源位置の決定精度	< 2 arcsec	空間分解したプラズマ構造（加速源候補）に対して、加速電子が存在する領域の位置を決定することが重要であり、その精度は、プラズマ構造の調査に必要な空間分解能と同じである必要がある。なお、この位置決定精度を達成するため、その2倍程度の空間分解能も必要である。
空間分解能	< 4 arcsec (FWHM)	
ダイナミックレンジ	> 10^3	ループの足元が増光しても、全てのZONEをくまなく観測できること
スペクトル毎の光子数	> 3200 photons	加速電子の総数の測定誤差をファクター2以下（50%〜200%）に収めること
加速された電子の運動の非一様性と最高到達エネルギーを調査するために必要な性能：軟ガンマ線偏光分光		
エネルギー範囲	20 keV – 300 keV, 数MeV	より高いエネルギーにまで加速された電子の情報を取得するため
エネルギー分解能	< 10 % (FWHM)	加速状態が異なる成分（冪型スペクトルの折れ曲り）も検出できること
測定可能な偏光度の下限値	< 10 % in >M5 class flares	加速電子の運動の非一様性を評価するため [6]。ただし測定手法に起因し、偏光測定のエネルギー範囲は60 keV – 300 keVになる。
スペクトル毎の光子数	> 500 photons	上記の偏光測定精度を達成するため

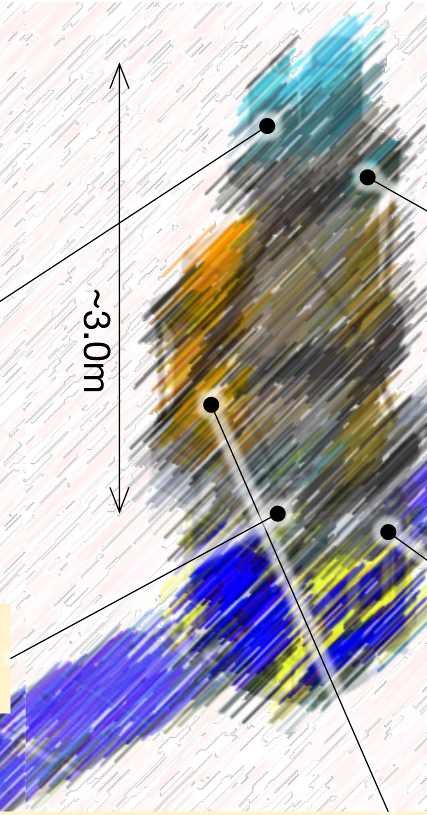
Instruments and Key technologies of PhoENiX

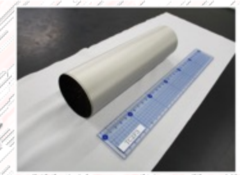
The basic developments of these technologies have been completed.

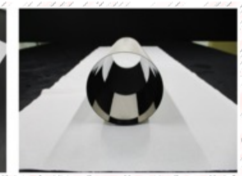
Soft X-ray Imaging Spectrometer (0.5 keV ~ 10 keV)

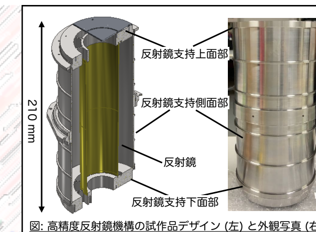
Hard X-ray Imaging Spectrometer (5 keV ~ 30 keV)





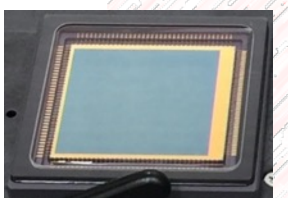


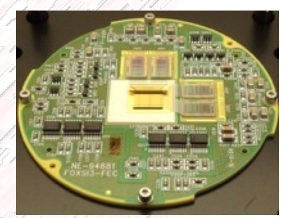




High-precision X-ray mirror
Resolution: < 2 arcsec
Low scatter: 10^{-4} @ 20 arcsec

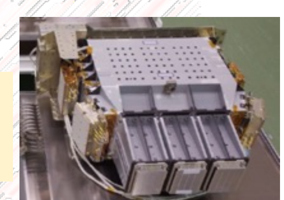
Large effective area X-ray mirror
Resolution: < 4 arcsec (FWHM)





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

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



Soft Gamma-ray SpectroPolarimeter

(20 keV ~ > 300 keV (> 1 MeV))

Si/CdTe Compton camera with active shield
Polarization measurement: > 60 keV

FOXSI sounding rocket series

– Demonstration of SXIS & HXIS of PhoENiX

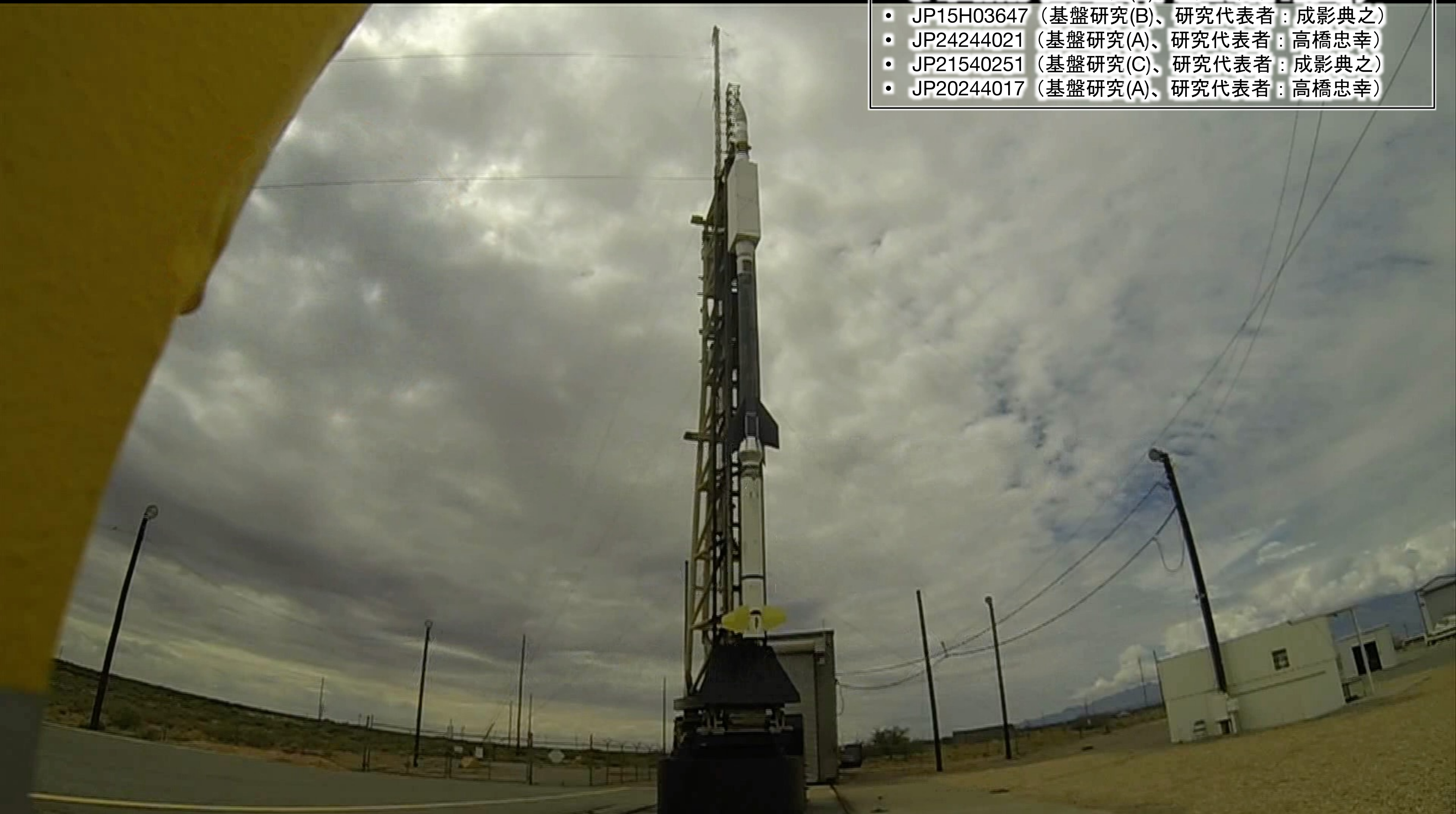
TODAY

	FOXSI-1 in 2012	FOXSI-2 in 2014	FOXSI-3 in 2018	FOXSI-4 in 2024
Obs. target	Quiet sun	Active region and Quiet sun	Full sun including Active region	**Solar flare**
Energy range	**Hard X-rays 5〜30 keV**		**Soft X-rays 0.5〜10 keV**	
Telescope	**7 shells x 7 modules**	**10 shells x 2 modules** 7 shells x 5 modules	(10 shells + **blocker**) x 1 (7 shells + **collimator**) x 2 10 shells x 3 modules 7 shells x 1 modules	**high resolution optics x 5** 10 shells x 2 modules
Detector	**Si (7.7 arcsec) x 7** **[for hard X-rays]**	**CdTe (6.7 arcsec) x 2** Si (7.7 arcsec) x 5 [for hard X-rays]	CdTe (6.7 arcsec) x 2 Si (7.7 arcsec) x 4 [for hard X-rays] + **CMOS (1.1 arcsec) x 1** **[for soft X-rays]**	CdTe (6.7 arcsec) x 5 [for hard X-rays] + CMOS (1.1 arcsec) x 2 [for soft X-rays]

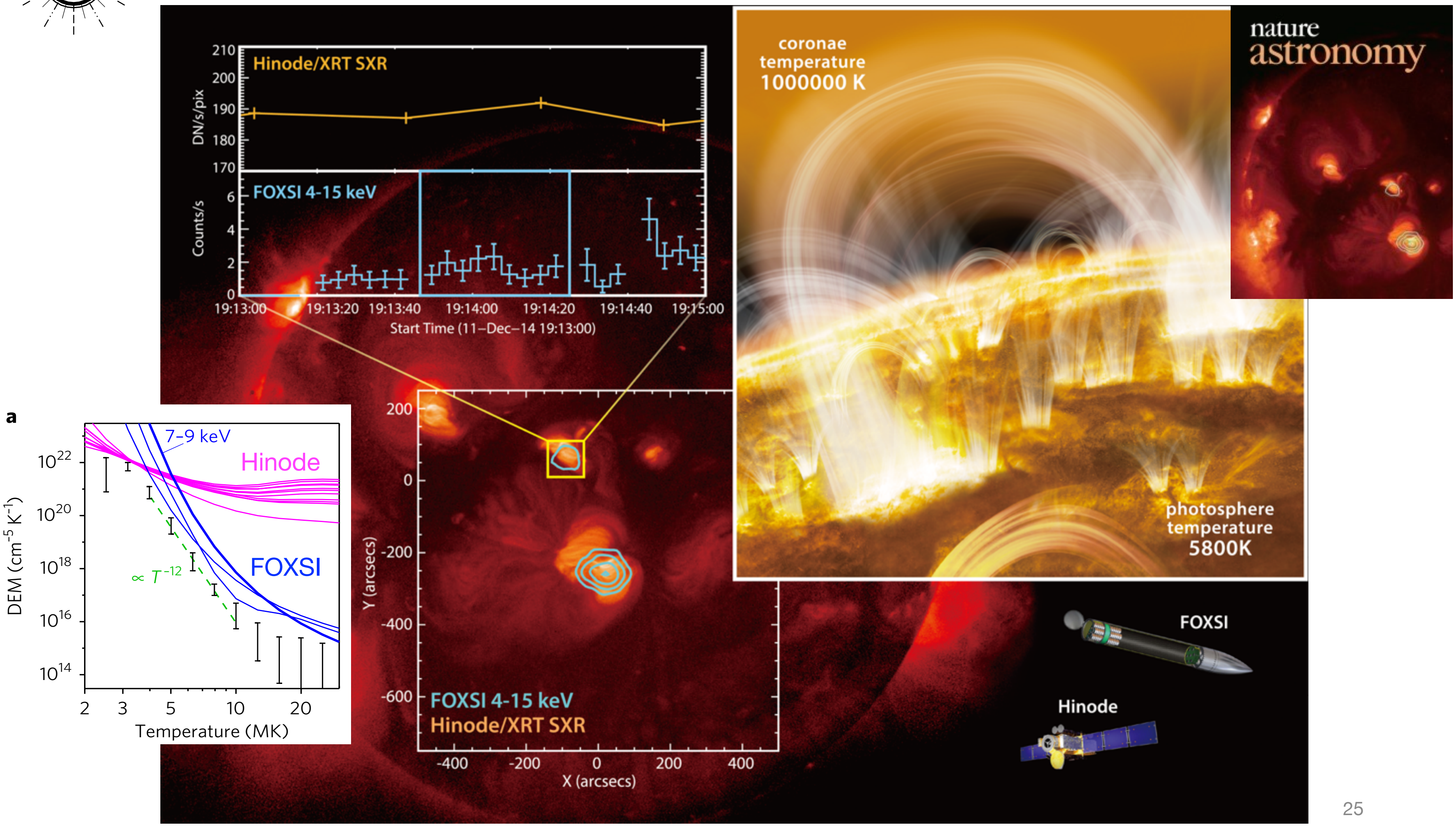
FOXSI-3 flight on 7 September 2018

本研究は、下記のJSPS科研費の助成を受けたものです。

- JP18H03724（基盤研究(A)、研究代表者：成影典之）
- JP17H04832（若手研究(A)、研究代表者：石川真之介）
- JP16H02170（基盤研究(A)、研究代表者：高橋忠幸）
- JP16H03966（基盤研究(B)、研究代表者：渡辺伸）
- JP15H03647（基盤研究(B)、研究代表者：成影典之）
- JP24244021（基盤研究(A)、研究代表者：高橋忠幸）
- JP21540251（基盤研究(C)、研究代表者：成影典之）
- JP20244017（基盤研究(A)、研究代表者：高橋忠幸）

