Hard X-ray Observations as Diagnostics of Particle Acceleration in Solar Flares

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Outline:

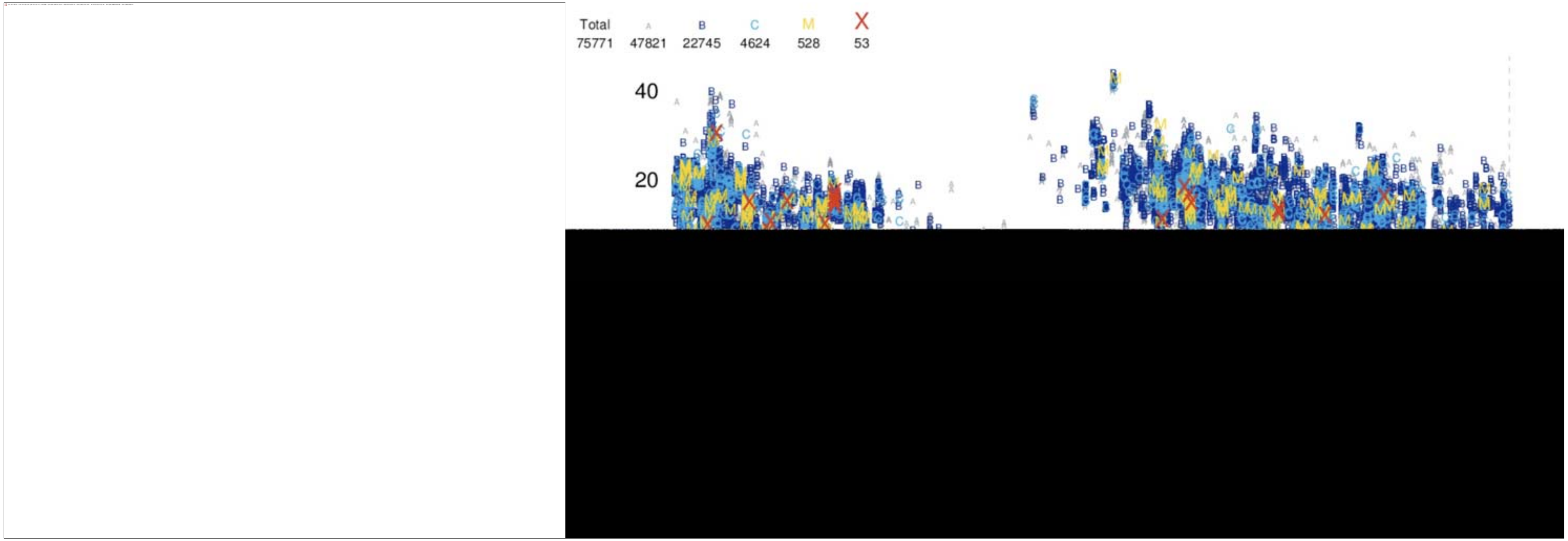
- Hard X-ray diagnostics: bremsstrahlung
- In-direct imaging: RHESSI, Solar Orbiter STIX
- Focusing optics: NuSTAR, FOXSI

