Photon-Counting Spectroscopy with X-ray Observations

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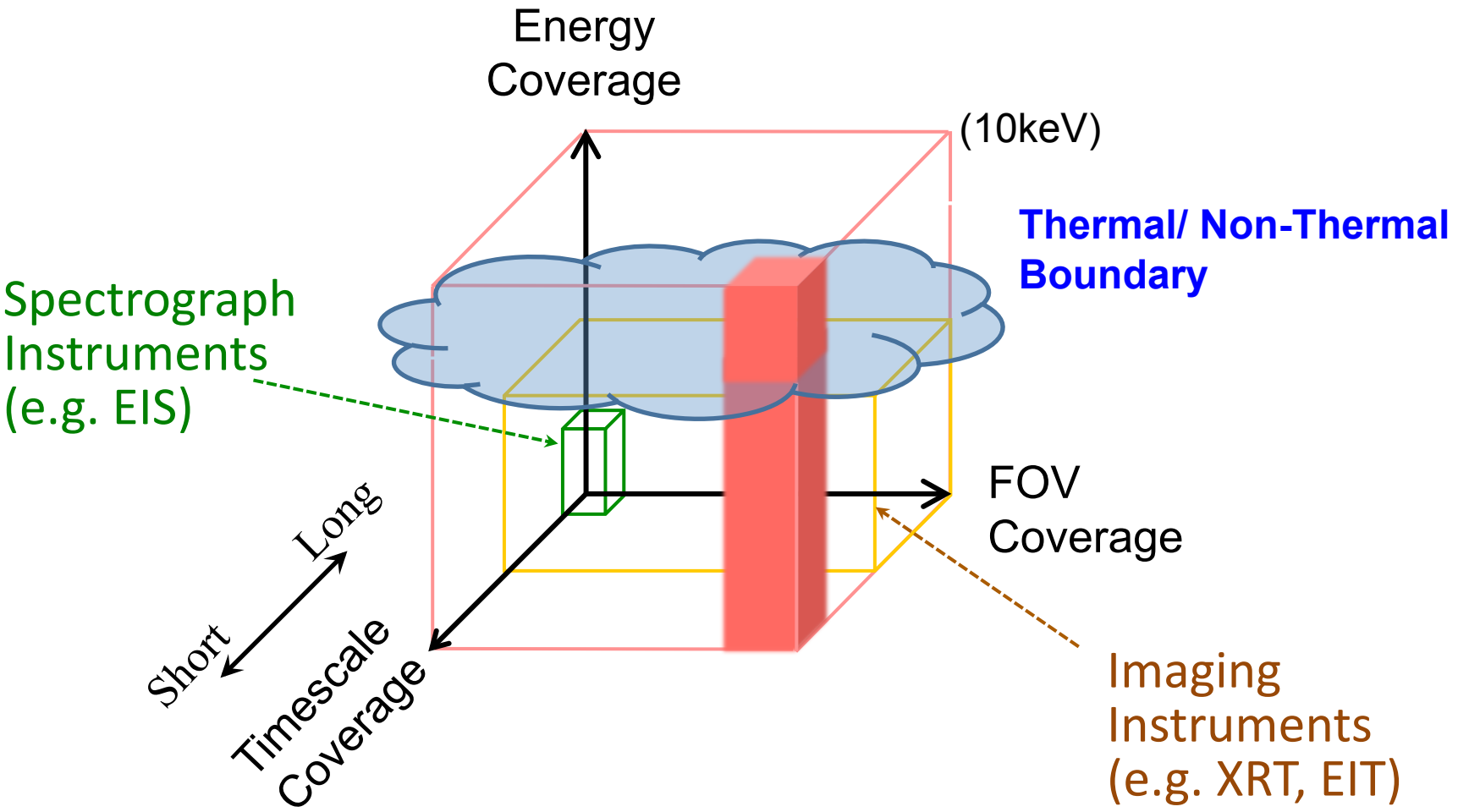
New Frontier in the Physics of X-ray Corona with Spectroscopic Imagery

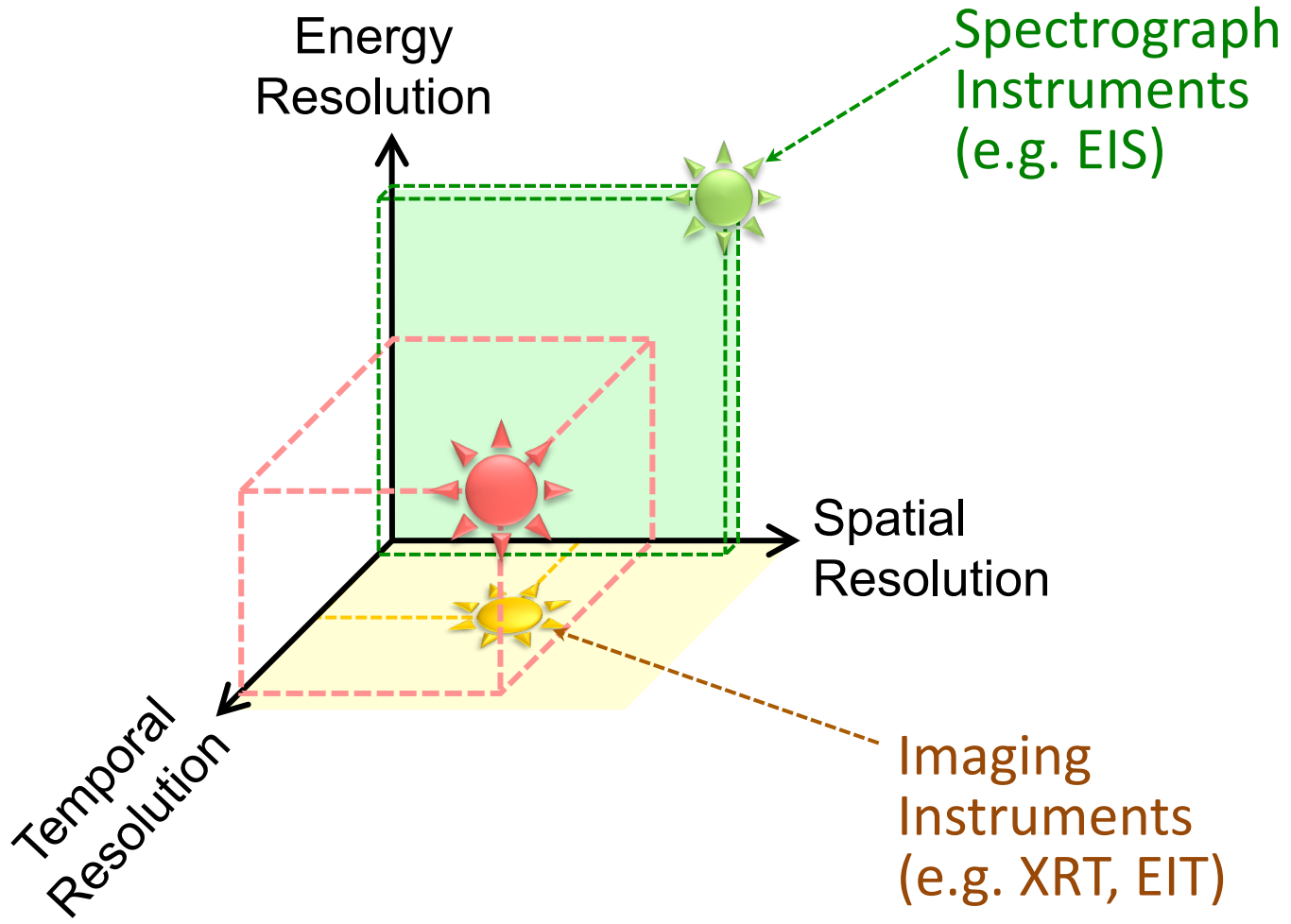
Concept

- Imaging spectroscopy of the solar corona with an X-ray telescope for
  - Energetic/Transient events
    ... Flares, CMEs, microflares, jets, ...
  - Background-free coronal structure
    ... Flows, loops, ...
- Quantitative identification of
  - Spectral structure around energy release region
  - Evolution of thermal/non-thermal components
  - Multi-temperature distribution of coronal structures

Scientific Standpoint of the Instrument (1)
– Coverage –



Scientific Standpoint of the Instrument (2) – Resolution –

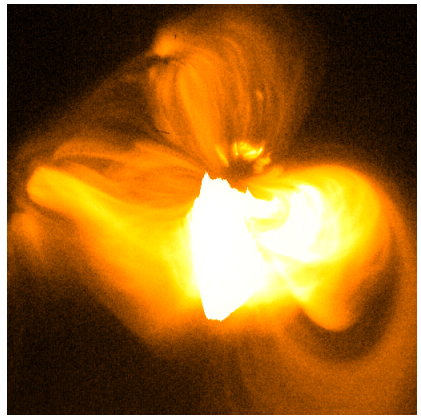


Outline

- Telescope and Detector
- Science Cases
  - Active Regions and Quiet Sun
  - Flares, CMEs, and Transient Events
- Detector
- Summary

Telescope and Deterctor

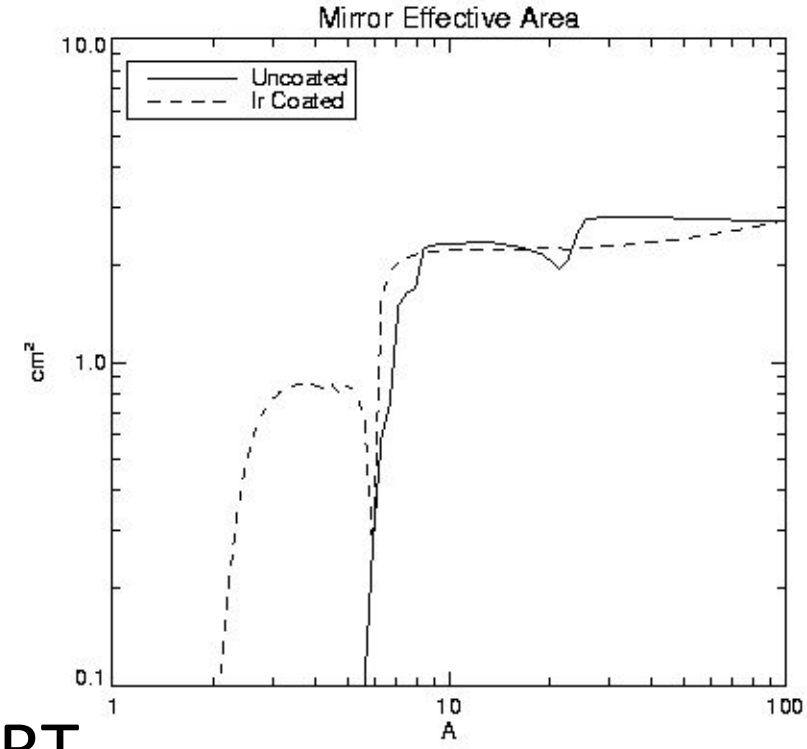
- Trade-offs:
  - NI vs GI
  - CCD vs CMOS/APS
- With GI:
  Continuous temperature coverage from 1 MK to >30 MK.
- With CMOS/APS:
  Photon counting capability.
  Blooming free ("Individual" pixels).