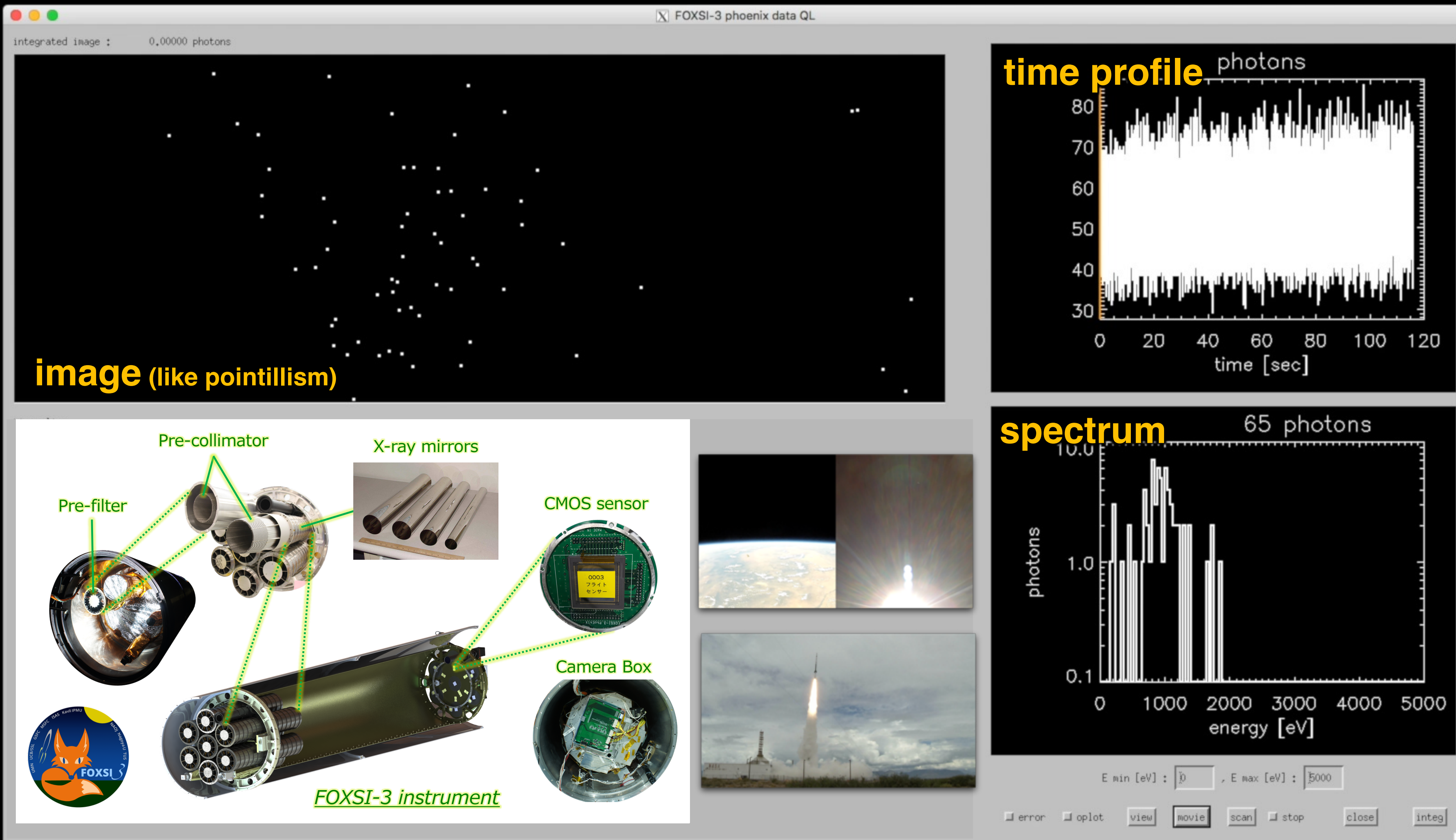


FOXSI-2 result was published from Nature Astronomy （Ishikawa et al. 2017）

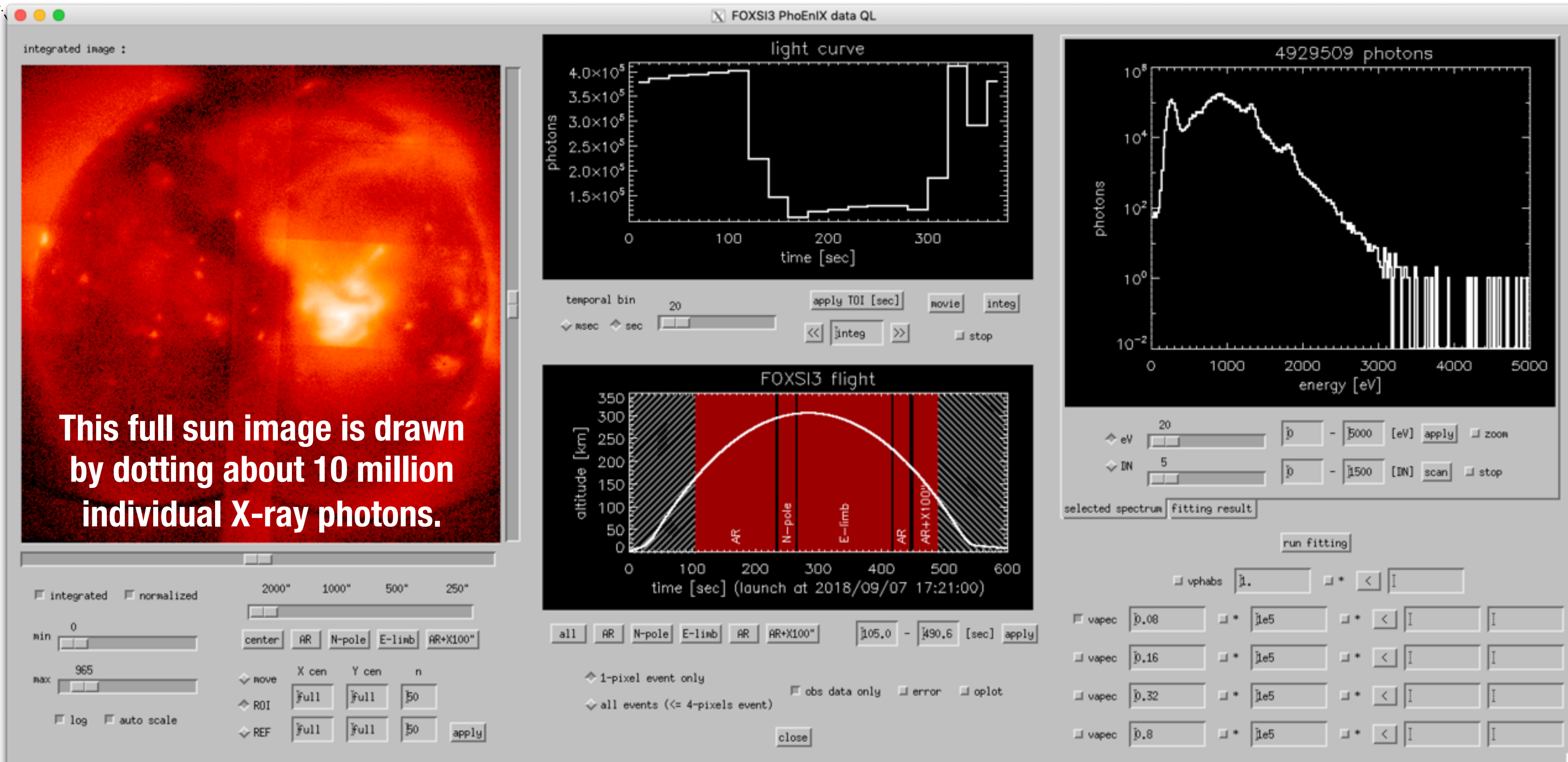


FOXSI-3 Soft X-ray data

250 FPS data (4 ms continuous exposure)



Data analysis software



Data analysis software (GUI tool) for FOXSI-3

1. Selection of area, timing and energy range
2. Adjustment of binning for space, time and energy
3. Spectral fitting with Xspec

This version is developed with IDL, which is widely used in solar physics community.

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)

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

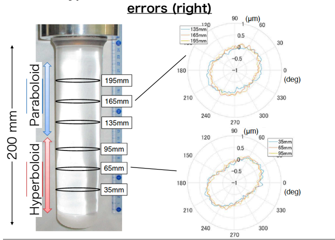
	Excellent	E/V G	Very Good	VG/ G	Good	G/F	Fair	F/P	Poor
'X': Overall grade.	X								

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

FOXSI-4 sounding rocket project

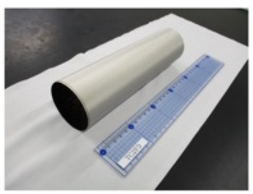
High-precision electroformed X-ray mirror

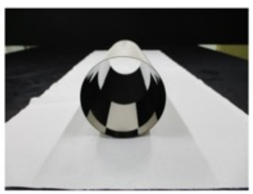
Wolter type I mandrel (left) and circumferential errors (right)



Goal (cf. FOXSI-3)

- <10” HPD (🡐 25” HPD)
- <4” FWHM (🡐 5” FWHM)





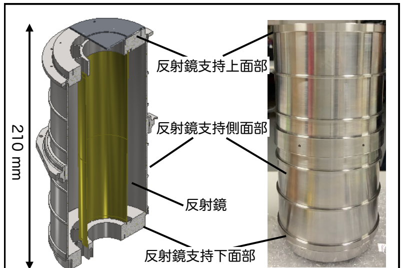
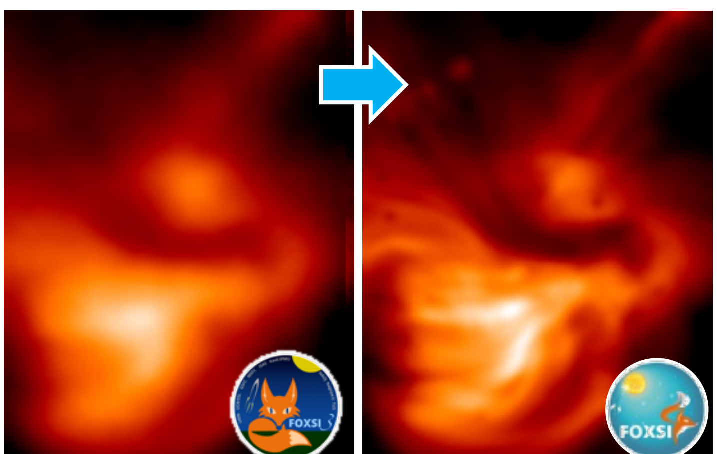


図: 高精度反射鏡機構の試作品デザイン (左) と外観写真 (右)

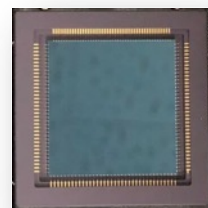


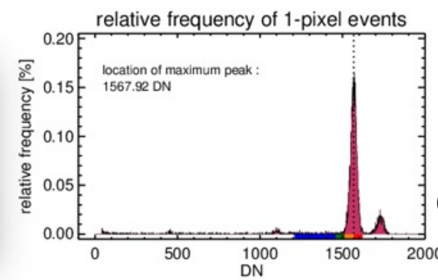
Updated CMOS (for soft X-rays) & CdTe (for hard X-rays) detectors

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

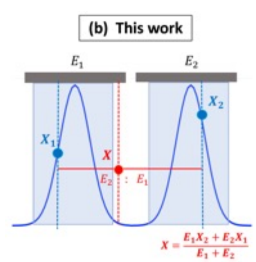


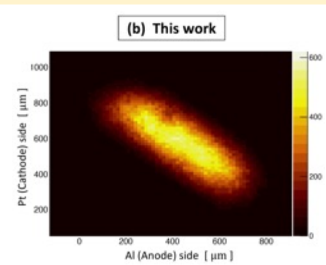


Photon counting capability of CMOS (with ^{55}Fe source)

CdTe detector (cf. FOXSI-3)

- Position resolution (~30 μm 🡐 60 um)
- High Count Rate (~5 k events / s / detector 🡐 500 events / s / detector)

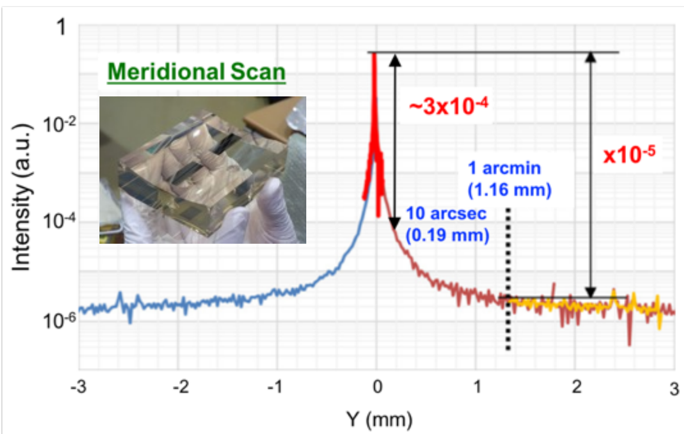


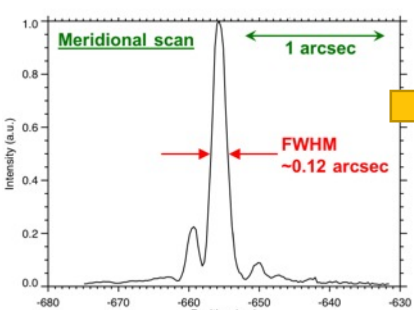


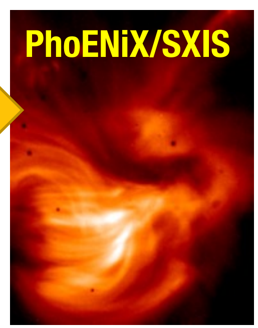
Sub-strip resolution (Furukawa et al., 2020)

Development of key technologies
– Soft X-ray mirror, Soft Gamma-ray spectropolarimeter