NASA Small Explorer

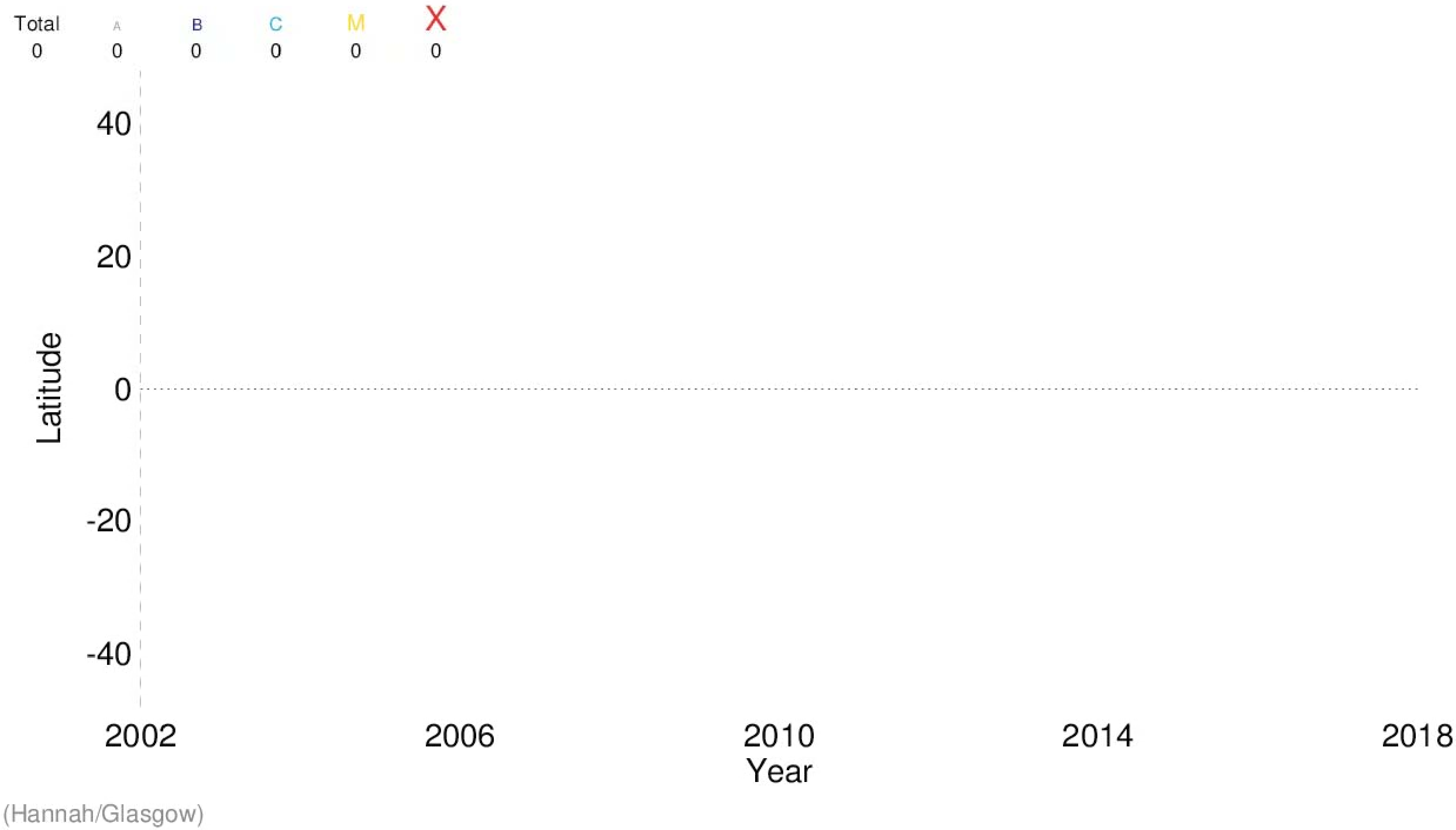
2002-2018

NASA's RHESSI mission (2002-2018) Over 75,000 solar flares observed

RHESSI broke new ground with high-resolution X-ray and gamma-ray observations of solar flares providing unique diagnostics of how energy is released and