CMOS/APS detector with HE-Enhanced XRT for feasibility study

High-Energy Enhanced XRT for Feasibility Study

- CMOS/APS photon-counting detector with High-Energy Enhanced XRT-equivalent telescope.
- Mirror must be coated with Ir. Bare glass without coating doesn't make sense for this instrument.

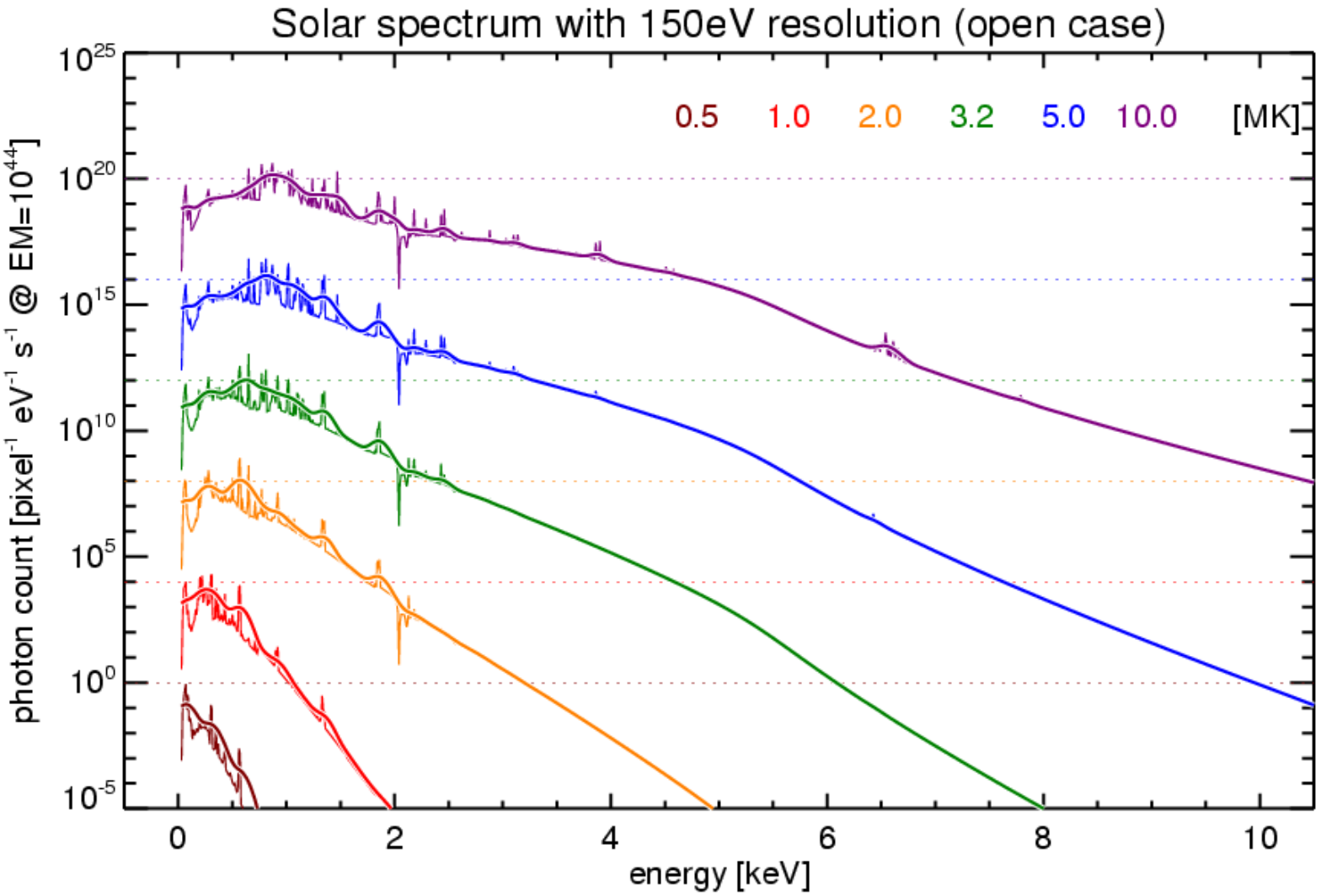


- Pre-filter same as that for XRT.
- Photon attenuation filter(s) for flare observations. (e.g., Be 3 mm)
- Focal-plane shutter optional.

Strawman detector concept

- CMOS/APS for photon counting of Solar X-rays
  - Device with high speed readout and short exposure capabilities

- Format: 2k x 2k (TBD). [N.B. Can be smaller.]
- Pixel size: < 15 μm (TBD)
- Exposure time (from reset to readout): ~1 ms/pxl (TBD)
- Image readout rate: ~1000 frame/s (TBD)
- Full well: TBD e^-
- Energy resolution: ~150 eV
- Wavelength range: ~0.1–100 A
- Sensitivity: Similar to CCD; Back-thinned device desired
- Read out noise: TBD e^-

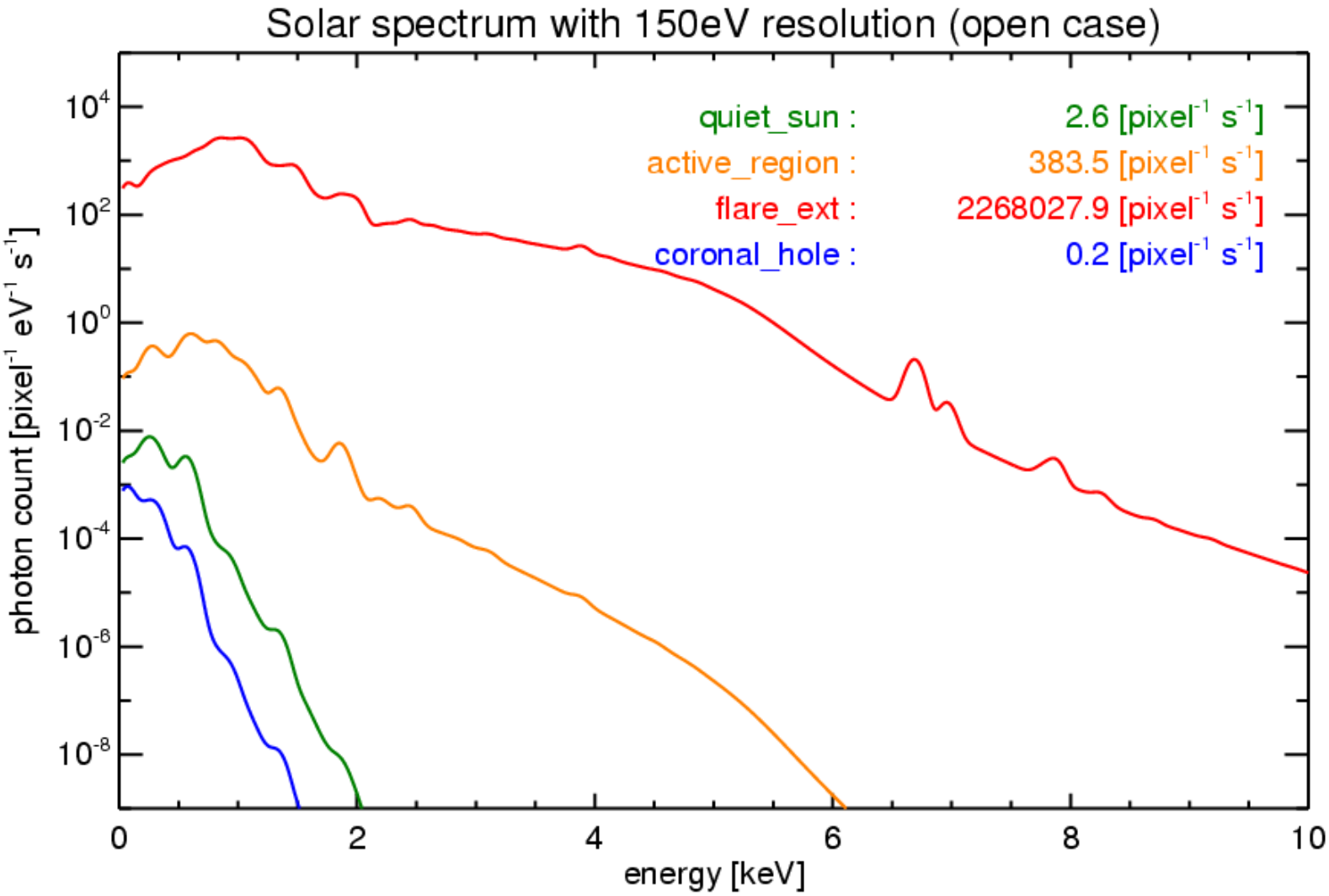


Solar spectra from various single-temeprature plasmas.

Each plot shifted vertically by a factor of 10^4 for the sake of clarity.

Spiky profiles: raw solar spectra.

Smooth profiles: convolved with assumed energy resolution of 150 eV for APS.



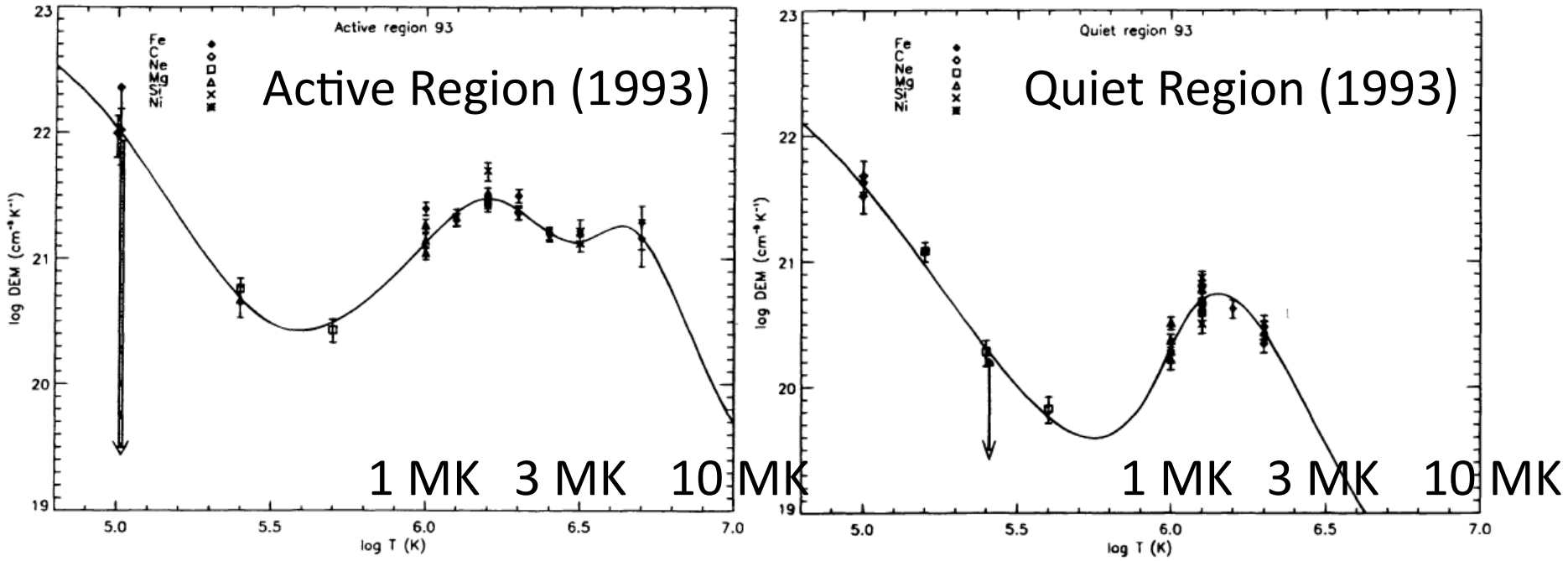
Solar spectra from various targets in the corona, convolved with assumed energy resolution of 150 eV for APS.