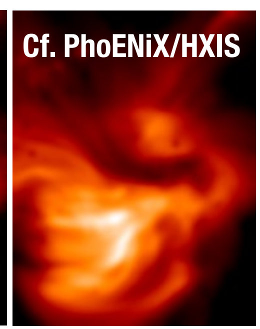
High precision soft X-ray glass-polished mirror





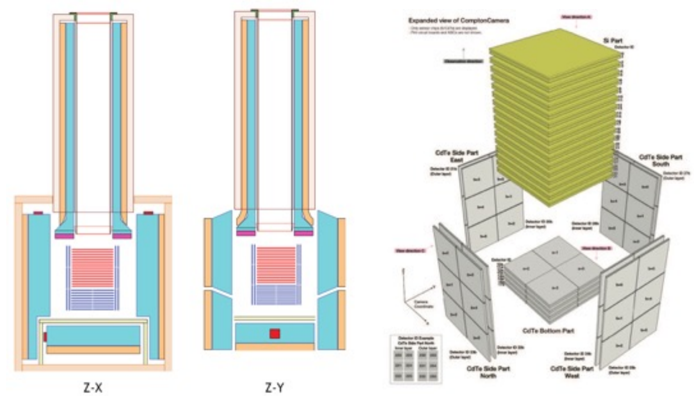


< 2” FWHM
(Hinode/XRT)

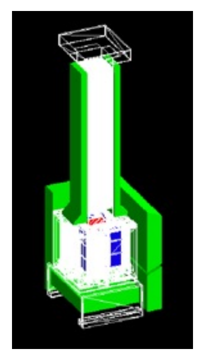


< 4” FWHM
(previous page)

Si/CdTe Compton camera with active shield

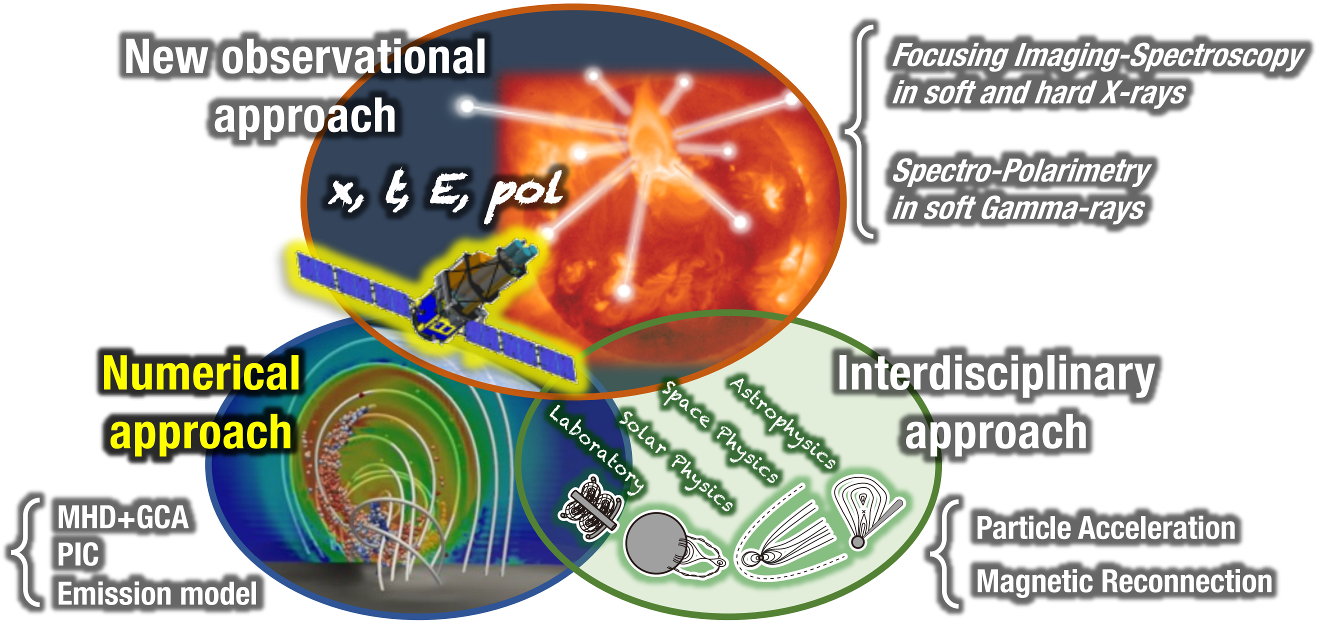


Design for PhoENiX: 1CC



BGO design as

- Active shield for **polarimetry**
- Detector to evaluate **maximum energy** (for above MeV detection)

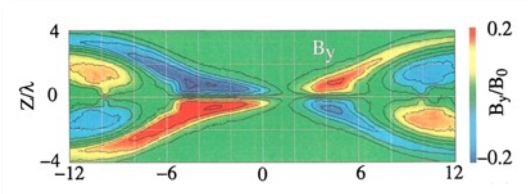


Science Objectives of *PhoENiX* mission

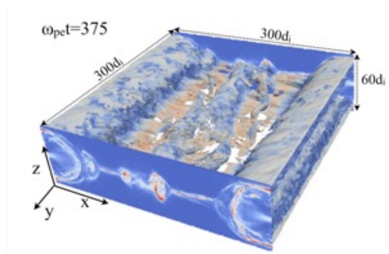
1. Identify particle acceleration sites in solar flares [where]
2. Investigate temporal evolution of particle acceleration [when]
3. Characterize properties of accelerated particles [how]

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

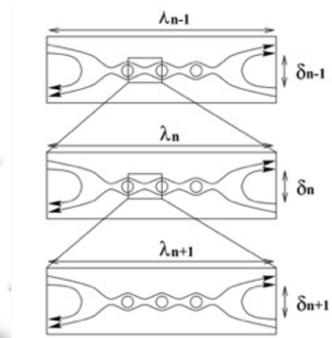
Numerical Approach



λ ~ 10 (Hoshino et al. 2001)



λ ~ 100 (Guo et al. 2015)

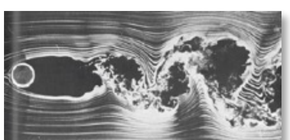


Model of Shibata & Tanuma 2001

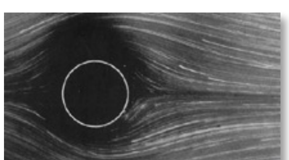
Lundquist number

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

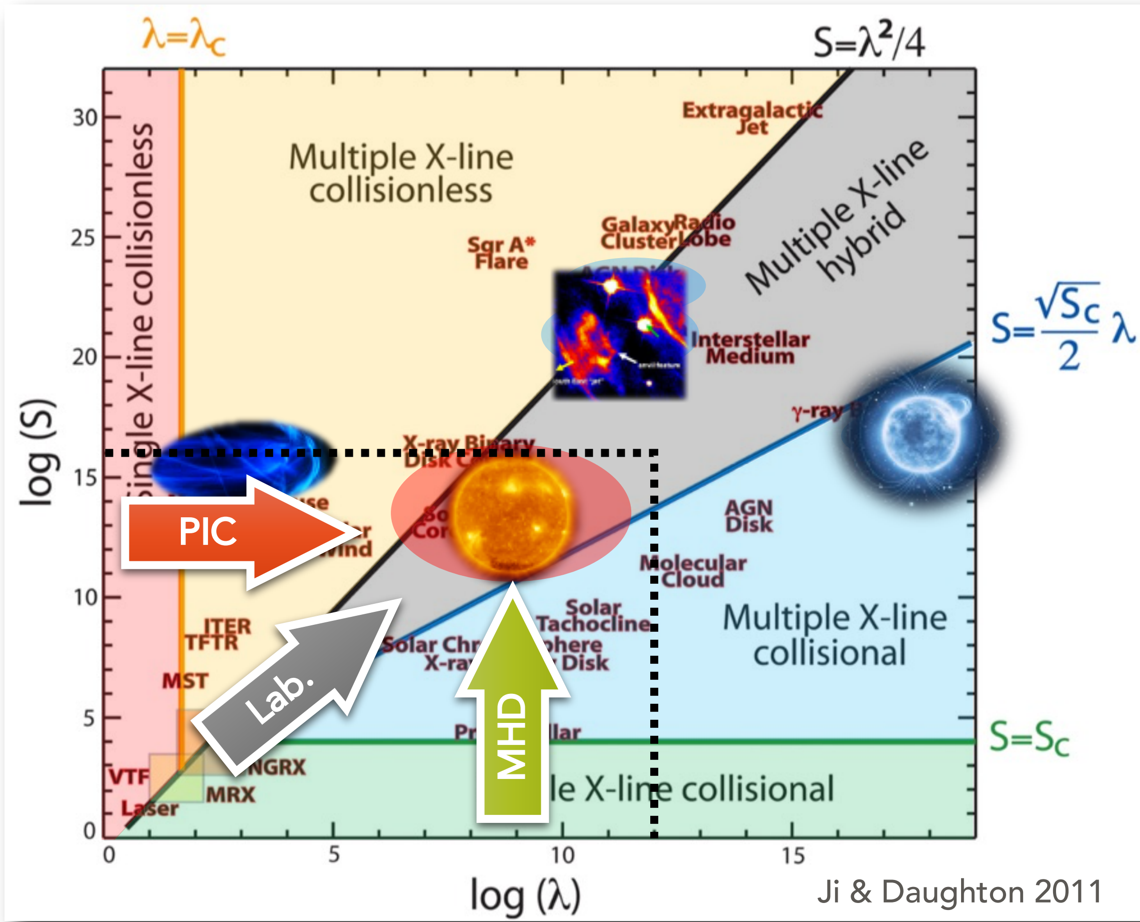
Cf. Reynolds number

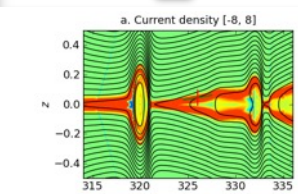


$R_e = 10^4$

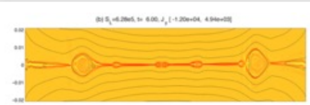


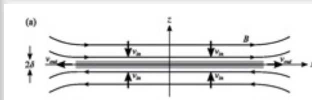
$R_e = 1.54$

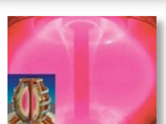




Dynamical Petschek $S < 10^6$ (Shibayama et al. 2015)

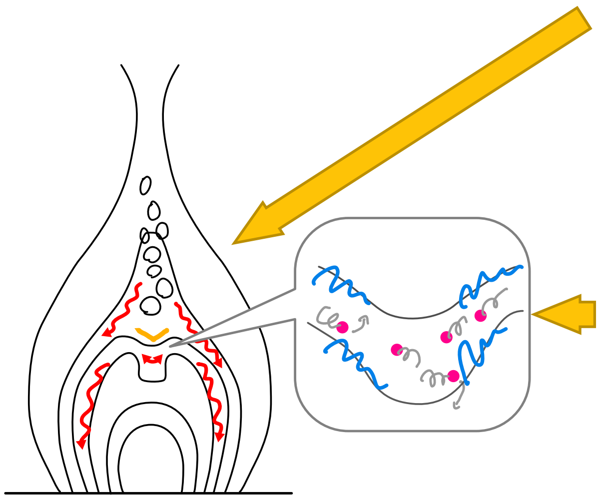

Plasmoid chain MR $10^4 < S < 10^6$


Sweet-Parker model $S < 10^4$



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

Strategy of numerical approach

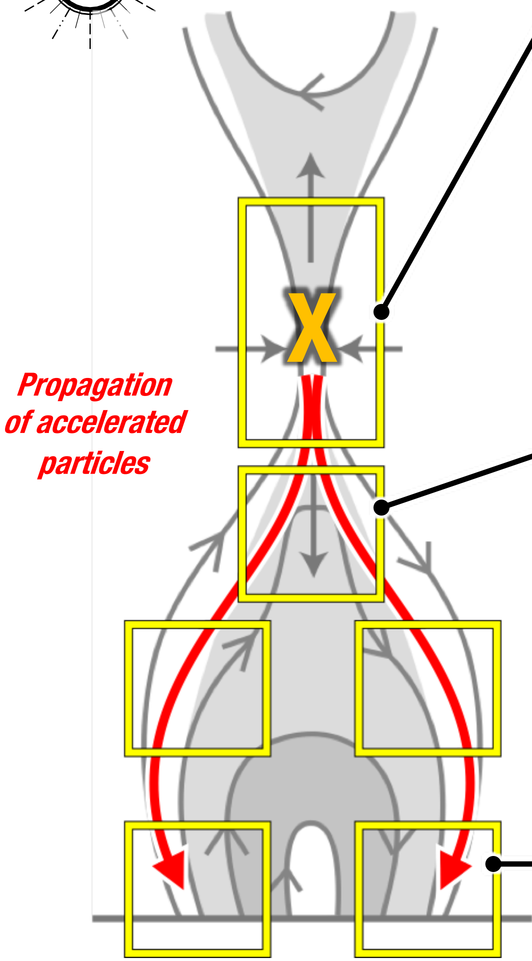


- **MHD calculation (~ 10^7 - 10^{10} cm) + test particle**
    - Determine global energy release process
    - Provide the magnetic field and velocity field structures (boundary conditions of particle calculations)
        - e.g., **Shocks, Magnetic mirror**
- **Particle calculation (~ 10^0 - 10^2 cm)**
    - e.g., **Scattering processes via the wave-particle interaction**, etc.

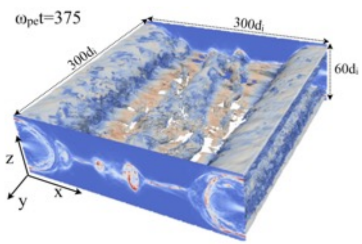
    →For example, pick up local regions and study acceleration & trapping processes using kinetic models (e.g., PIC)

- **Comparison between numerical simulation and observation**
    - via emission model
        - **Energy spectrum ⇔ Photon spectrum**
        - **Electron anisotropy ⇔ Polarization,** etc.