particles are accelerated in magnetized plasma.



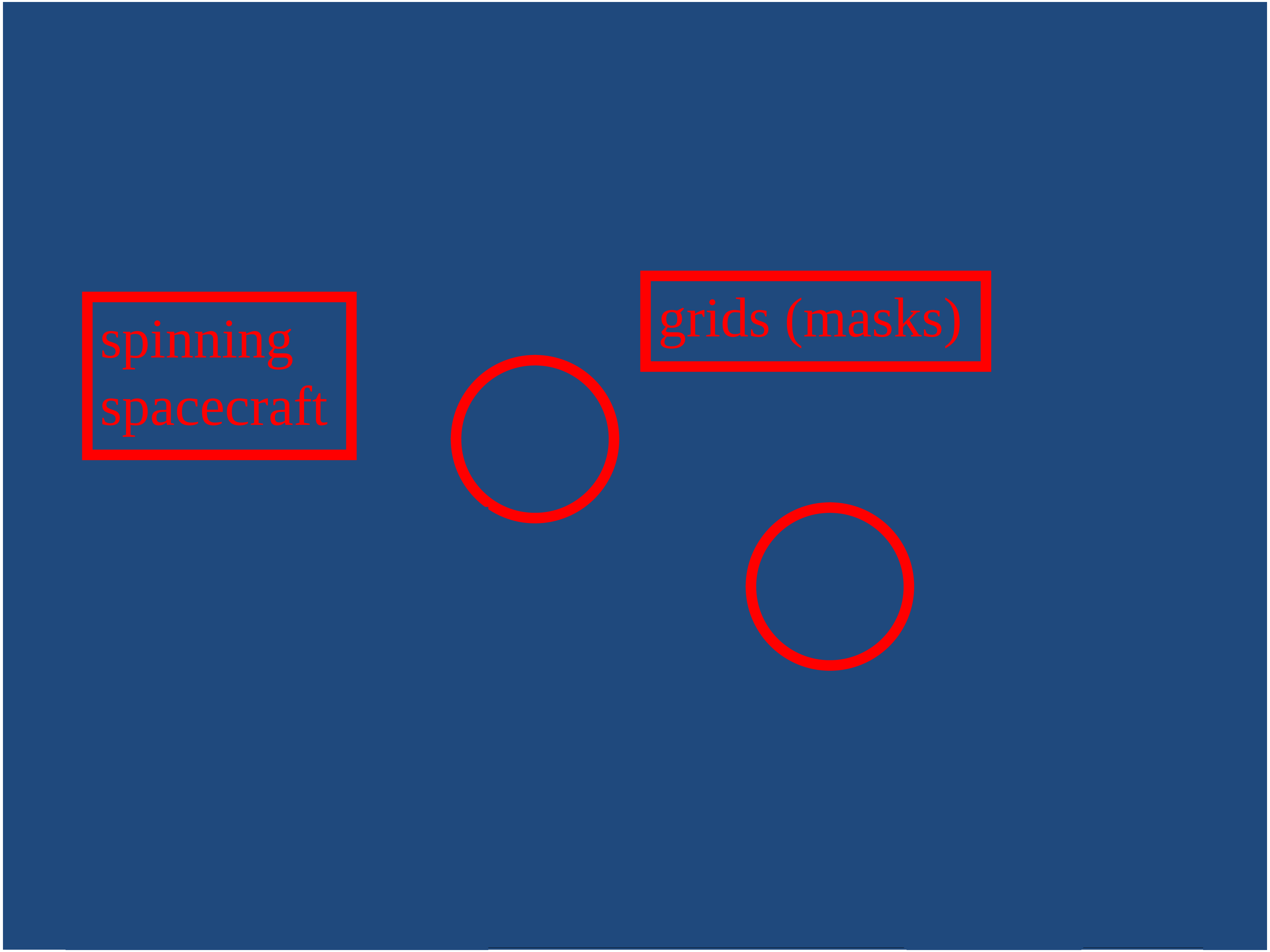
The figures above show that X-ray flare locations observed by RHESSI follow the same progression in solar latitude as active regions over two sunspot cycles. Hence, flares must be magnetically driven.