Science Cases

1. Active Regions and Quiet Sun

Active Regions and Quiet Sun

- DEM determination

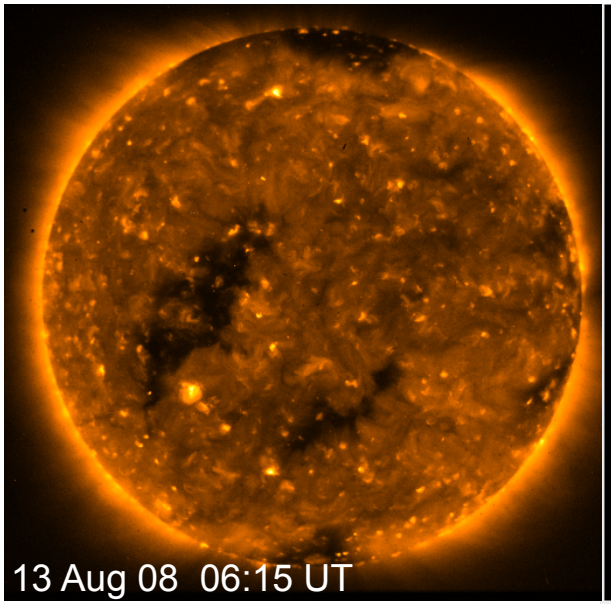


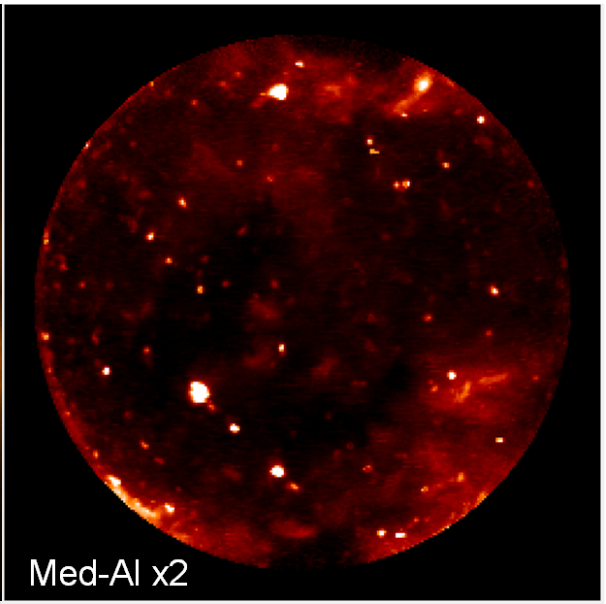
(Brosius et al. 1996)

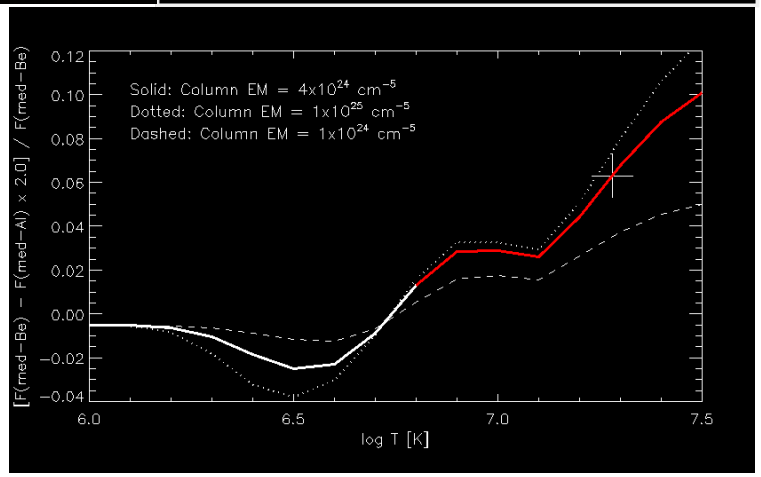
* DEM above 5 MK not known.

High-Temperature Components across Active Regions and Quiet Sun

Hot plasmas with temperature 5–32 MK (most likely >10 MK) present not only in Active (X-ray bright) Regions but also in the Quiet Sun and near the poles, even during solar minimum.







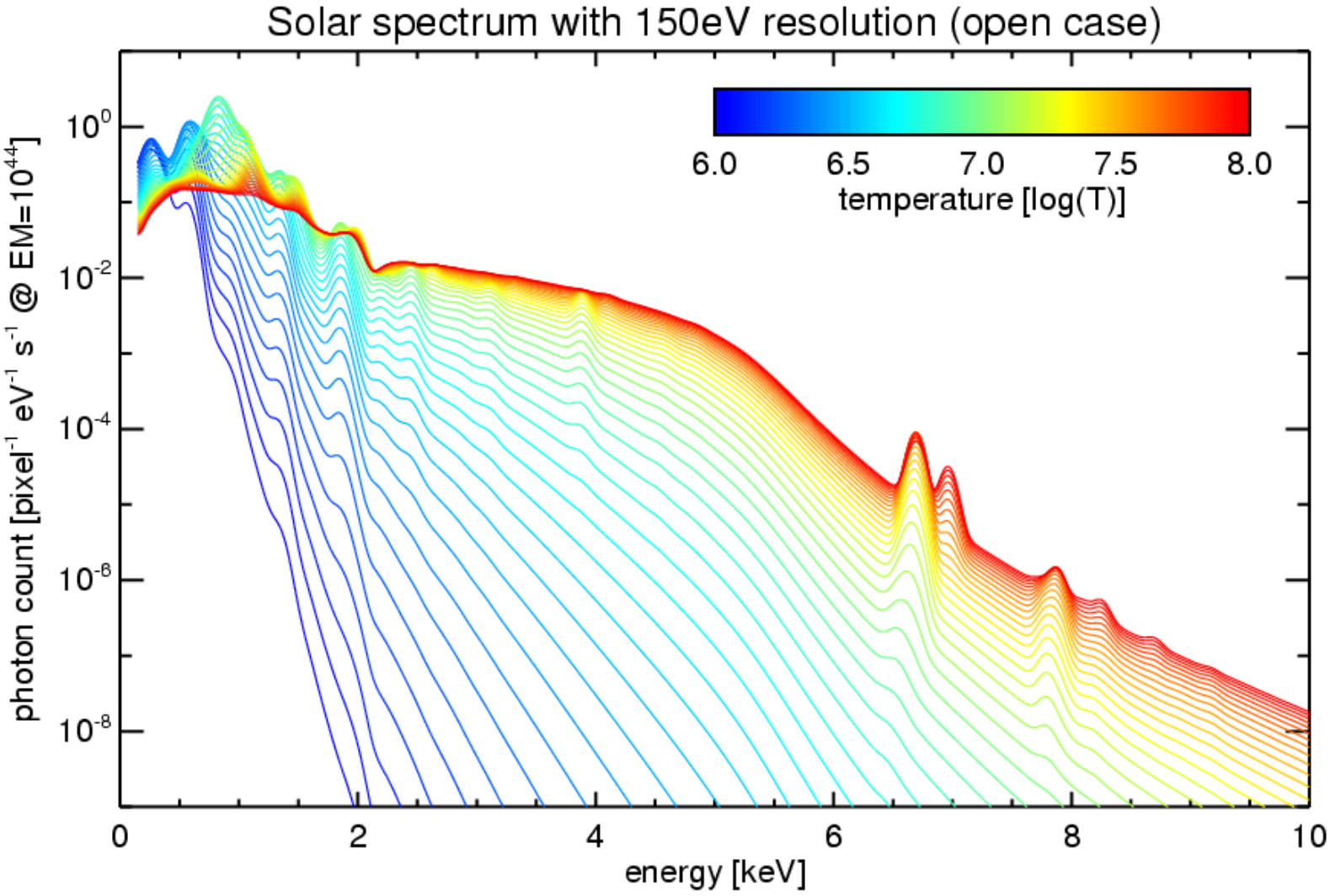
(Ishibashi 2008)

→ How are they heated?

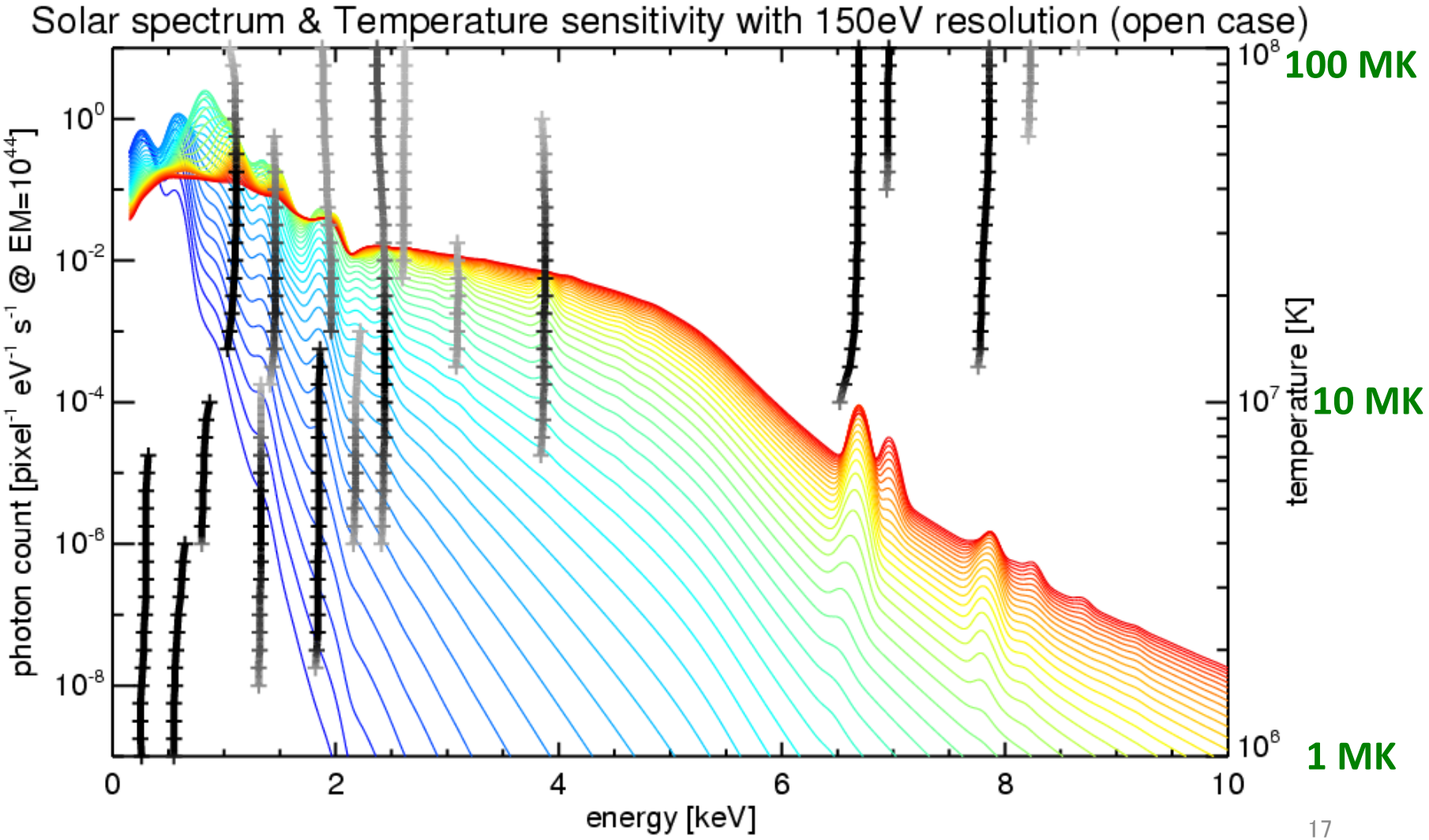
→ How are they maintained?