Numerical Approach to combine micro and macro scales for comparison with observations



Reconnection region

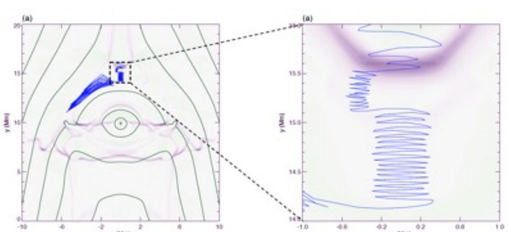


λ ~ 100 (Guo et al. 2015)

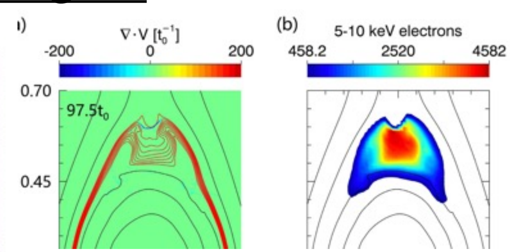
Huang & Bhattacharjee 2016

See also
Shibata & Tanuma 2001,
Drake et al. 2006, Oka et al. 2010,
Shibayama et al. 2015,
S. Wang, Yokoyama, Isobe 2015,
Kowal et al. 2017,
Hoshino 2017

Above-the-loop-top region



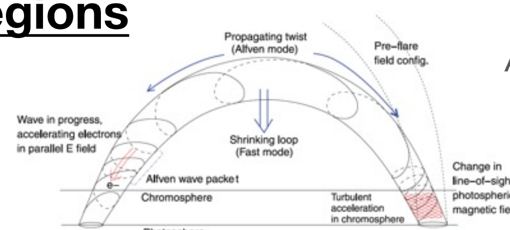
Kaneko & Takasao in prep.



X. Kong et al. 2019, 2020

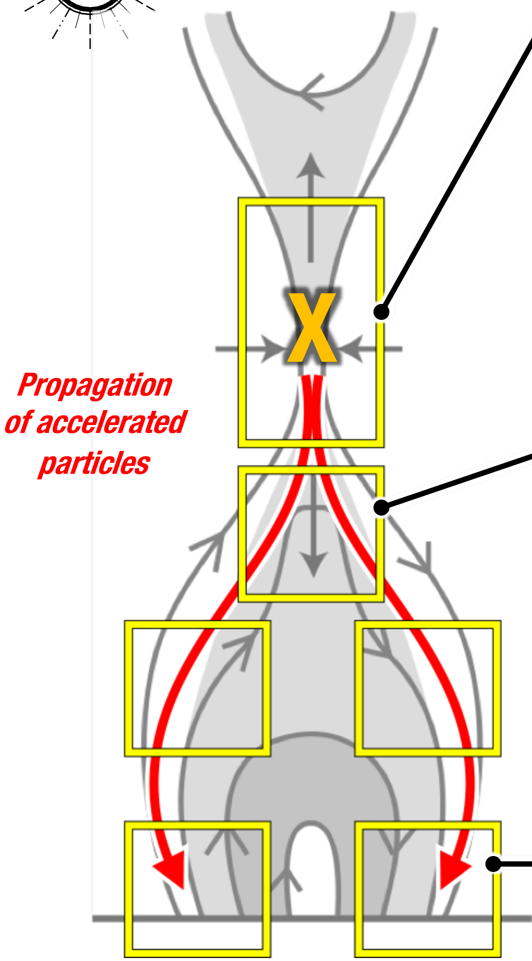
See also
Takasao & Shibata 2016,
Shen et al. 2018

Foot-point regions

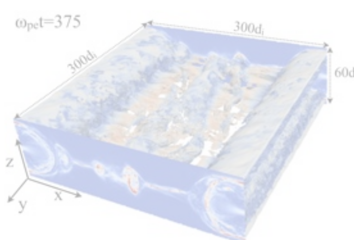


Acceleration by Alfven waves:
Fletcher & Hudson 2007,
Reep et al. 2018

Numerical Approach to combine micro and macro scales for comparison with observations



Reconnection region



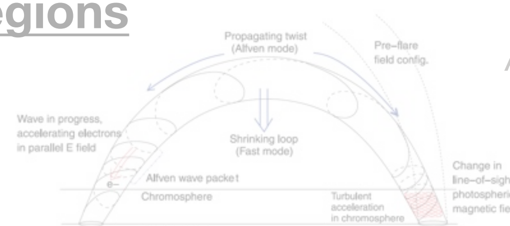
See also
Shibata & Tanuma 2001,
Drake et al. 2006, Oka et al. 2010,
Shibayama et al. 2015,
S. Wang, Yokoyama, Isobe 2015,
Kowal et al. 2017,
Hoshino 2017

Most previous studies focus on electron acceleration processes in specific regions in a solar flare system.

However, it is highly possible that electrons experience multiple accelerations, trapping, etc. at different locations.

So we need a model to combine them within a single framework for comprehensive understanding.

Foot-point regions



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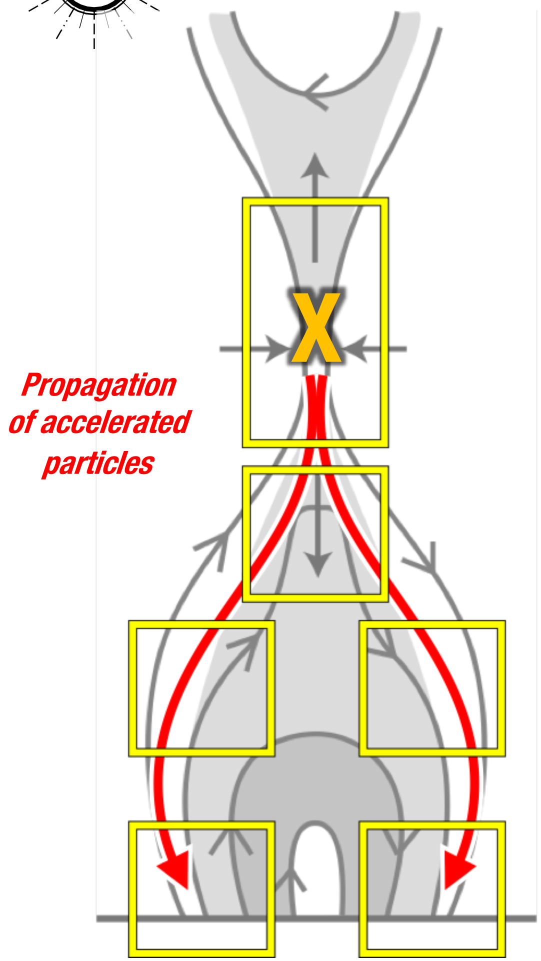


<u>Multi-zone model:</u>

Pick up the important regions (“zones”) for shaping electron energy spectra (acceleration, trapping, etc.).

Solve the approximated Fokker-Planck eq (e.g. Petrosian 2012) for multi-zones,

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial N}{\partial E}\right) - \frac{\partial}{\partial E}[(A - \dot{E}_L)N] \boxed{-\frac{N}{T_{\mathrm{esc}}}} + \boxed{\dot{Q}}$$

N(E) : electron energy distribution function

Escape to the next zone

Injection from the previous zone

Using the multi-zone model, we can

- Consider the propagation of electrons across multiple structures
- Examine/test different acceleration mechanisms by trying corresponding coefficients (*A*, D_{EE}, etc) for each zone
  → Identify electron acceleration/propagation processes through comparisons with observations

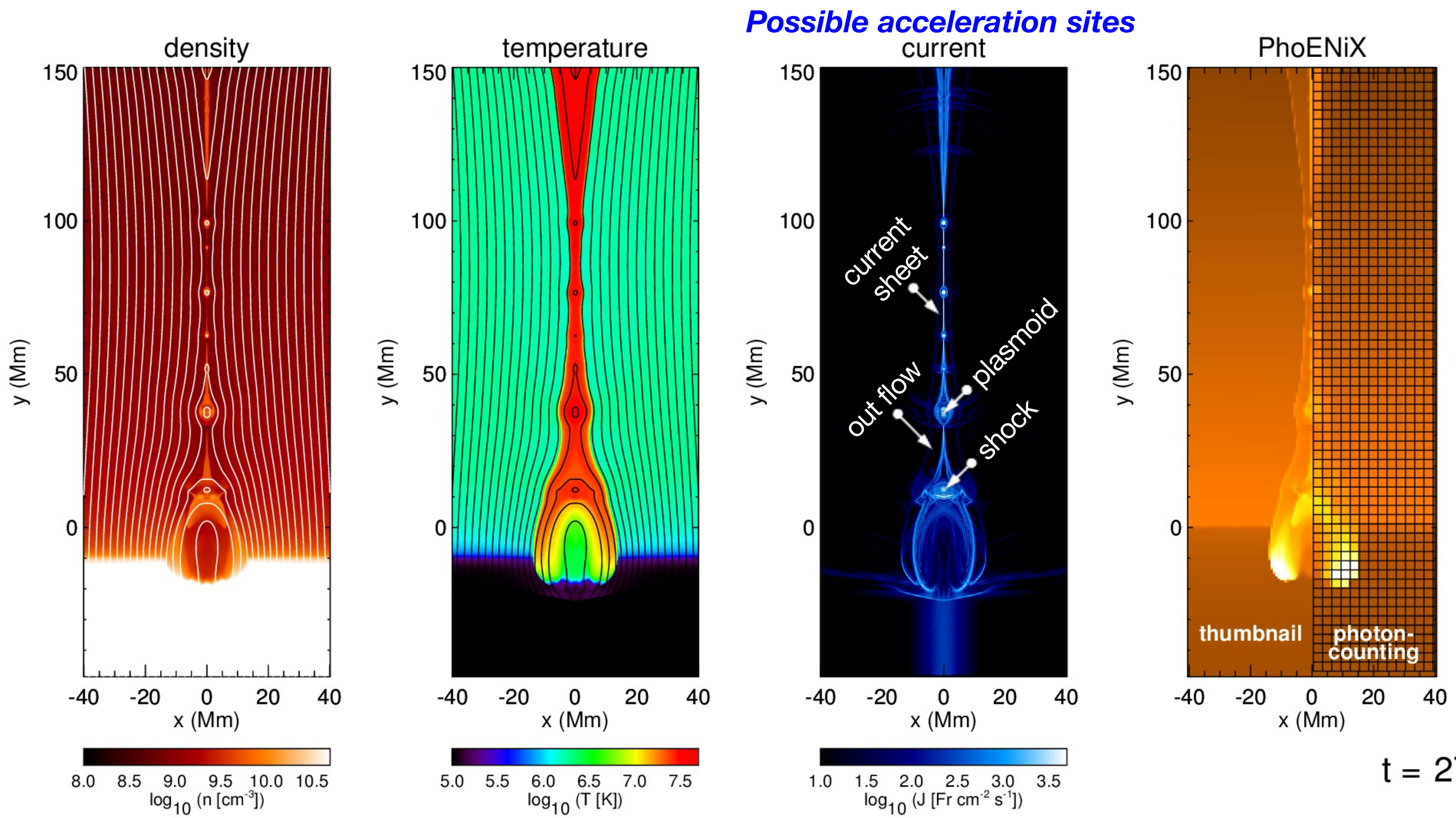
A key task of numerical & analytical studies:
Identify important zones and derive effective coefficients

Numerical Approach in macro scale

MHD for understanding of ambient plasma

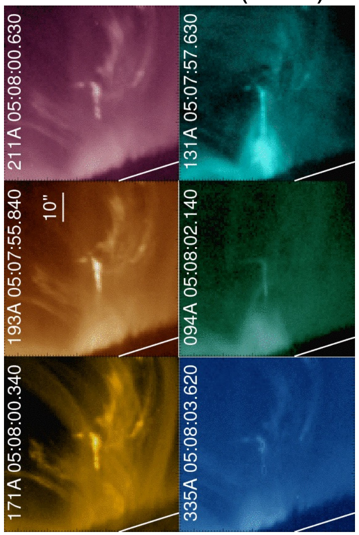
MHD simulation of a solar flare (magnetic reconnection)

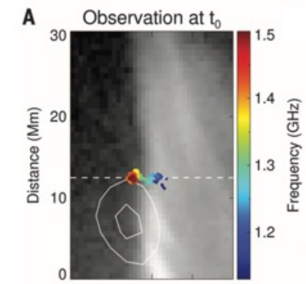
calculated by Kaneko



t = 270.0 sec

Takasao et al. (2012)