Total
0
A
0
B
0
C
0
M
0
X
0
40
20
0
-20
-40
Latitude
2002
2006
2010
2014
2018
Year
(Hannah/Glasgow)

Instrument overvi

9 detectors (7x7x8.5cm)
~3 keV – 10 MeV
resolution
1 keV @ 100 keV
3 keV @ 2223 keV

Germanium
detectors


spinning spacecraft
grids (masks)

RHESSI indirect imaging

incoming X-rays

grid

grid

detector

detected signal
is modulated

Hard X-ray spectrum

thermal
bremsstrahlung
T ~ 30 MK

non-thermal
bremsstrahlung
accelerated
electrons with
typical energies
above ~10 keV

Bremsstrahlung

Inverse Compton (too weak)

Synchrotron seen in radio

- Two components
  - Thermal
  - Non-thermal
- Steep spectra!
- Quantitative measurements
- Temperature and EM
- Energy in non-thermal electrons

Hard X-ray spectrum

thermal
bremsstrahlung
T ~ 30 MK

non-thermal
bremsstrahlung
accelerated
electrons with
typical energies

~10-50% of released energy is in accelerated electrons

Bremsstrahlung

Inverse Compton (too weak)
Synchrotron seen in radio

- Two components
  - Thermal
  - Non-thermal
- Steep spectra!
- Quantitative measurements
- Temperature and EM
- Energy in non-thermal electrons

Hard X-ray timing

thermal:

Fast rise (few minutes up to an hour), slow decay (up to two days)

non-thermal:

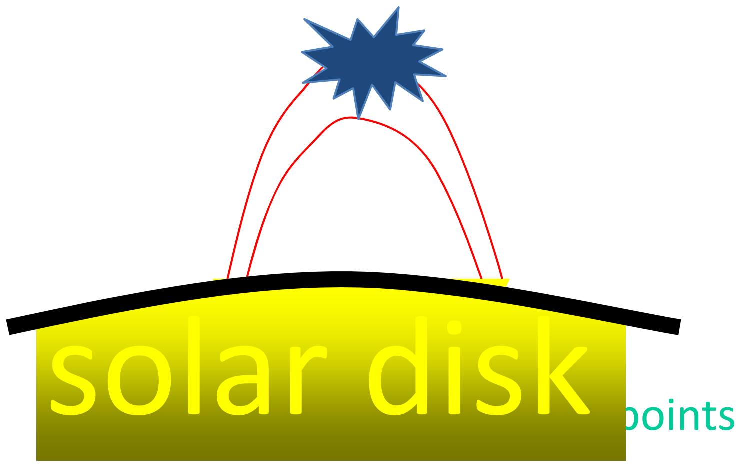
Often bursty with peaks of duration of seconds to a few minutes
Generally during rise phase of thermal emission with occasional late phase bursts.