→ What DEM?

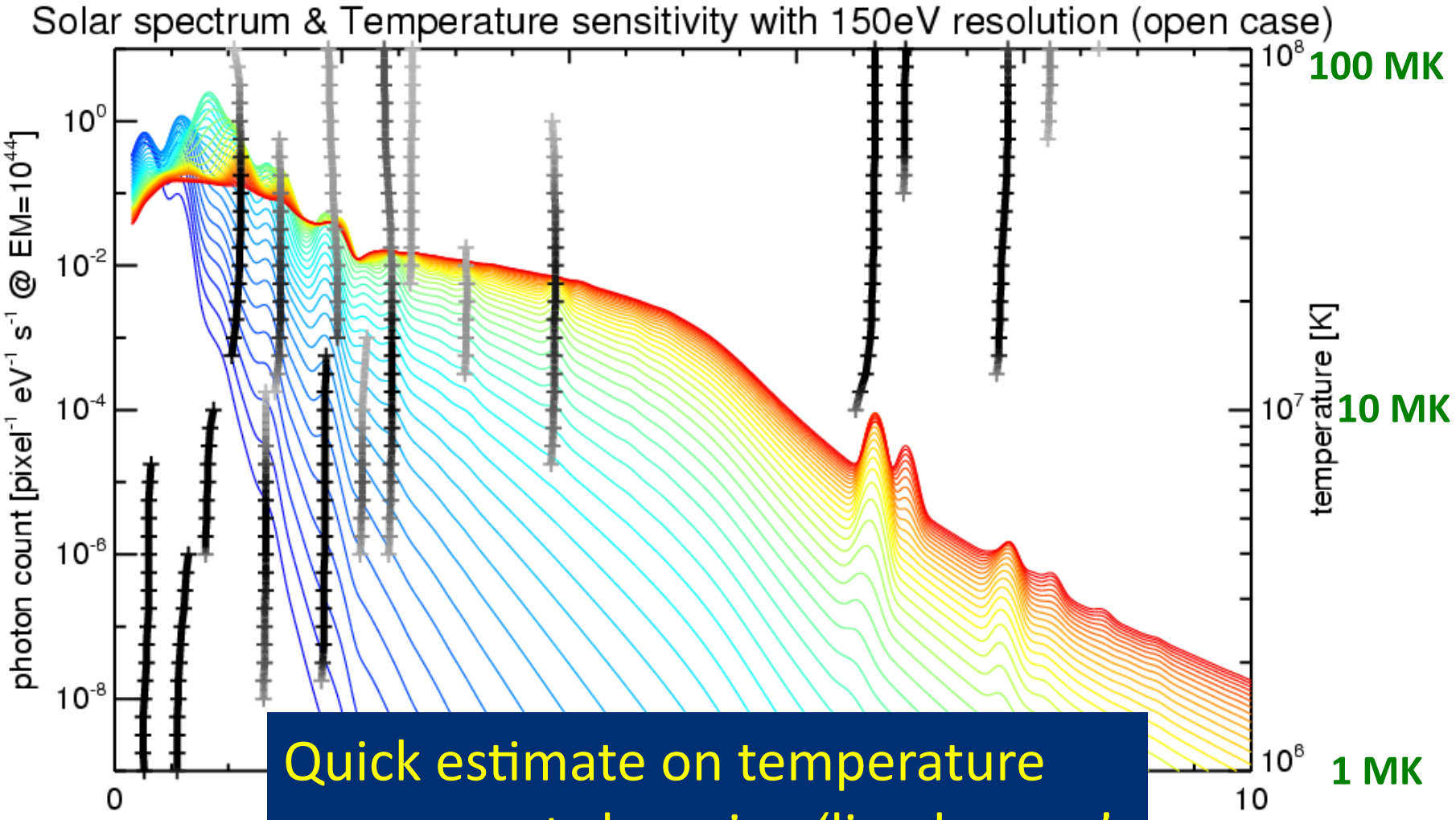
Count Spectra with Different Temperatures



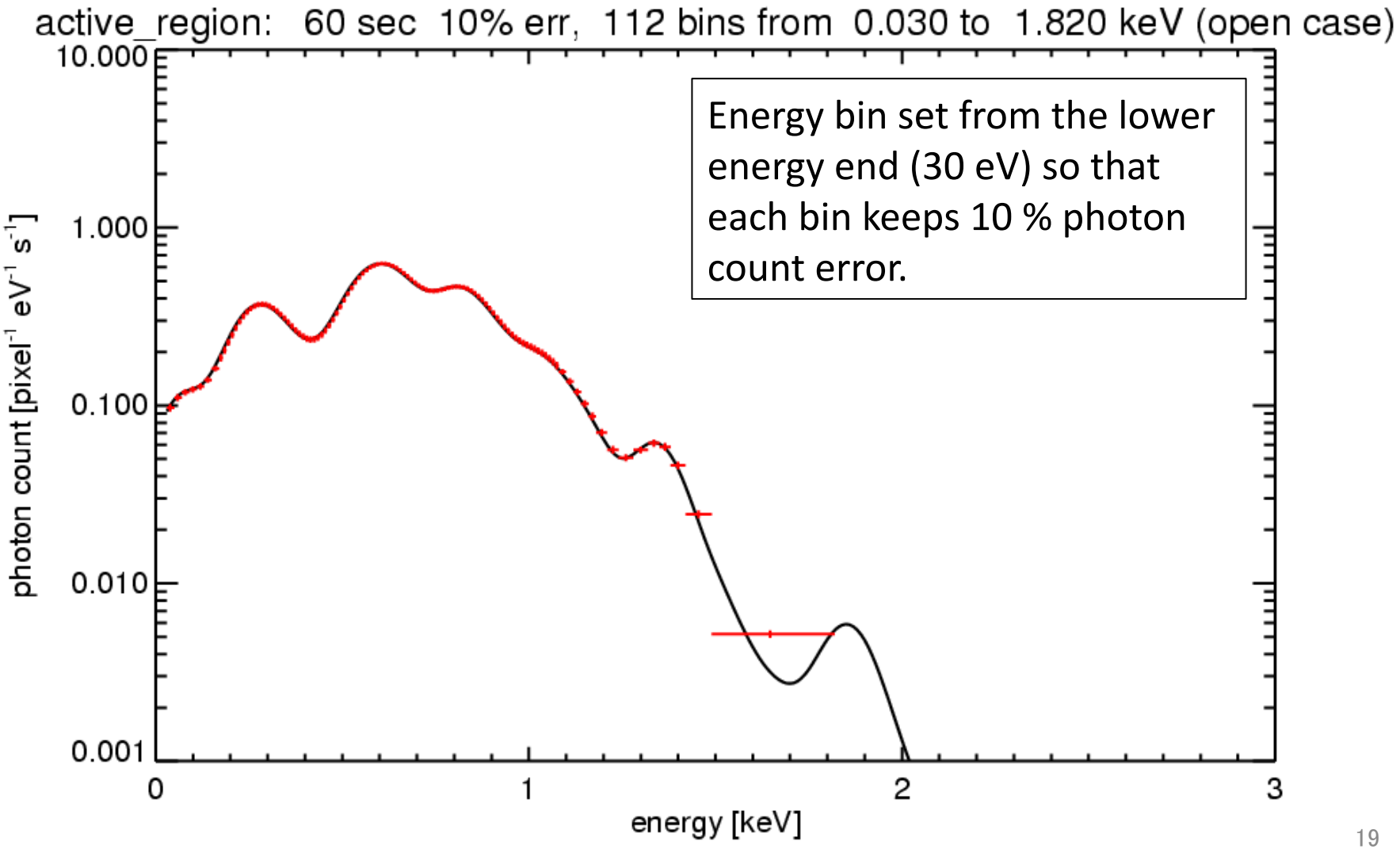
Count Spectra with Different Temperatures