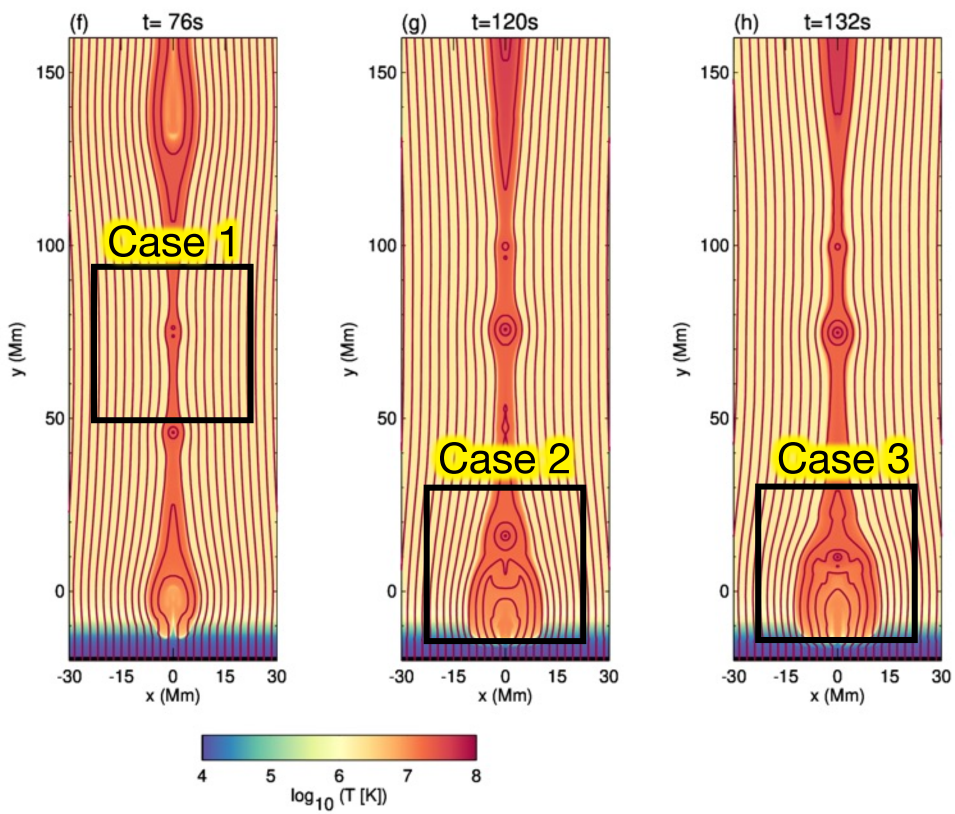


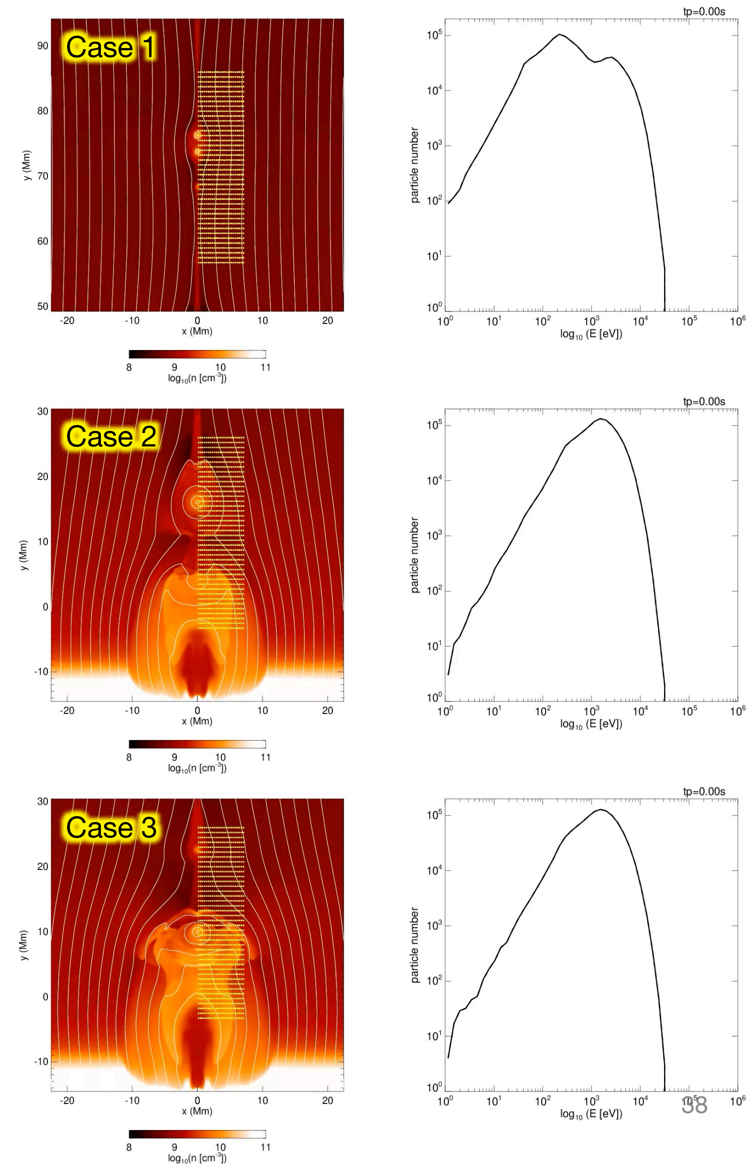
Chen et al. (2015)

Numerical Approach in macro scale

MHD + GCA for understanding of particle acceleration

calculated by Kaneko

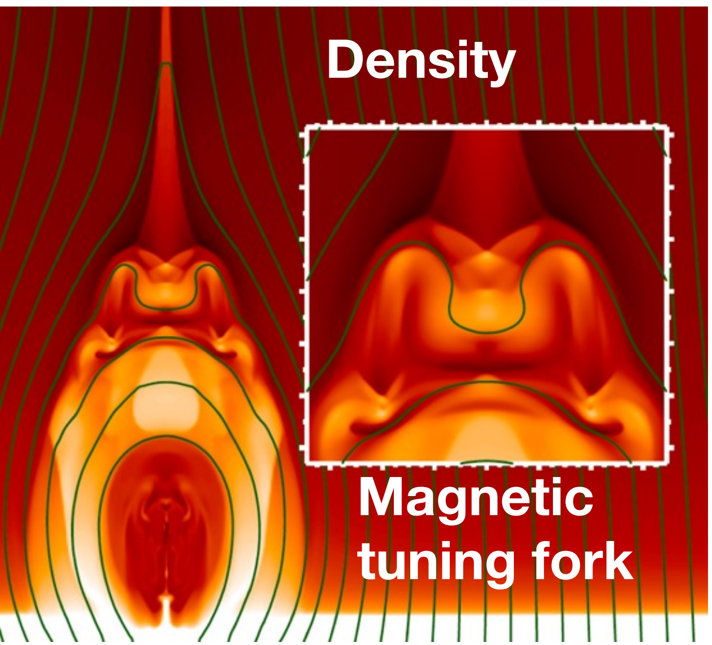


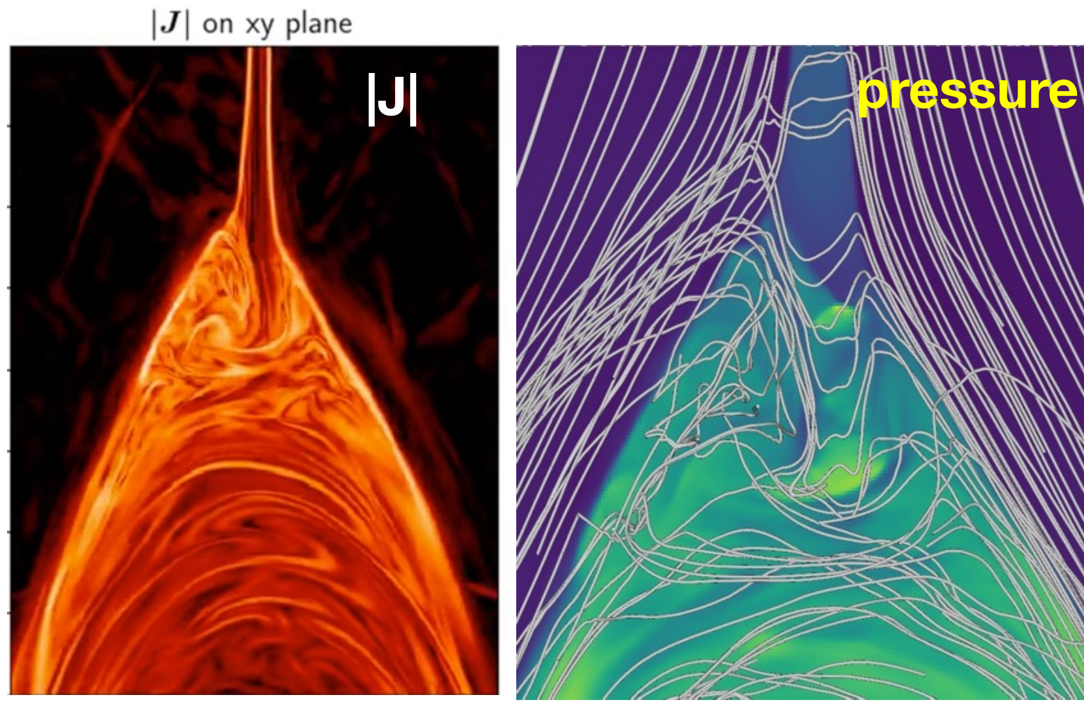


Numerical Approach in macro scale:
detailed MHD modeling of the above-the-loop-top region

2D model of Takasao & Shibata 2016

3D model (without heat conduction. By Shibata-san, Osaka U.)



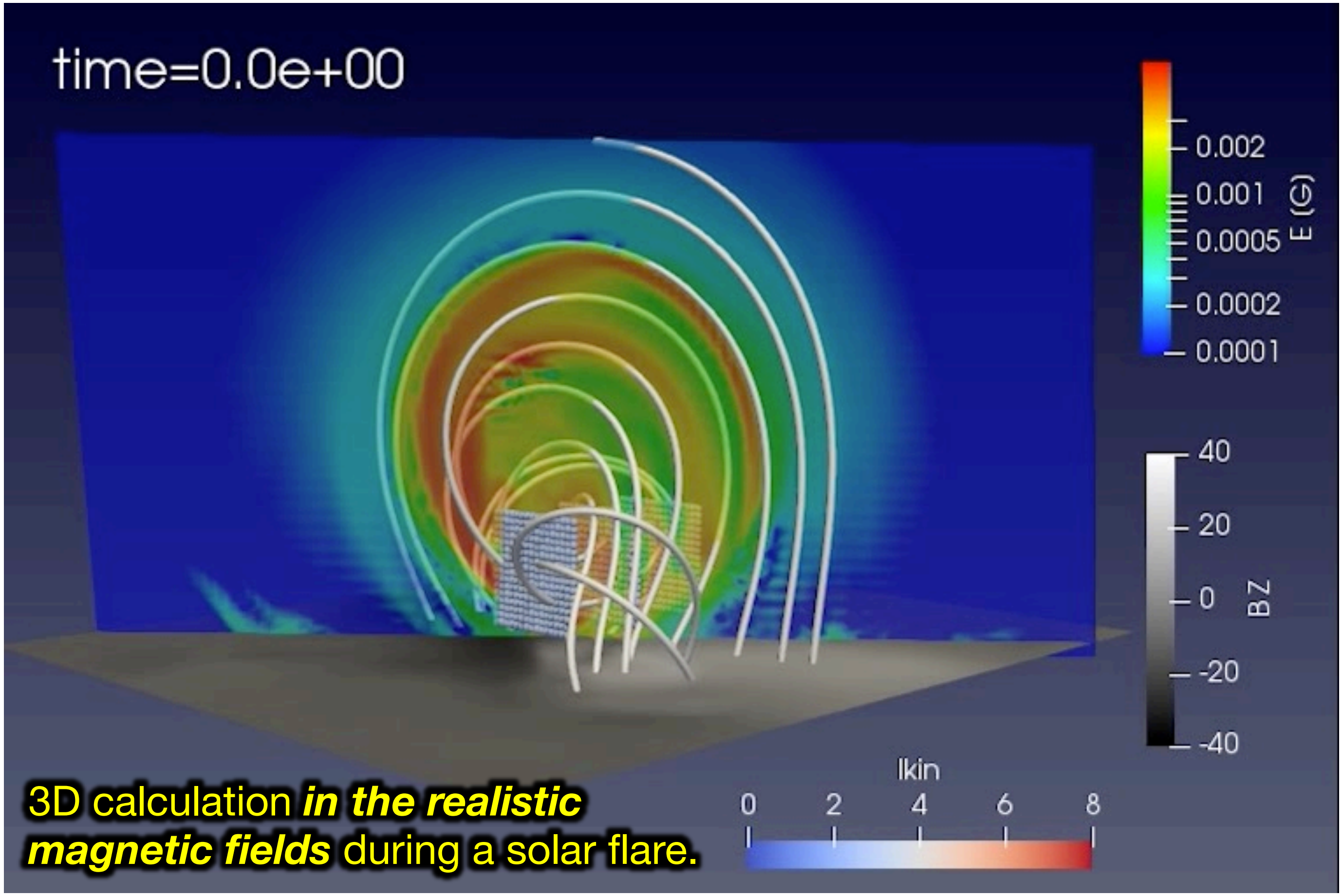


Magnetic tuning fork oscillation locally produces turbulence
even when the reconnection outflow is laminar (possibly as a result of ballooning instability)
→ We will examine the impact on the stochastic acceleration and trapping via turbulence

Numerical Approach in macro scale

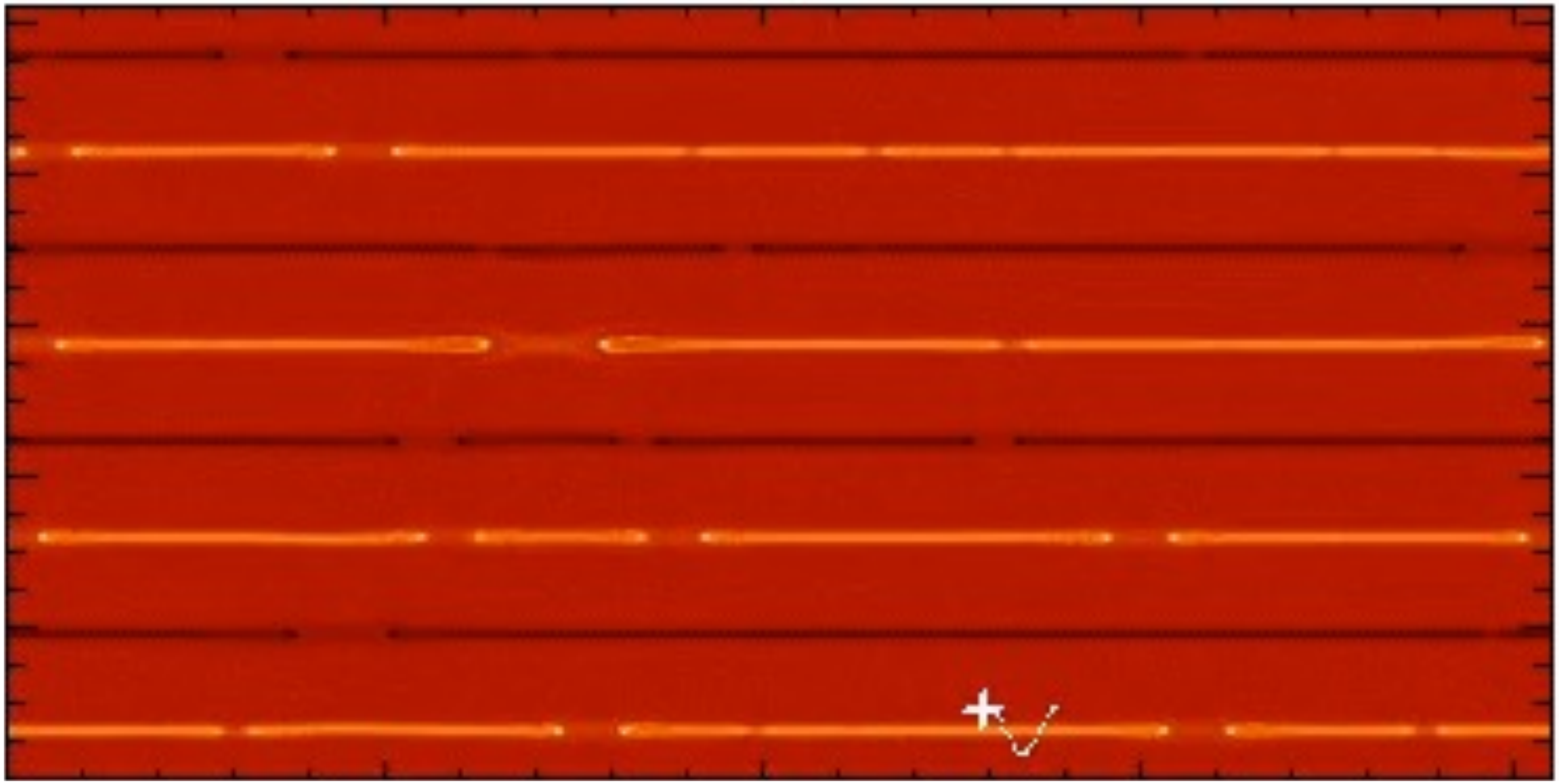
MHD + GCA for understanding of particle acceleration