Derivative of thermal profile often similar as non-thermal profile

Flare cartoon

Emission from partially limb-occulted flares

for flares occurring behind the solar limb,
footpoint emission is occulted
→ purely coronal emission can be studied



Statistical studies:
Roy & Datlowe 1975, McKenzie 1975,
Mariska et al. 1996,
Tomzcak 2001, Krucker & Lin 2008

Emission from partially limb-occulted flares

typical spectrum of partially occulted flare shows 2 components:
-) thermal
-) faint emission at higher energies

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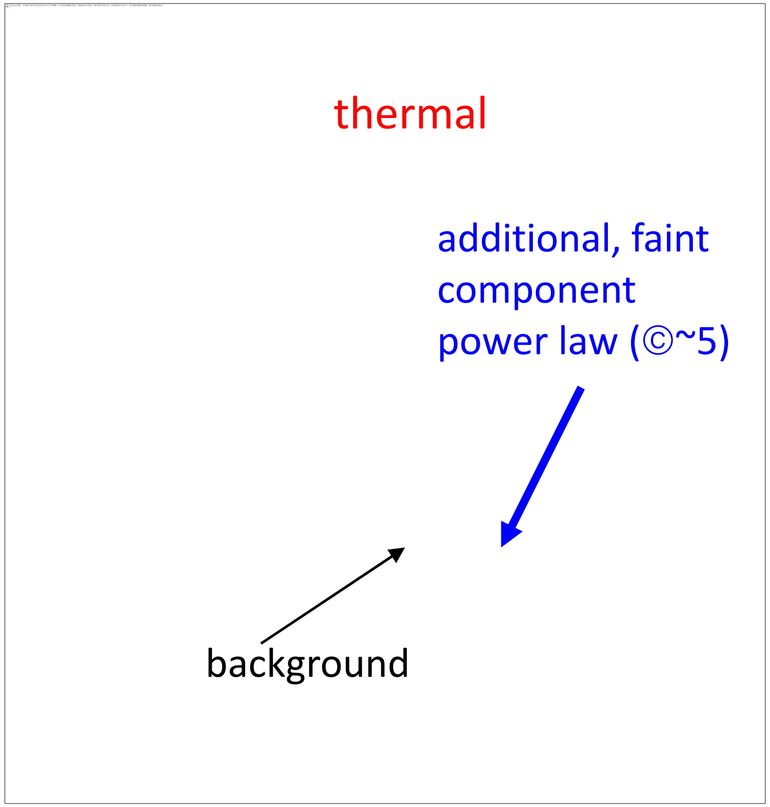
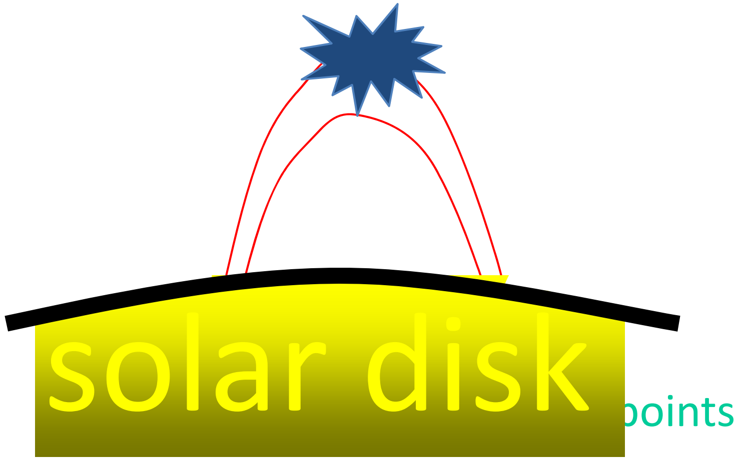


Krucker & Lin 2008



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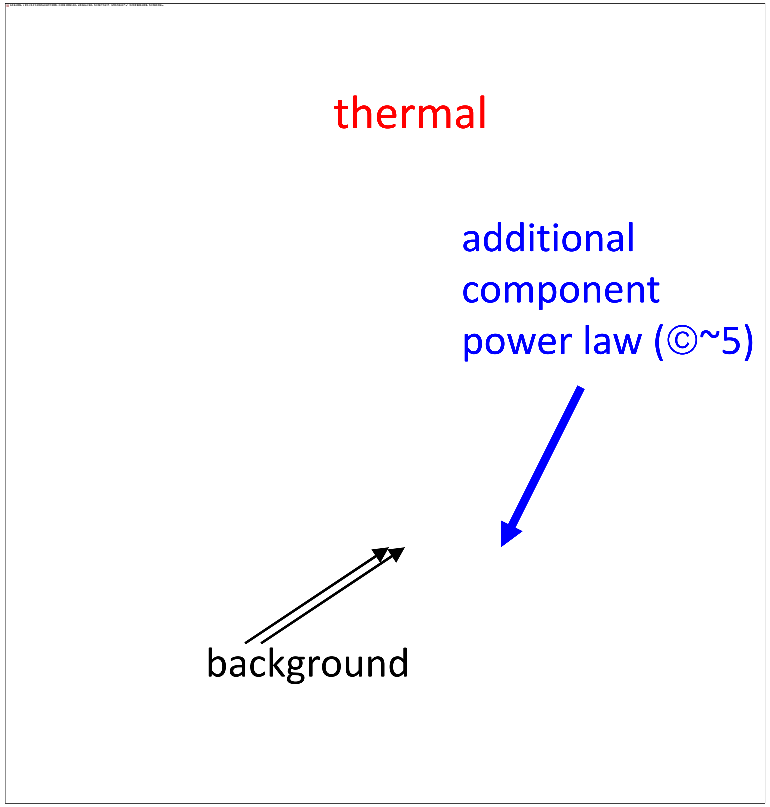
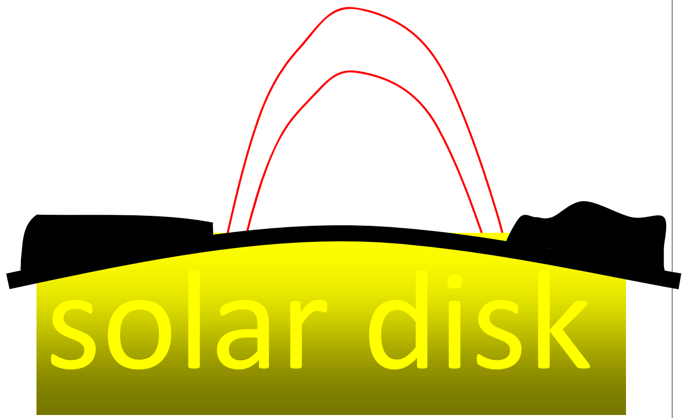