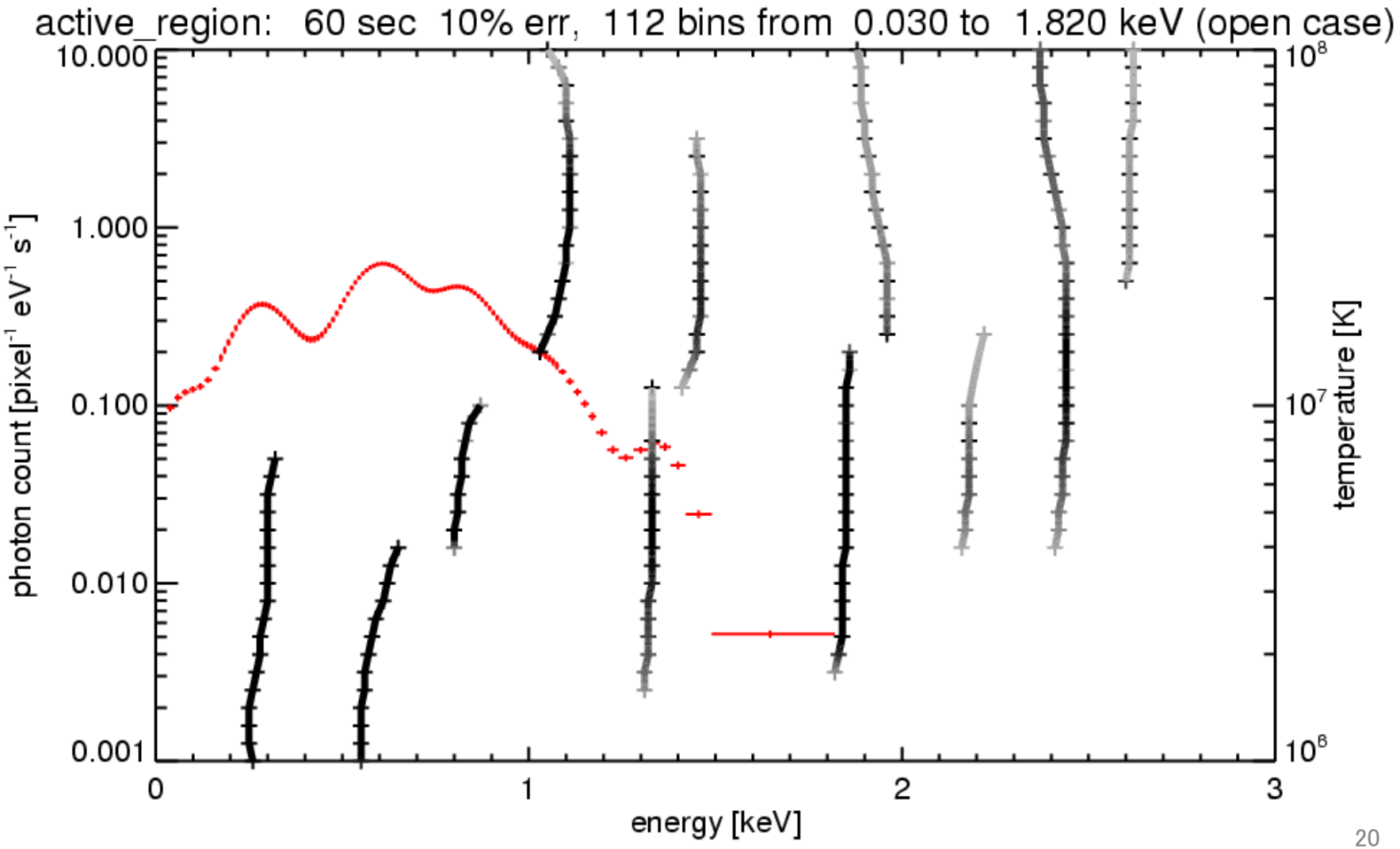
Count Spectra with Different Temperatures



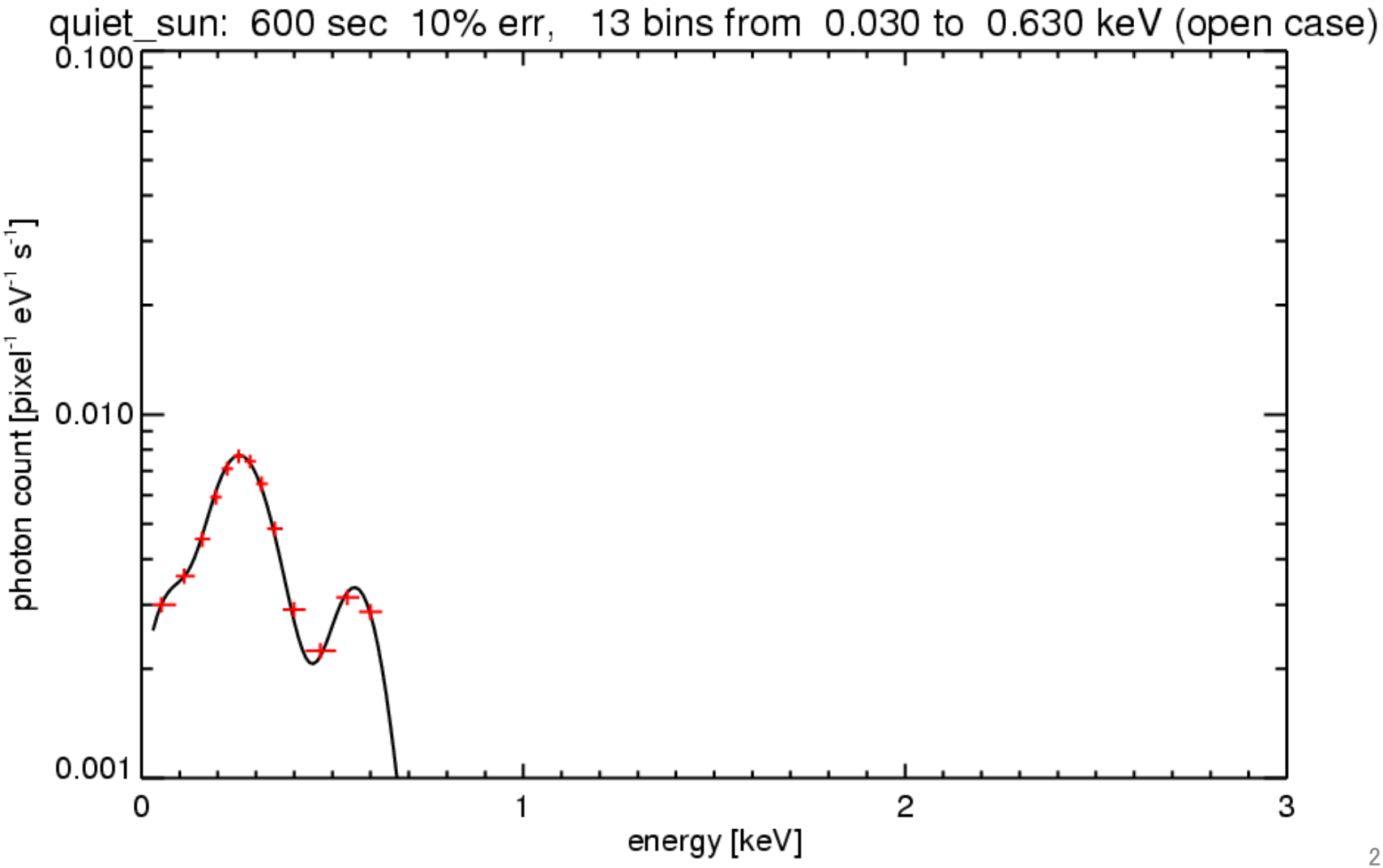
Active Region: 1-minute Integration, 1”x1”



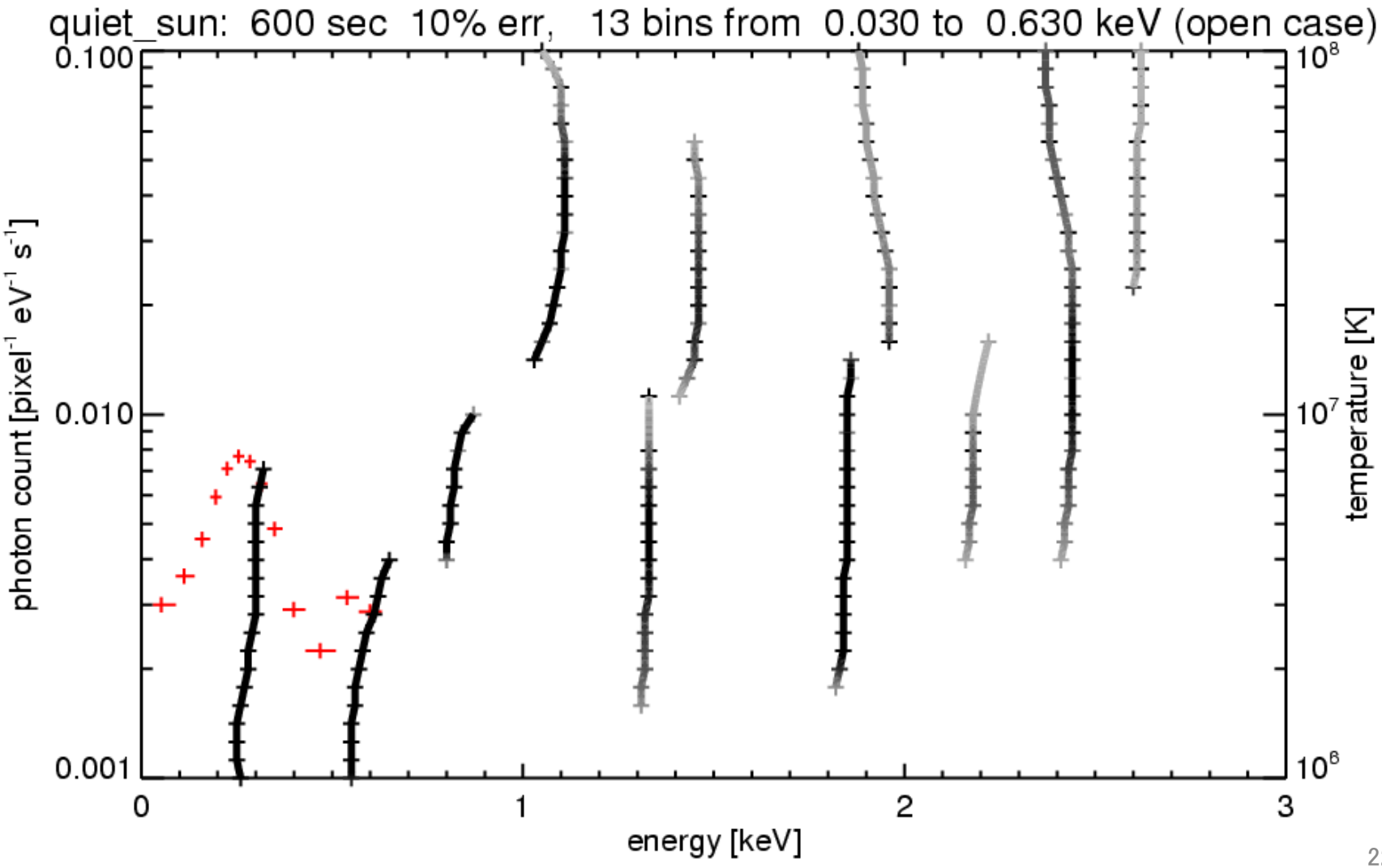
Active Region: 1-minute Integration, 1”x1”



Quiet Sun: 10-minutes Integration, 1”x1”



Quiet Sun: 10-minutes Integration, 1”x1”