calculated by Kaneko



Numerical Approach in micro scale

PIC for understanding of micro-scale physics

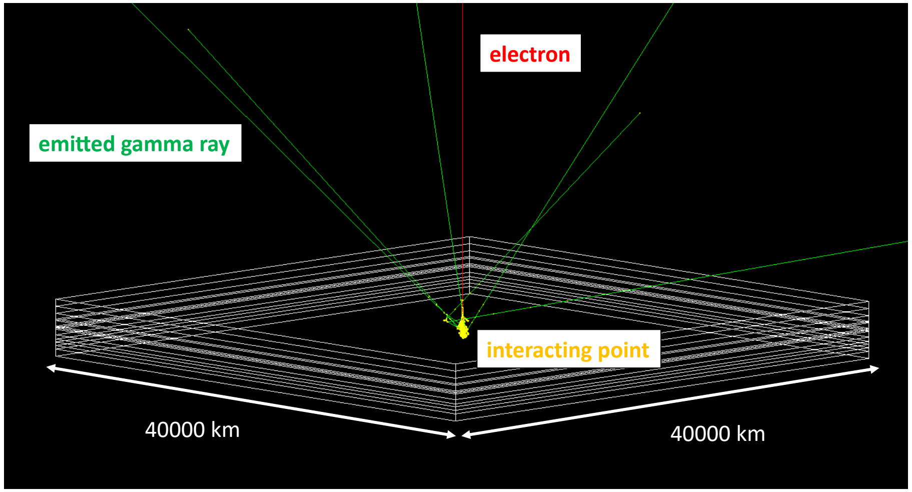


Numerical Approach [Emission model]

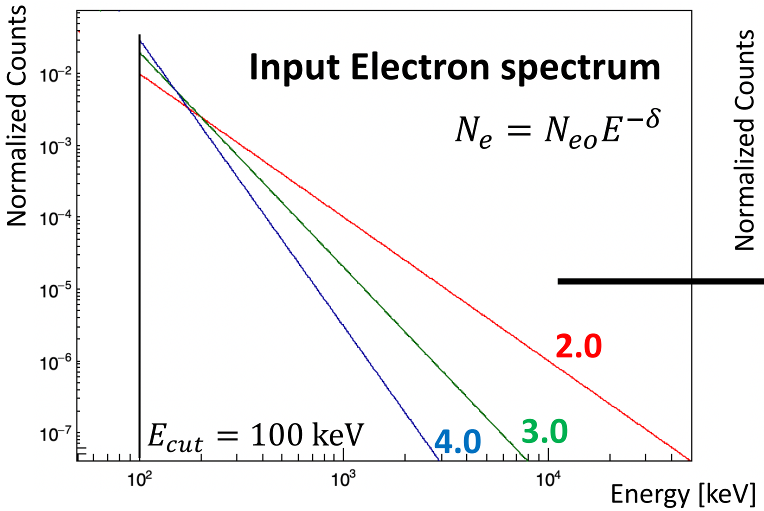
for comparison

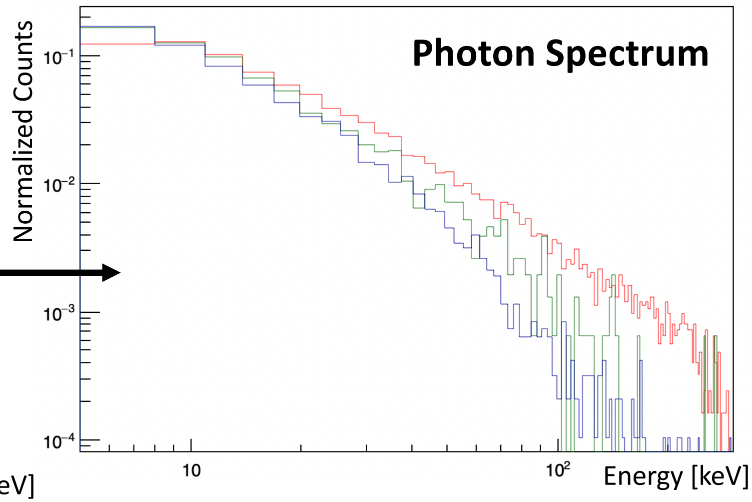
between observation and numerical simulation

calculated by Nagasawa

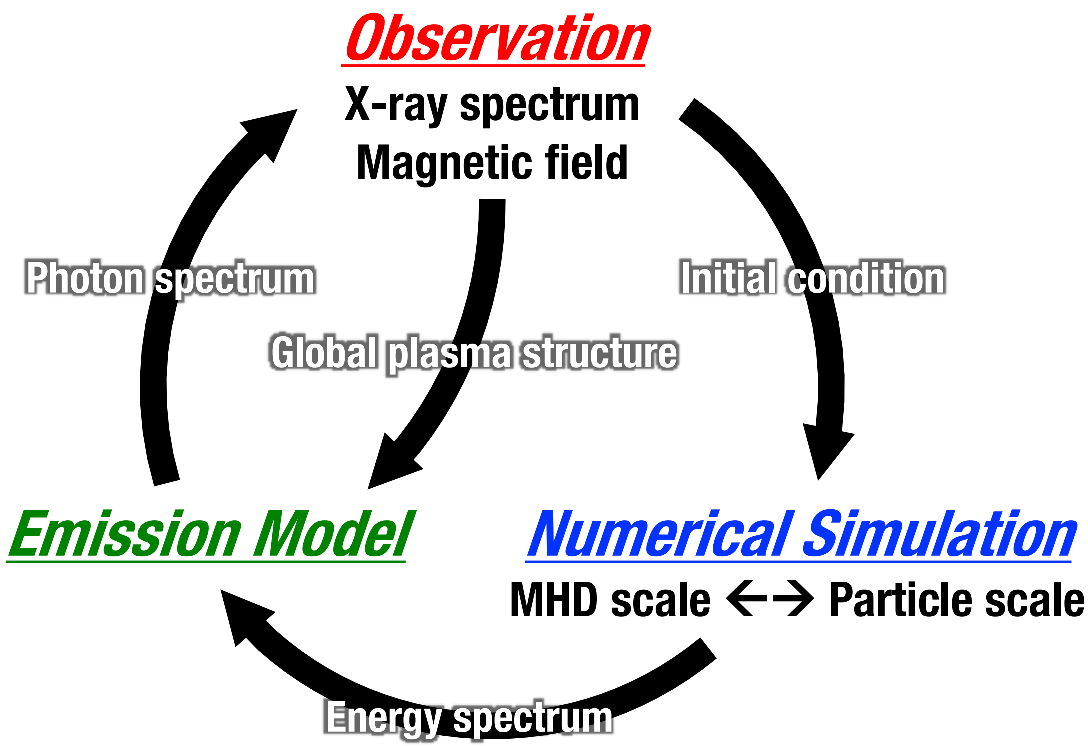


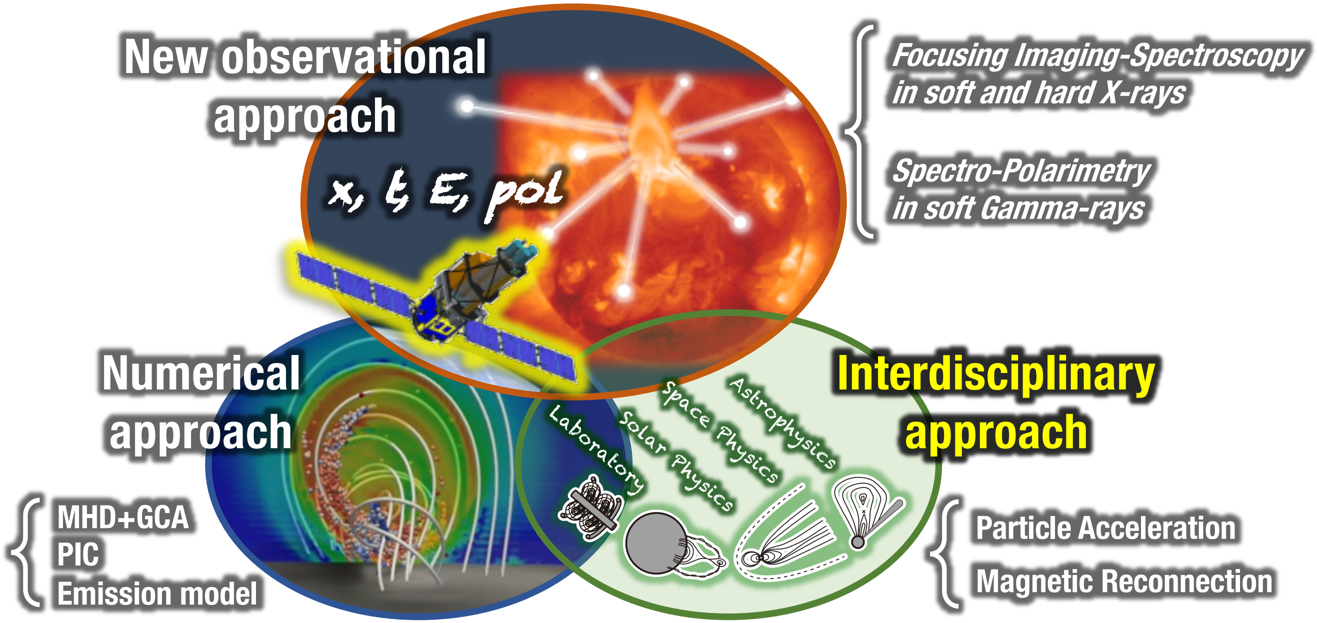
Solar corona model
in ComptonSoft





Iteration between observation and numerical simulation





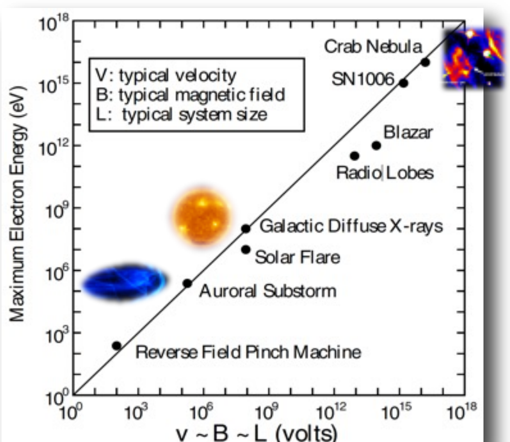
Science Objectives of *PhoENiX* mission

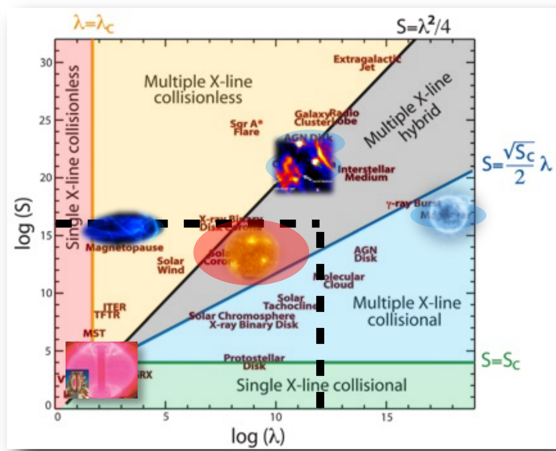
1. Identify particle acceleration sites in solar flares [where]
2. Investigate temporal evolution of particle acceleration [when]
3. Characterize properties of accelerated particles [how]