Krucker & Lin 2008

different time profiles:
emission from flare-accelerated electrons!



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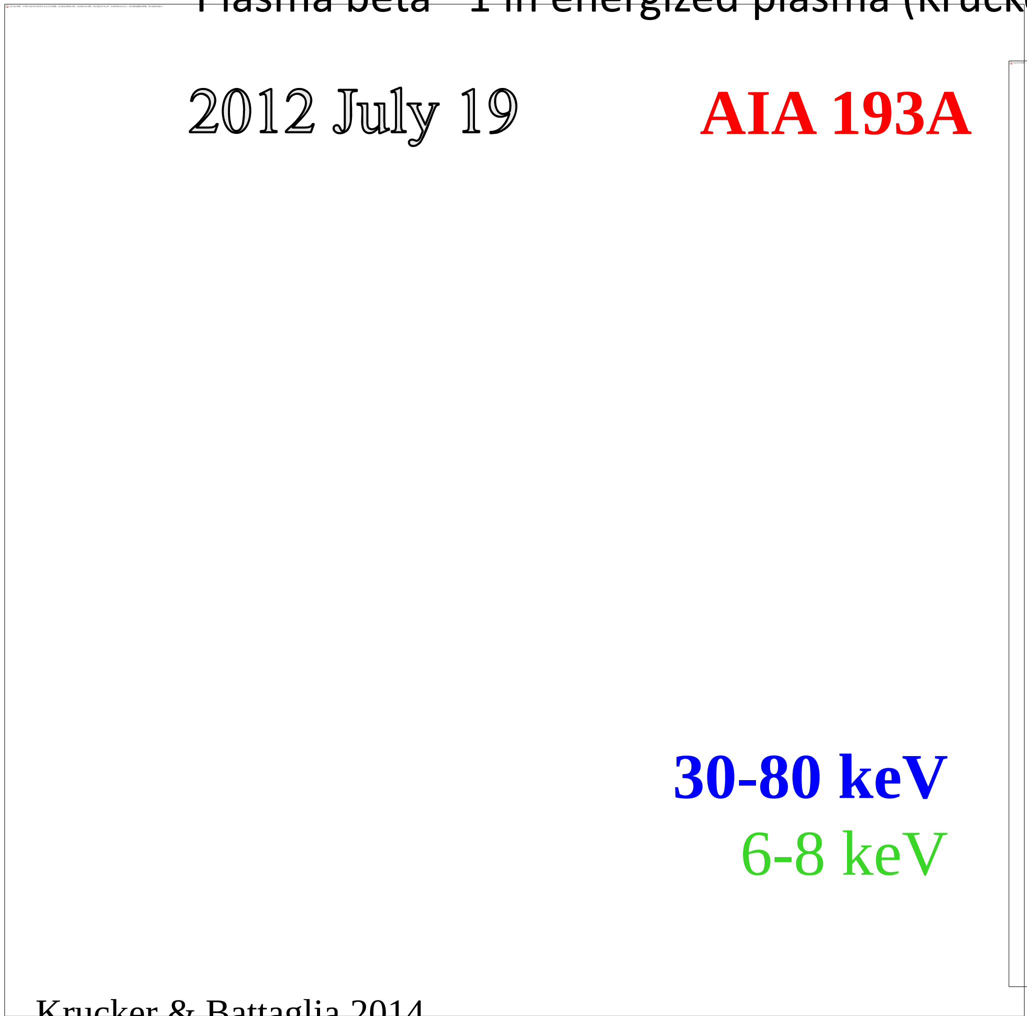
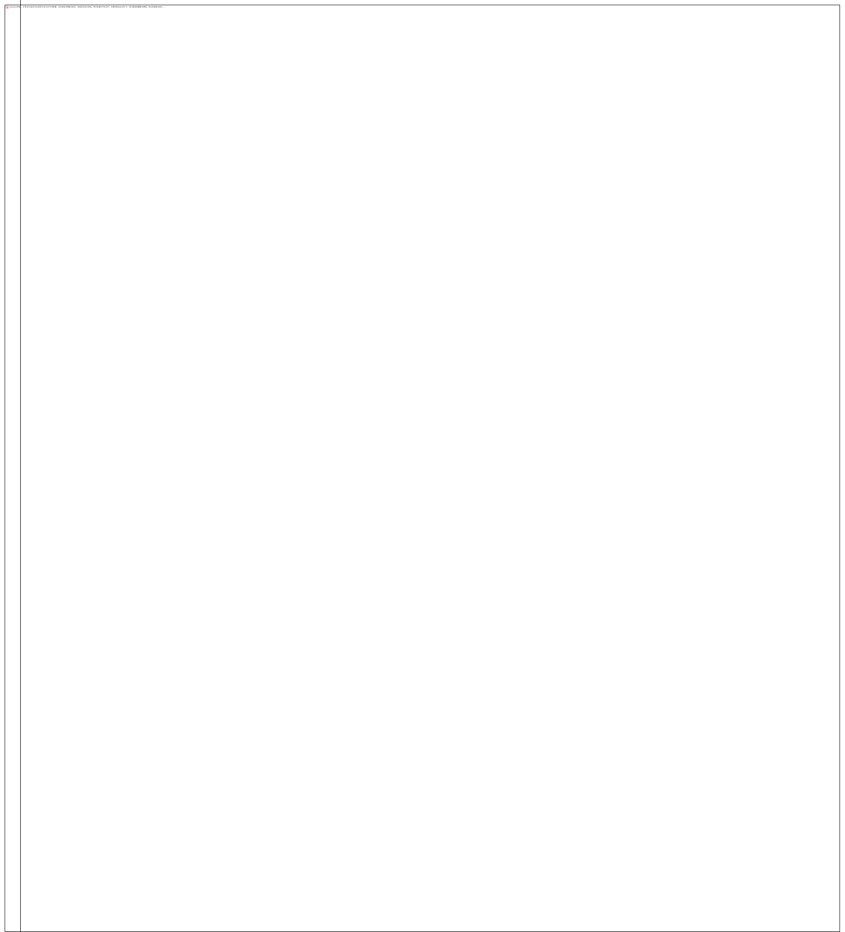
For a few events: Coronal HXR visible