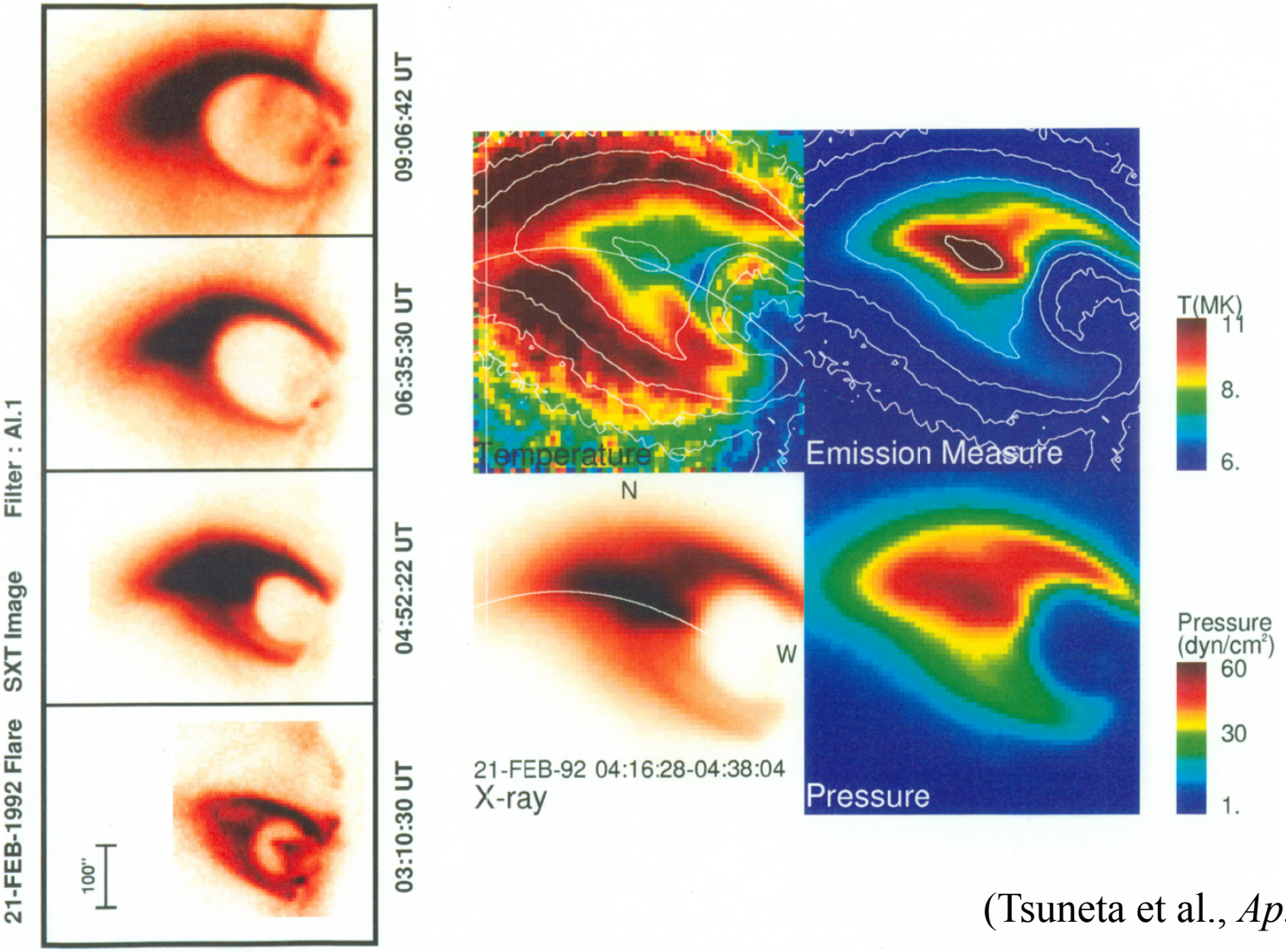


2. Flares, CMEs, and Transient Events

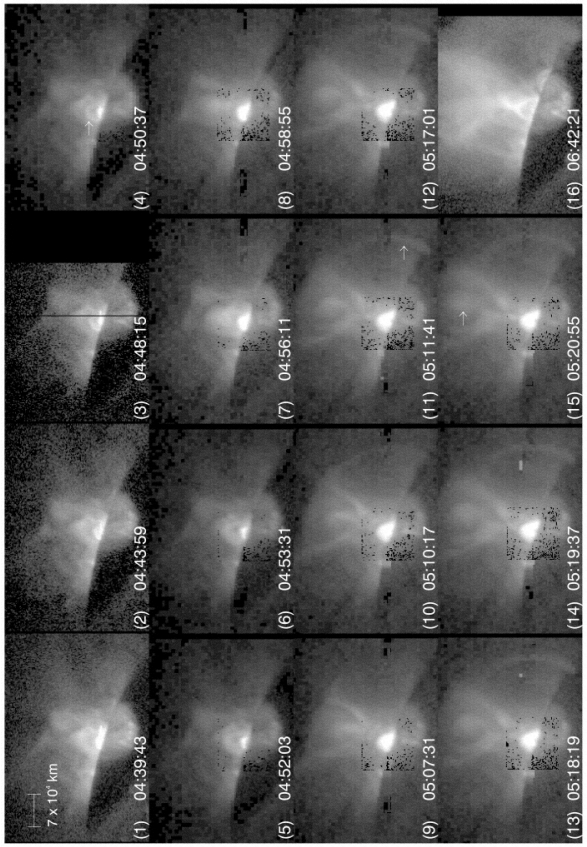
Energy Release and Particle Acceleration in Flares

- Spectral structure around energy release site and its dynamical evolution
  - Shock structure
  - Presence and evolution of non-thermal tail in a few keV range
  - Together with evolution of seed thermal distribution
- Spectra with background corona removed for optically-thin target

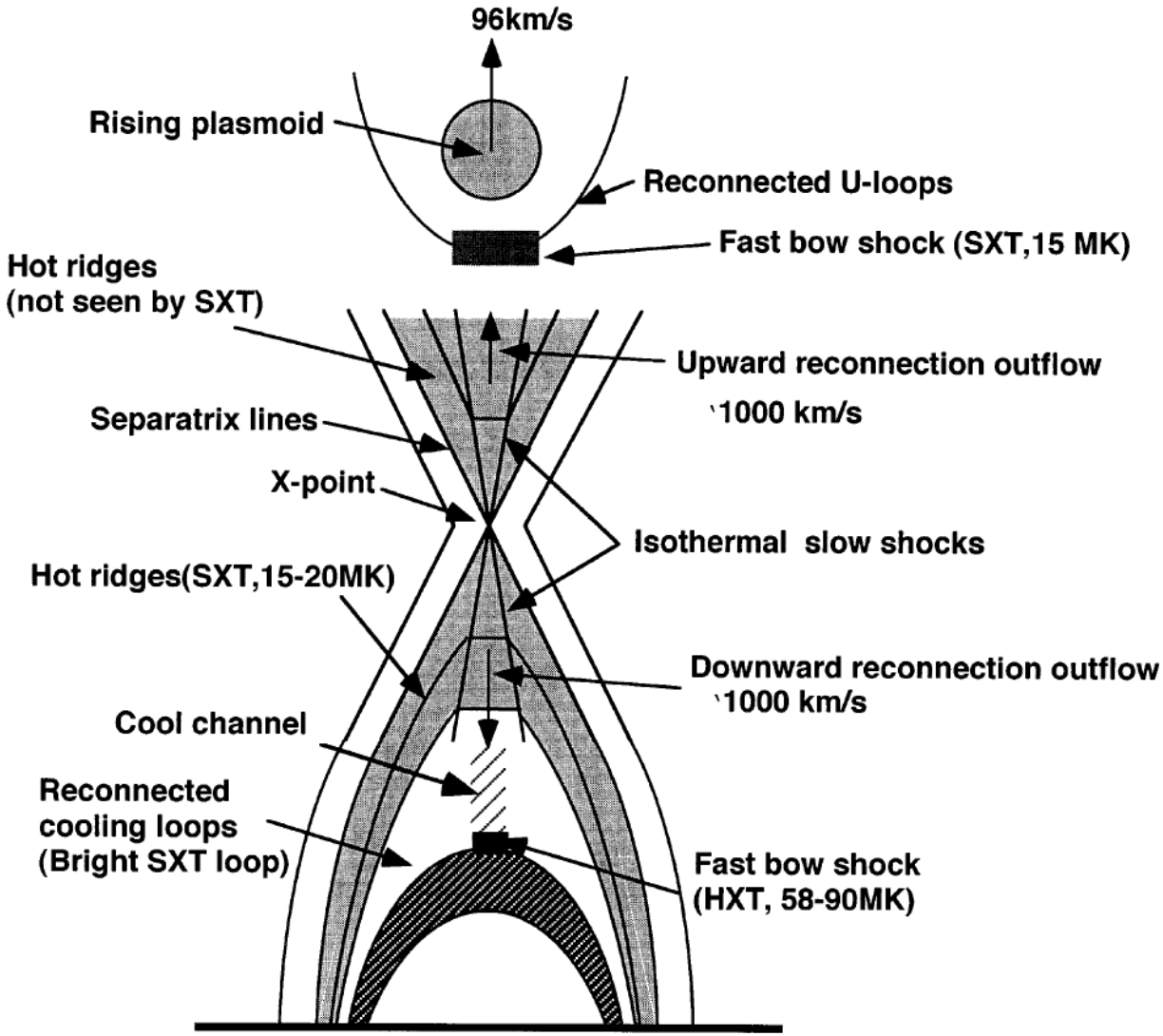
Possibilities: Particle Acceleration Site

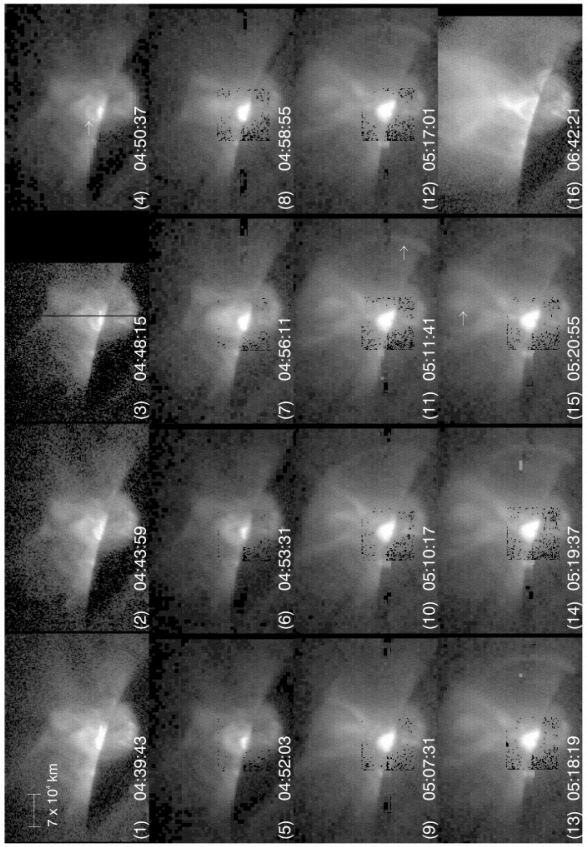


(Tsuneta et al., *Ap.J.* 1996)