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





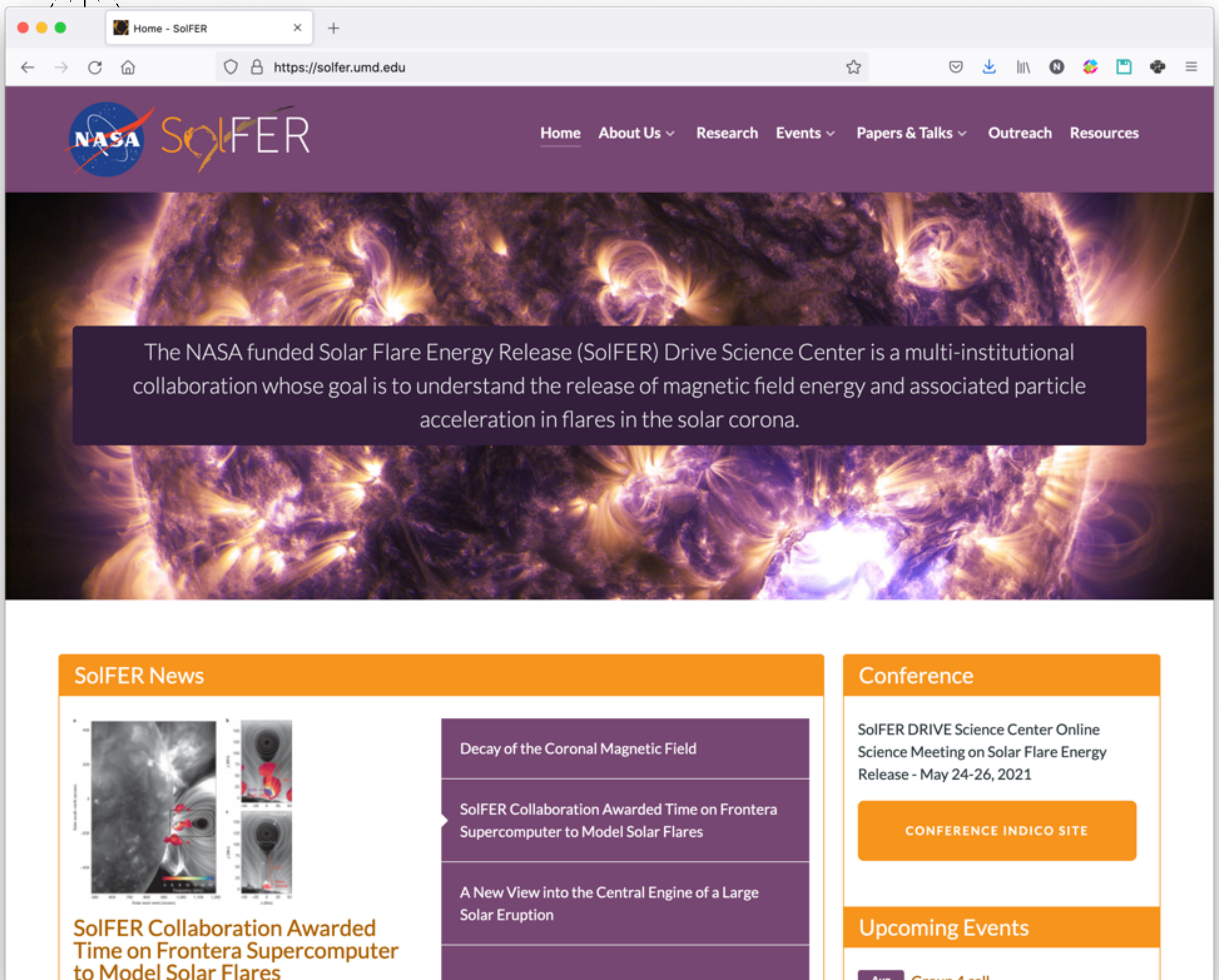
- **Laboratory plasma physics**
  - Laboratory experiment of MR

- **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

SolFER (Solar Flare Energy Release) – NASA funded Drive Science Center



1. **Fast Release Mechanisms**
2. **Onset of Energy Release**
3. **Energization of Electrons**
4. **Energization of Ions**
5. **Particle Transport**
6. **Plasma Heating**

PhoENiX can contribute to and collaborate with these topics.

Team members

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	Tokyo Univ. of Science	HXIS science study	HXIS J-lead, camera study
Tsunefumi Mizuno	Hiroshima U.	SGSP science study	SGSP lead, detector study
Masanori Ohno	Eötvös U.	SGSP science study	SGSP lead
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	Nagoya 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	Kobe U.	Science study	Science study
Takuma Nakamura	IWF/ ÖAW	Science study	Science study
Hiroshi Tanabe	Tokyo U.	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
Toshio Terasawa	NAOJ	Science advisory	Science advisory
Hiroyasu Tajima	Nagoya U.	Science advisory	Science advisory
Tadayuki Takahashi	Kavli IPMU	Science advisory	Science advisory
Kuniaki Masai	TMU	Science advisory	Science advisory
Masaaki Yamada	Princeton U.	Laboratory-based science advisory	Laboratory-based science advisory

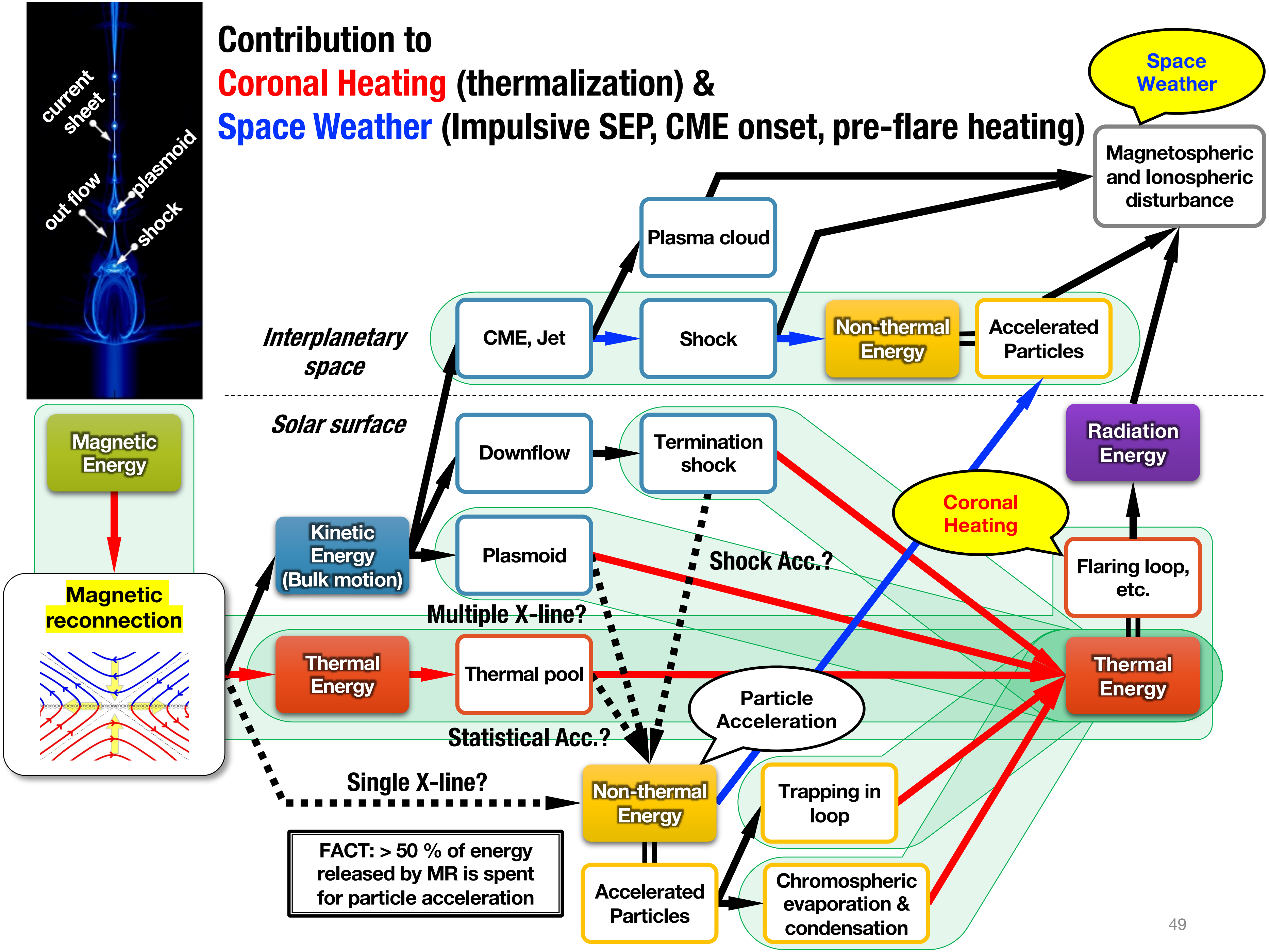
太陽物理	高エネルギー宇宙物理	地球・惑星磁気圏プラズマ物理	実験室または核融合プラズマ物理	工学など、左記以外

Collaborator name	Affiliation	Area of collaboration
Yoshinori Suematsu	NAOJ	SXIS mirror study
Satoshi Miyazaki	NAOJ	SXIS detector study
Shin'ichiro Takeda	Kavli IMPU	HXIS design & science study
Hiromitsu Takahashi	Hiroshima U.	SGSP design & science study
Takao Kitaguchi	RIKEN	SGSP design & science study
Takashi Minoshima	JAMSTEC	SXIS/HXIS science study with simulations
Shinsuke Imada	Nagoya U.	SXIS science study
Yoshiyuki Inoue	RIKEN	SGSP/HXIS science study
Kyoko Watanabe	NDA	Science study
Takuma Matsumoto	Nagoya U.	Science study
Haruhisa Iijima	Nagoya U.	Science study
Satoshi Kasahara	Tokyo U.	Science study
Tomoki Kimura	Tohoku U.	Science study
Aya Bamba	Tokyo U.	Science study
Teruaki Enoto	RIKEN	Science study
Herman Lee	Kyoto U.	Science study
Yoko Tsuboi	Chuo U.	Science study
Ryo Yamazaki	Aoyama Gakuin U.	Science study
Yutaka Ohira	Tokyo U.	Science study
Toshihiro Obata	Tokyo U.	System advisory
Kazunari Shibata	Kyoto U.	Science advisory
Yoshifumi Saito	ISAS/JAXA	Science advisory
Kazuhiro Nakazawa	Nagoya U.	Science advisory
Yoshizumi Miyoshi	Nagoya U.	Science advisory
Masahiro Hoshino	Tokyo U.	Science advisory
Kazutaka Yamaoka	Nagoya U.	Science advisory
Yasushi Ono	Tokyo U.	Laboratory-based science advisory

Extra Science

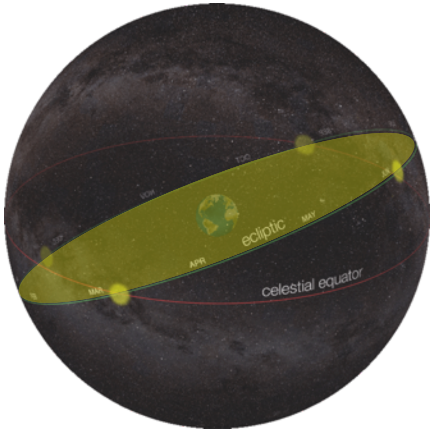
Beyond the PhoENiX Scientific Objectives

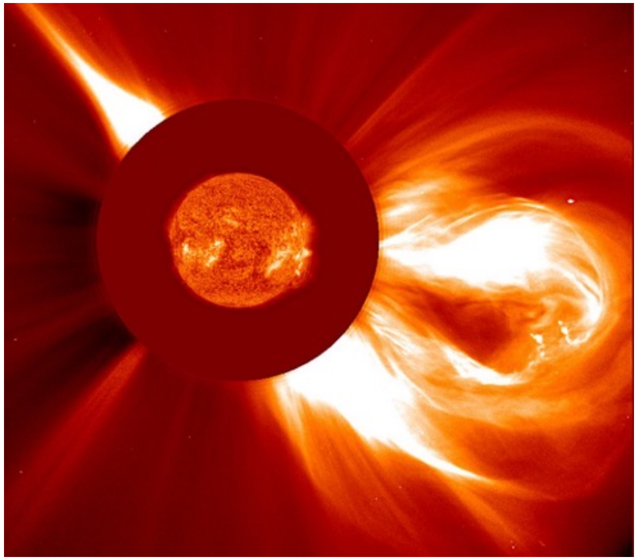
Contribution to Coronal Heating (thermalization) & Space Weather (Impulsive SEP, CME onset, pre-flare heating)

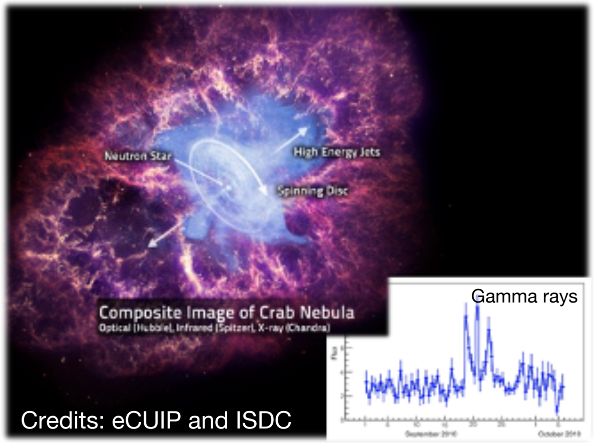


Observation of CME and astronomical objects

PhoENiX can observe
the CME and astronomical objects
near the ecliptic plane (within 5 degree).