Power-law spectrum → non-thermal
The strongest coronal HXR sources are consistent with bulk energization
Plasma beta ~1 in energized plasma (Krucker et al. 2010)

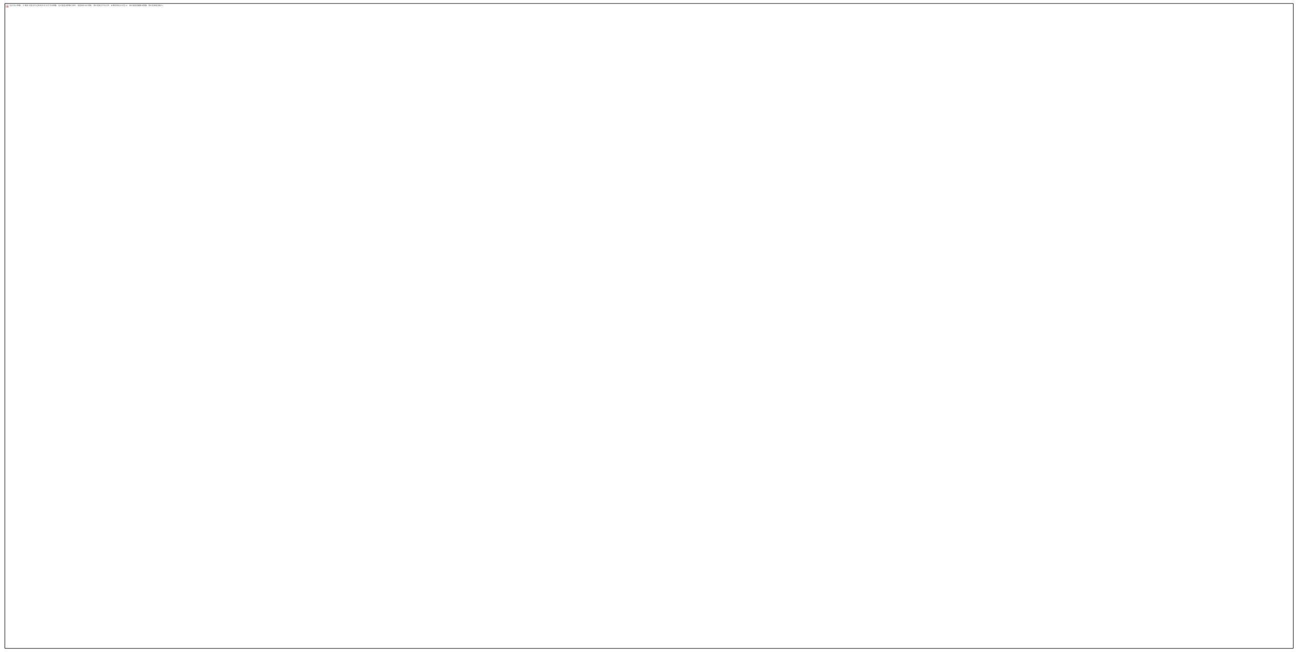


Krucker & Battaglia 2014

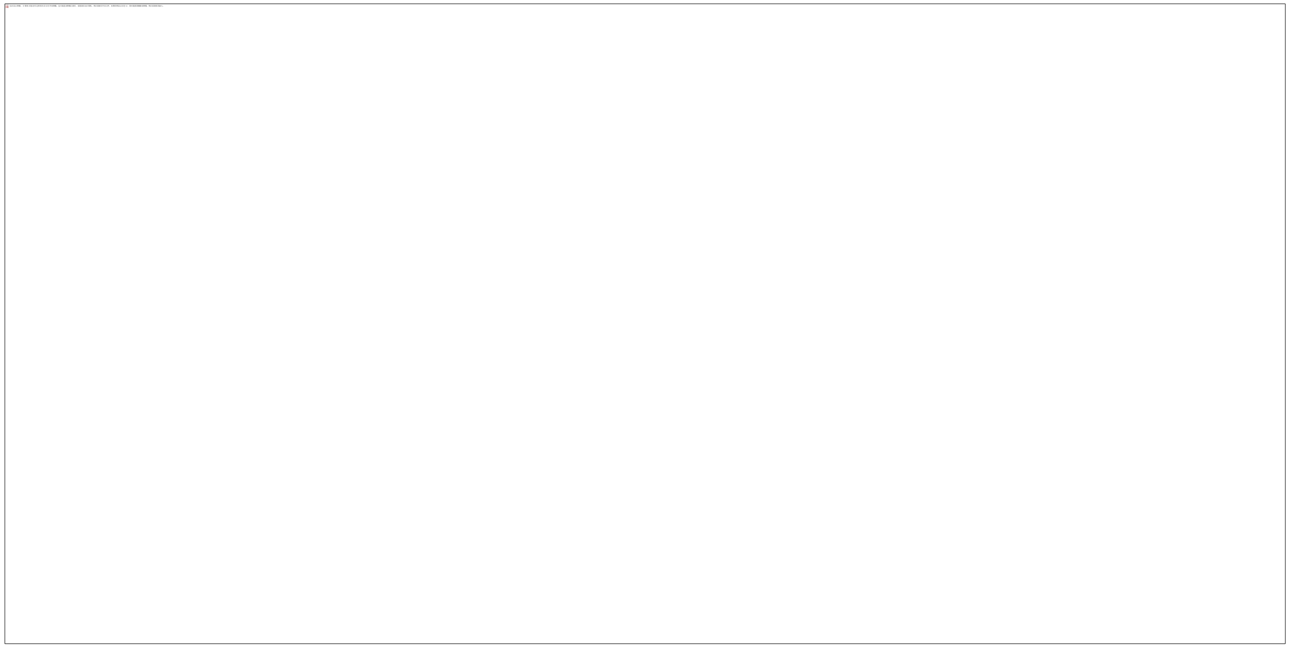


Electron heating multi-island during reconnection

Dahlin et al. 2014, 2015



2D



3D

Dahlin et al. 2015

Microwave – HXR diagnostics

17 GHz
30-80 keV
6-8 keV

34 GHz
30-80 keV
6-8 keV

Bremstrahlung of ten's of keV electrons → HXR
Gyrosynchrotron from 100's of keV electrons → MW

Upcoming observatory :Chinese Spectral RadioHeliograph

Motivation for my stay at ISEE, Nagoya University

Sep 10 X8 flare:
Extended Owen Valley Solar Array (EOVSA)

EOVSA & RHESSI

18 GHz

3 GHz

Sept 10, 2017 (X8)

Gary et al. 2018 (ApJ)

[redacted]

ESA’s Solar Orbiter Mission

First concept: ~1990
First design: ~2000
Instrument selection: 2007
Mission approved: 2011
Instrument delivery: July 2017
Launch: Feb 2020
Prime mission: 2022-2027

Launch: Feb 2020

In-direct imaging with STIX

Transmission through grids/masks is a sensitive function of the incident X-ray photon

Similar concept as HXT onboard Yohkoh

7.2 kg

8 W

Entrance window

Heat protection & absorption of low energy X-rays

grid 1

grid 2

Detectors and electronics box

grid 1

X-ray source

grid 2

detector

Fun slides

Fun slides

Stereoscopic HXR observations

?