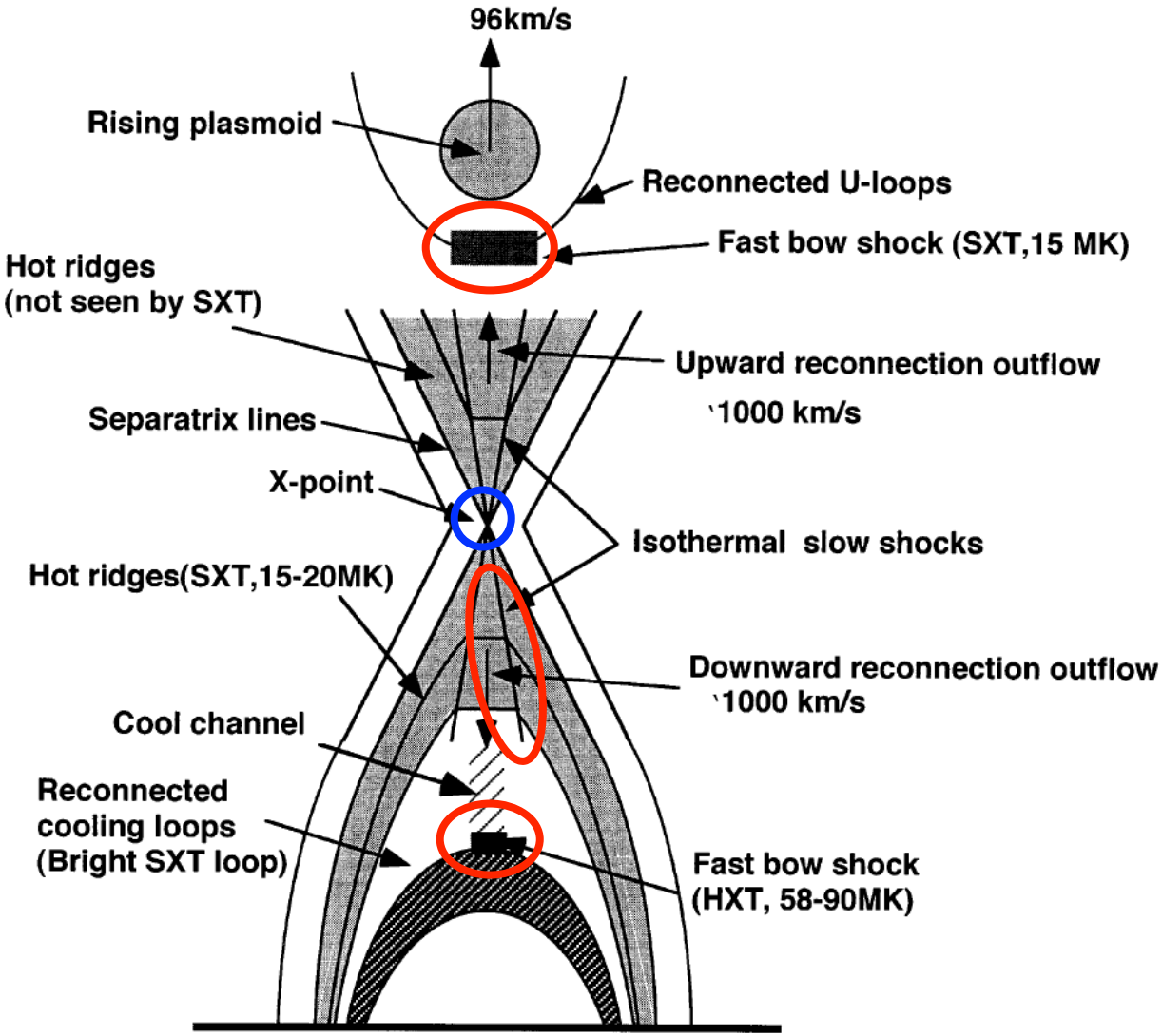


(Tsuneta, *Ap. J.* 1997)



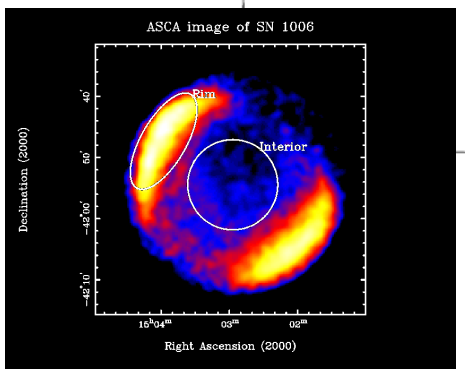


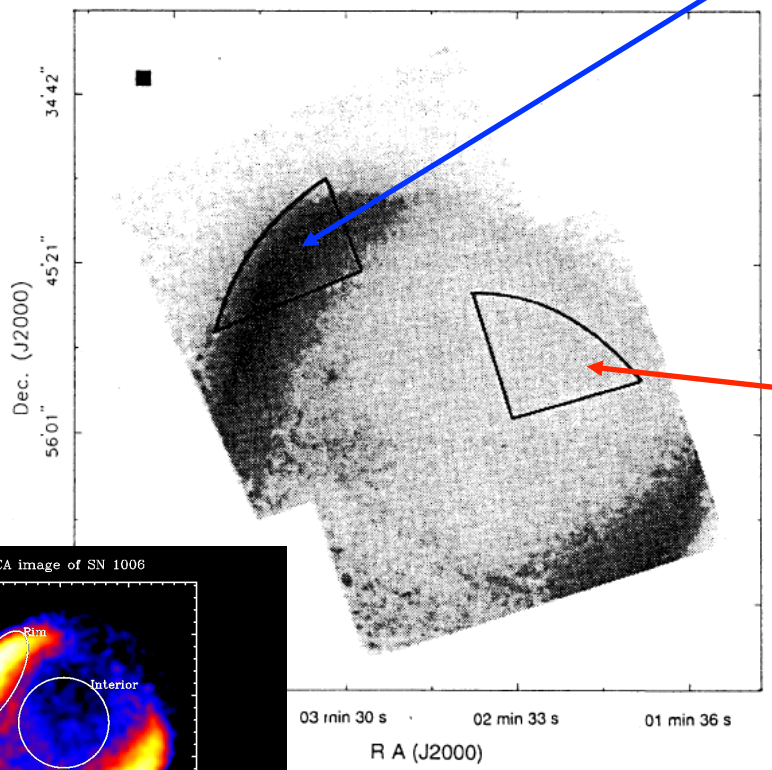
(Tsuneta, *Ap. J.* 1997)

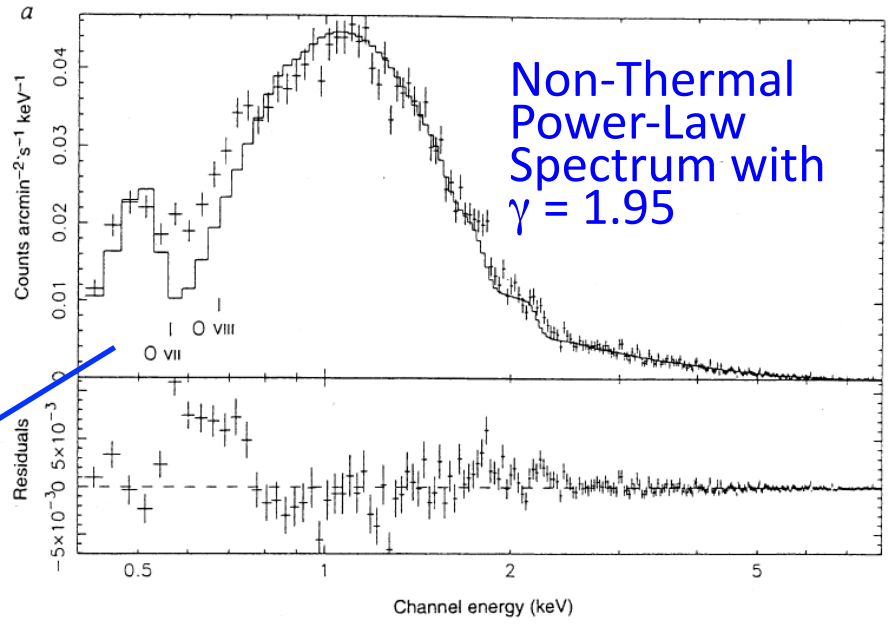


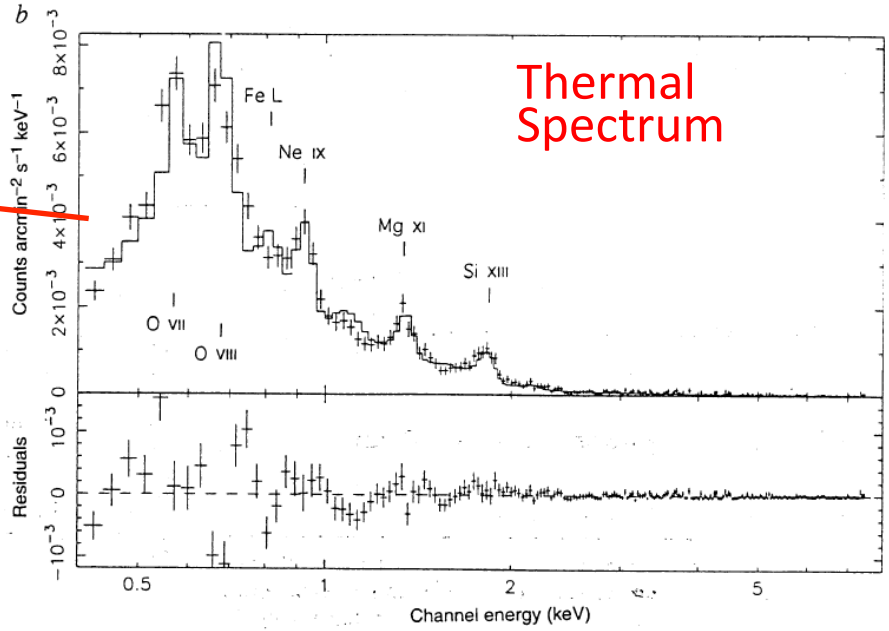
Shock Acceleration of Electrons in Cosmic Plasmas

SN1006 ASCA Observation



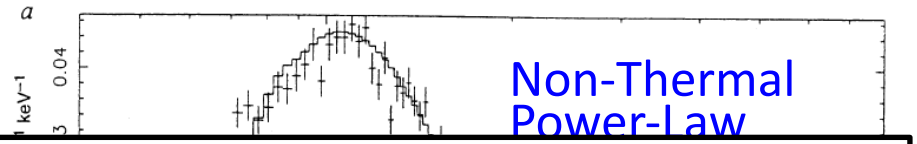




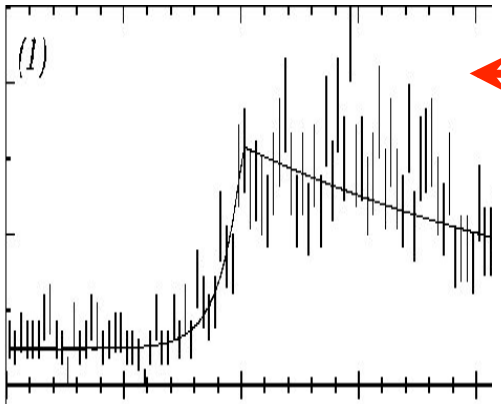


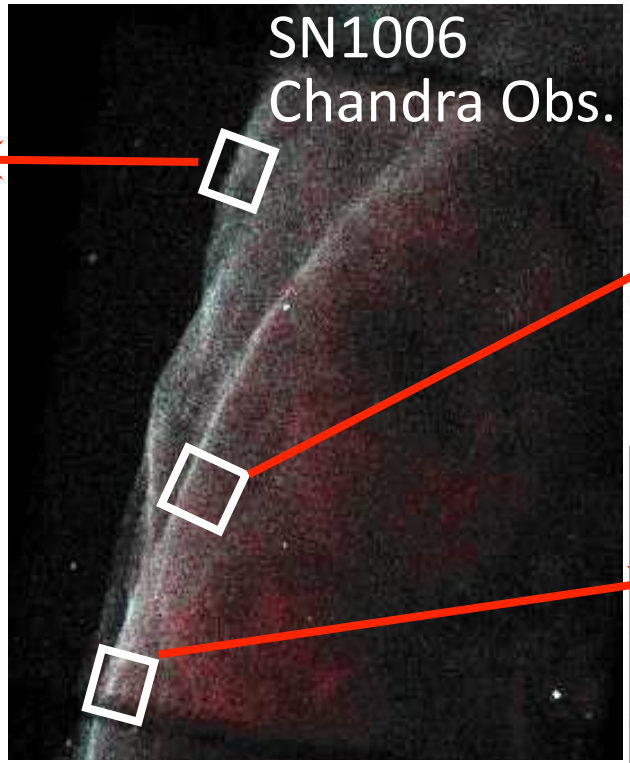
(Koyama et al. 1995)