Balbo+ 2011

CME

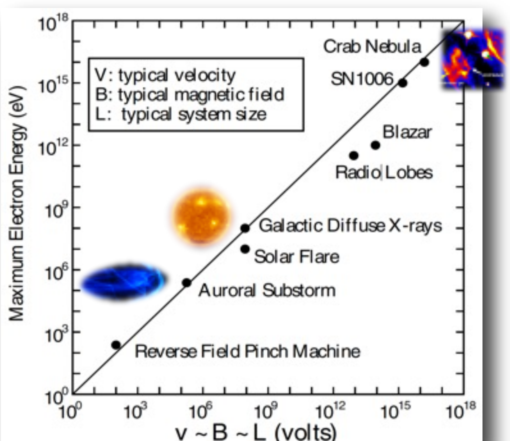
Carb Nebula

Scorpius X-1

Interdisciplinary approach

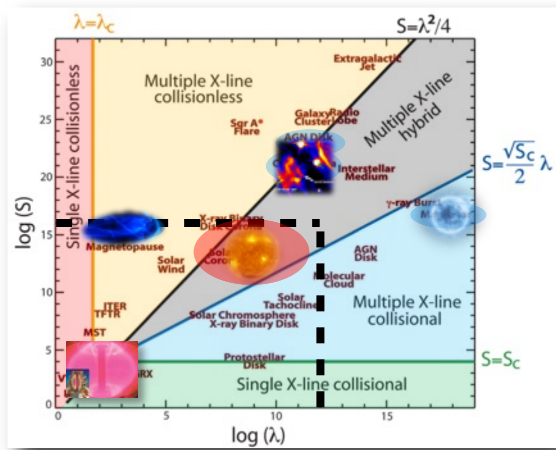
for the understanding of plasma physics beyond individual research field

Maximum Energy



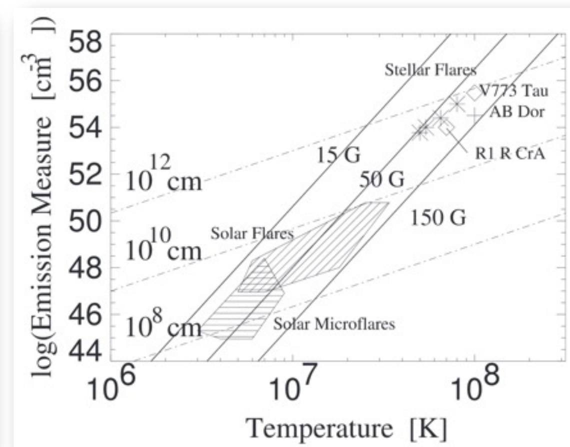
Makishima (1999)

Magnetic Reconnection



Ji & Daughton (2011)

Flare



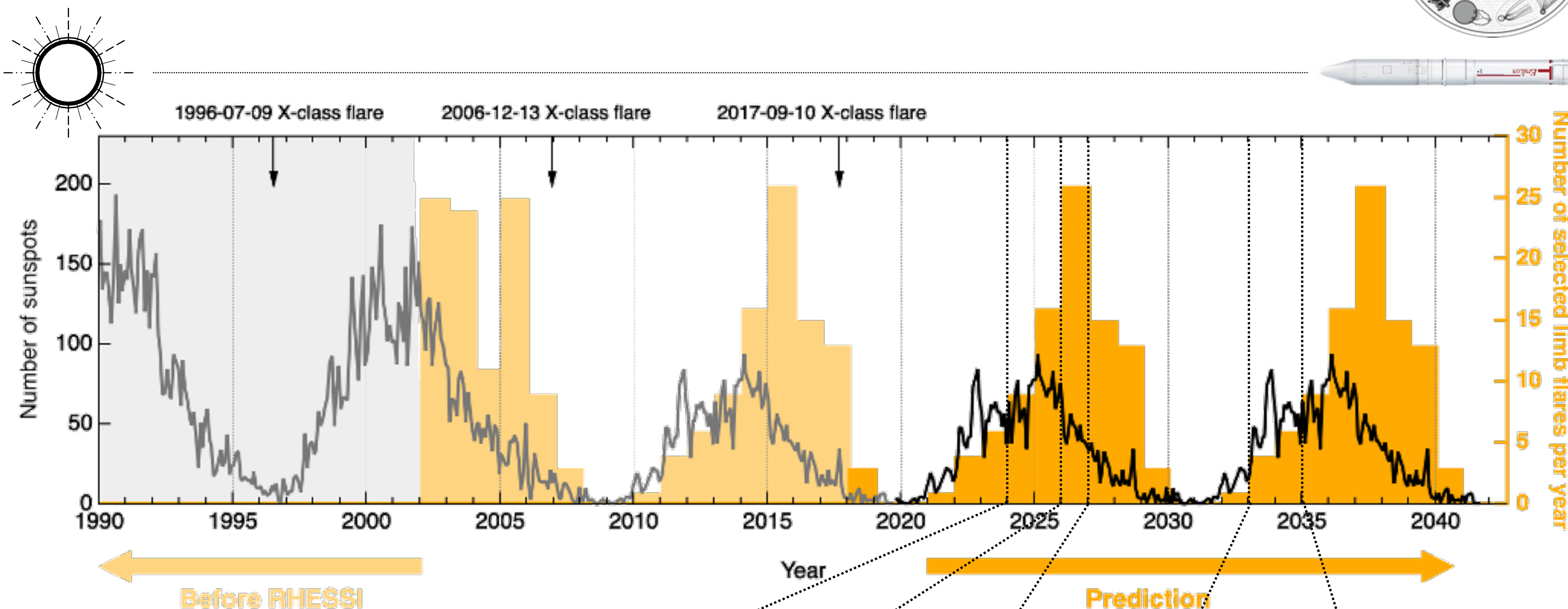
Shibata & Yokoyama (1999)

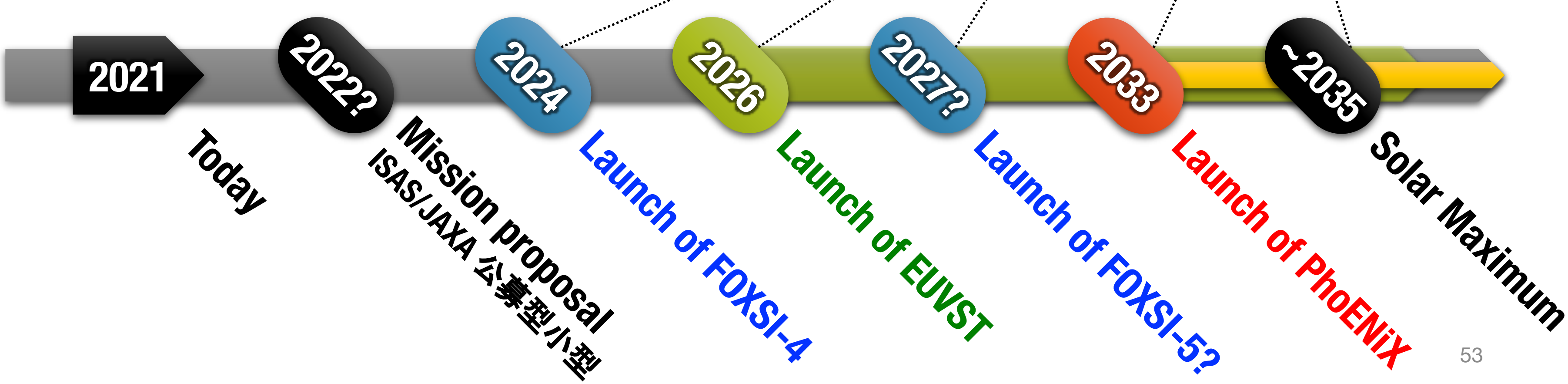
One-Page Ideas

PhoENiX team is looking for your scientific ideas that is wanted to be realized with X-ray imaging spectroscopic and soft gamma-ray spectropolarimetric observations for solar flares, i.e., by PhoENiX mission.

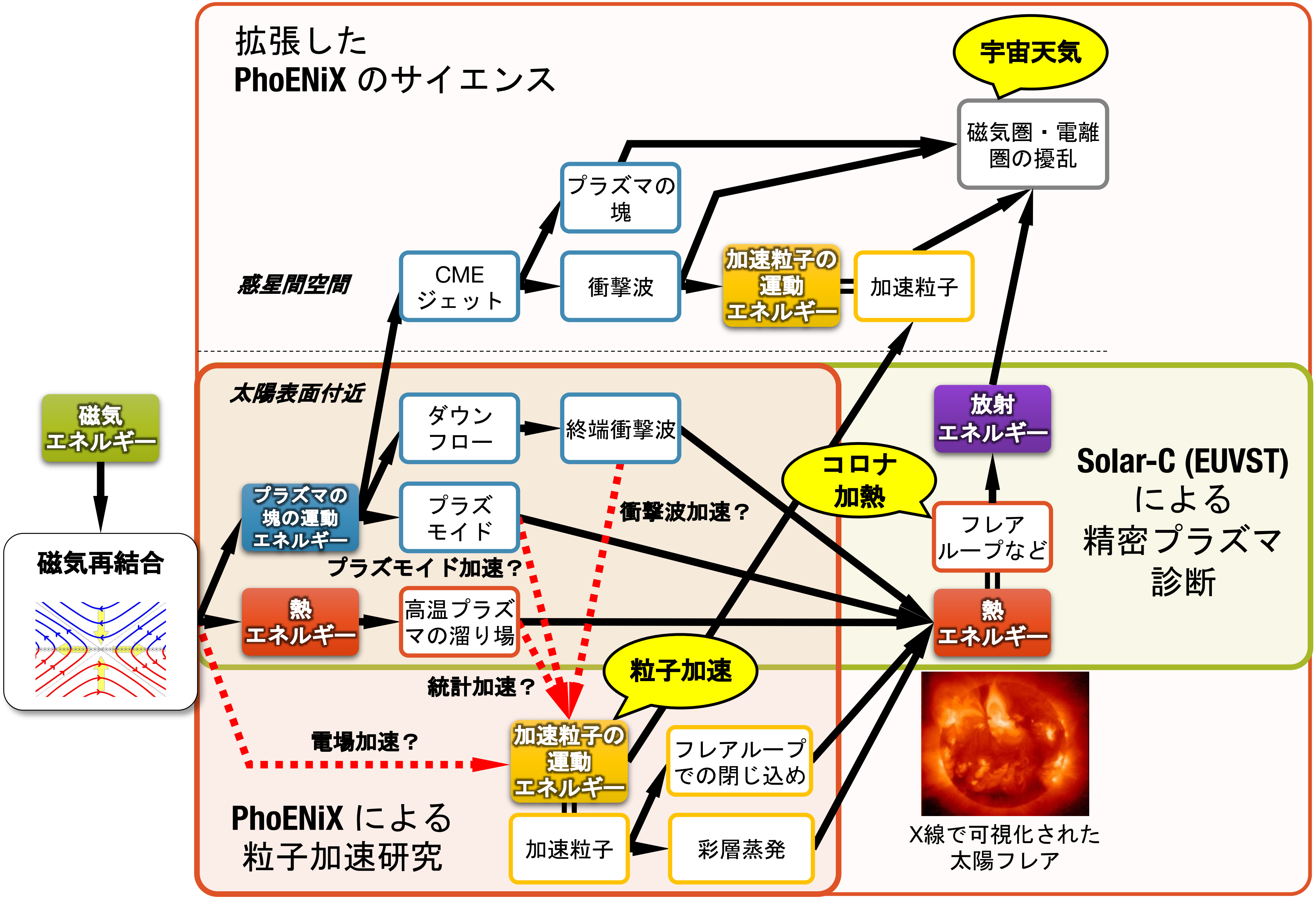
https://phoenix-project.science/one-page-idea

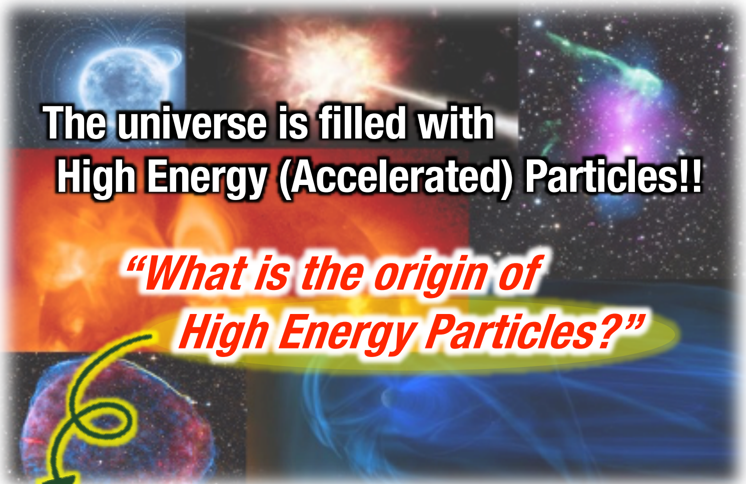
Schedule of PhoENiX





Solar-C (EUVST) から PhoENiX へ





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]

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

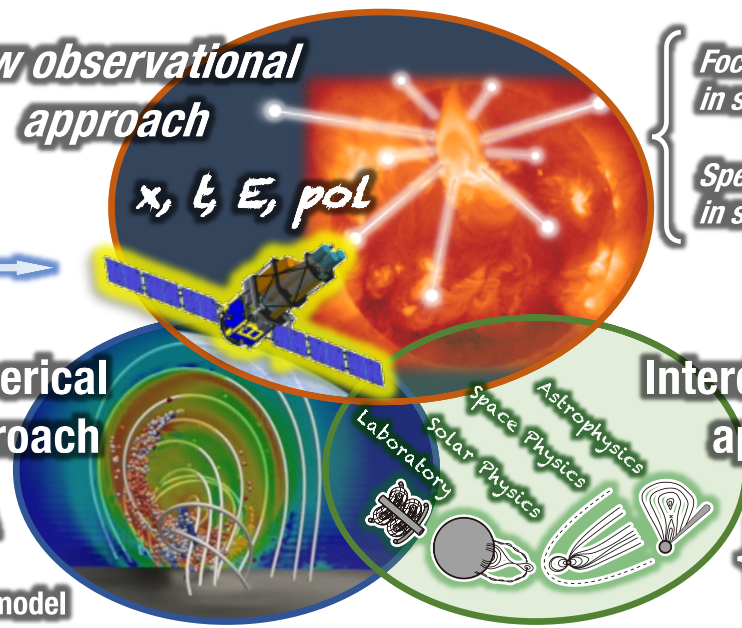
Sounding Rocket *FOXSI* series

2012 2014 2018

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

MHD+GCA
PIC
Emission model

Particle Acceleration
Magnetic Reconnection

https://indico.ipmu.jp/event/395/

Particle Acceleration in Solar Flares and the Plasma Universe -- Deciphering its features under magnetic reconnection

15-19 November 2021
Virtual
GMT timezone

- Overview
- Timetable
- Contribution List
- Registration and Abstract Submission
- Participant List
- Kavli IPMU Code of Conduct

Contact
seminar@ipmu.jp

Dates and time:

Monday, 15 November - Fri, 19 November, 2021
22:00–3:00 JST* each day
(* 21:00–2:00 CST / 14:00–19:00 CET / 8:00–13:00 EST / 5:00–10:00 PST)

Venue:

The workshop will be held as a virtual, online-only event. A link for connection will be sent out later to registered participants.

Registration and Abstract Submission:

Abstract submission deadline is October 19, 2021, 23:59 JST. Registration is available through November 10, 2021.