STIX in combination with Earth-orbiting instrument (e.g. HXI on ASO-S)

The next generation HXR telescope: direct focusing optics

Advantage:

- high imaging dynamic range
- high sensitivity

FOXSI sounding rocket flight in 2012

FOXSI proposed to NASA's 2016 Heliophysics Small Explorer AO (PI Steven Christe, GSFC). Selected for phase A in July 2017. Final selection: Spring 2019

Detector Bench

Optics Bench

FOXSI Small Explorer

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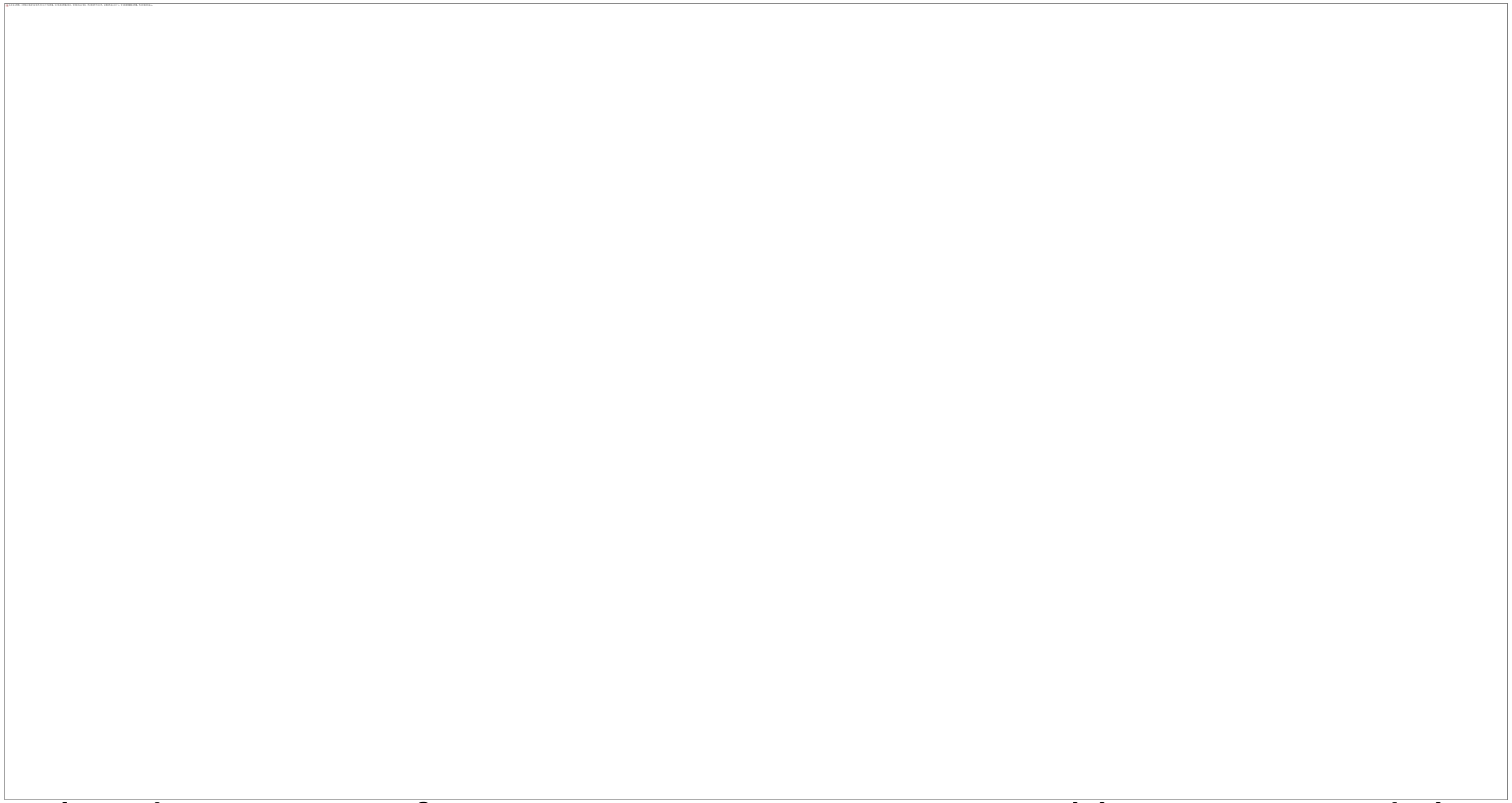
Detector Bench

Optics Bench

HXI on ASO-S provides imaging spectroscopy at higher energies

FOXSI sounding rocket result:
>10 MK emission in non-flaring active region
Ishikawa et al. 2017 (Nature Astronomy)



The detection of >10 MK constrains coronal heating models

NuSTAR solar observations

2017 September 11

Flare loops one day after flare onset.

EUV 171A: flare loops cooled to ~1 MK

NuSTAR: newly reconnected loops above cooling loops.

See also Kuhar et al. 2016

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Take-home message

- Solar HXR: bremsstrahlung
  - heated plasma
  - accelerated electrons
- Magnetic energy release
- Future instrumentation
  - Solar Orbiter STIX
  - HXI onboard ASO-S
  - Focusing optics (FOXSI*)