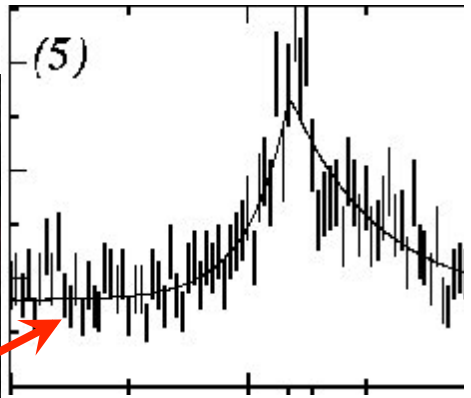
Shock Acceleration of I
Cos

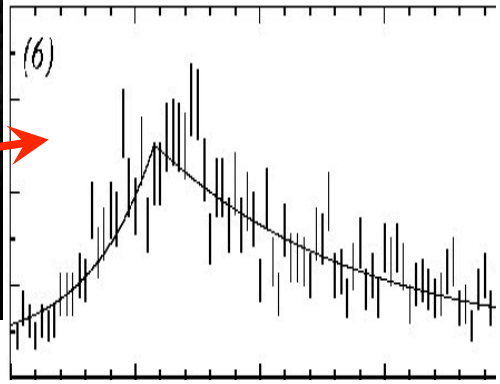


2-10 keV Spatial Profiles

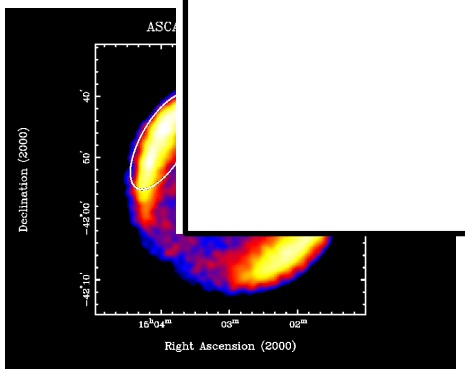








(Bamba et al. 2003)



Channel energy (keV)

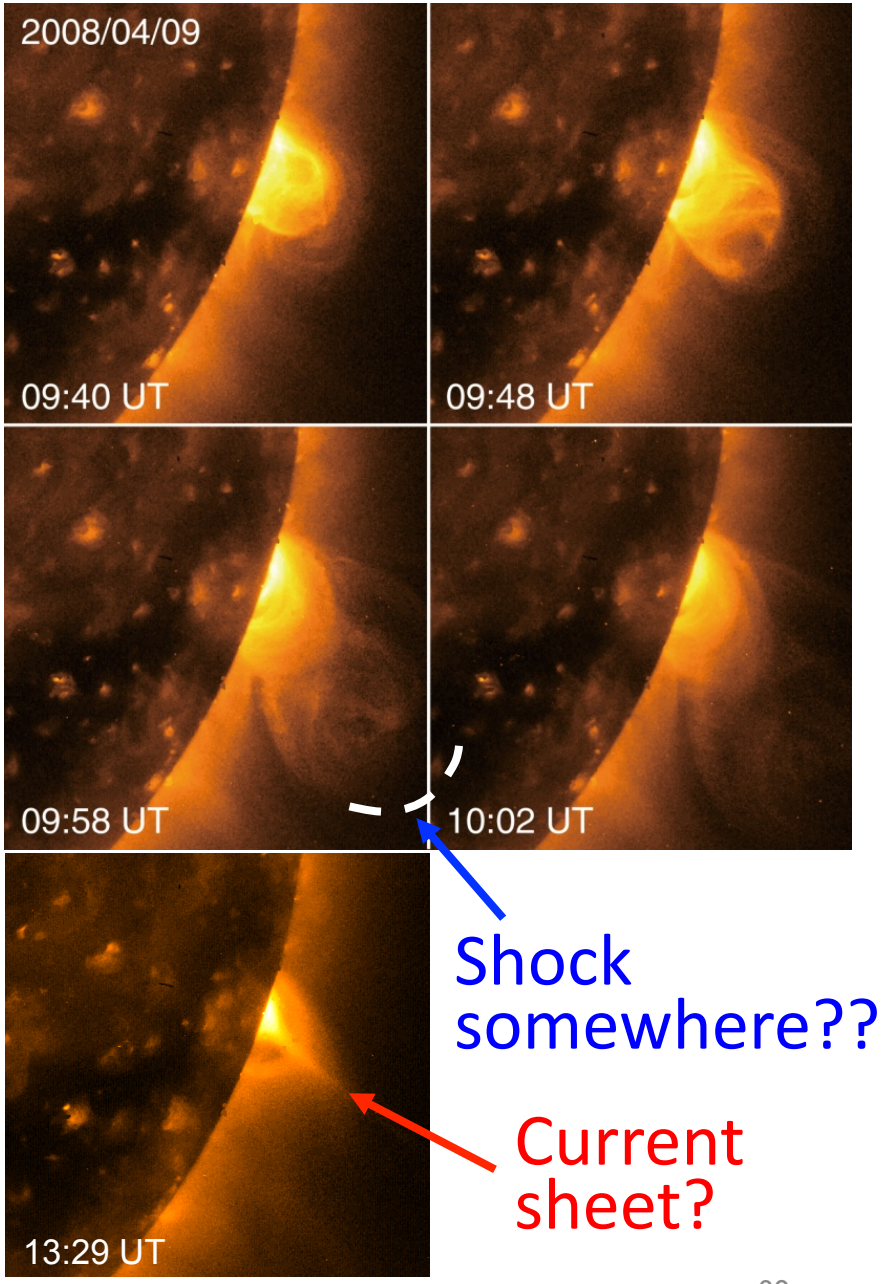
(Koyama et al. 1995)

Spectral Investigation on CME Structure

Spectral structure around CMEs

- Shock structure?
- Physical condition of current sheet

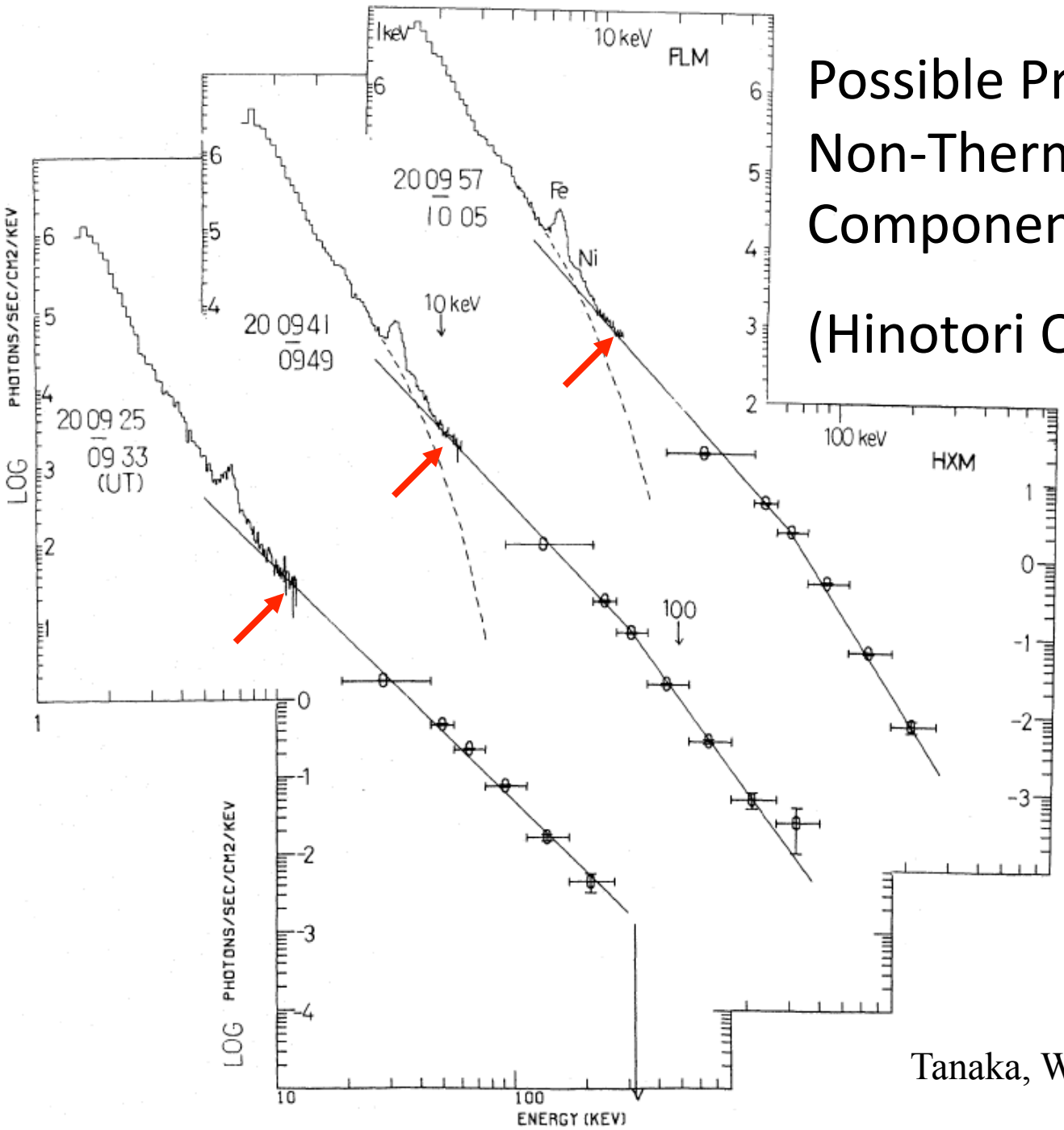
With e.g., 3”x3” resolution, <60 s integration would suffice for <10 MK range (TBD)



Non-Thermal Spectra in Flares

- Low-energy portion of non-thermal (power-law) spectra
  - Lowest energy for accelerated electrons?
  - Energy budget for non-thermal electrons?

- Power-law spectrum often extends down below 10 keV
  → Within energy range for the instrument
  - What non-thermal spectrum evolves out of what seed (or background) thermal distribution?
  - What spatial distribution for the non-thermal component?

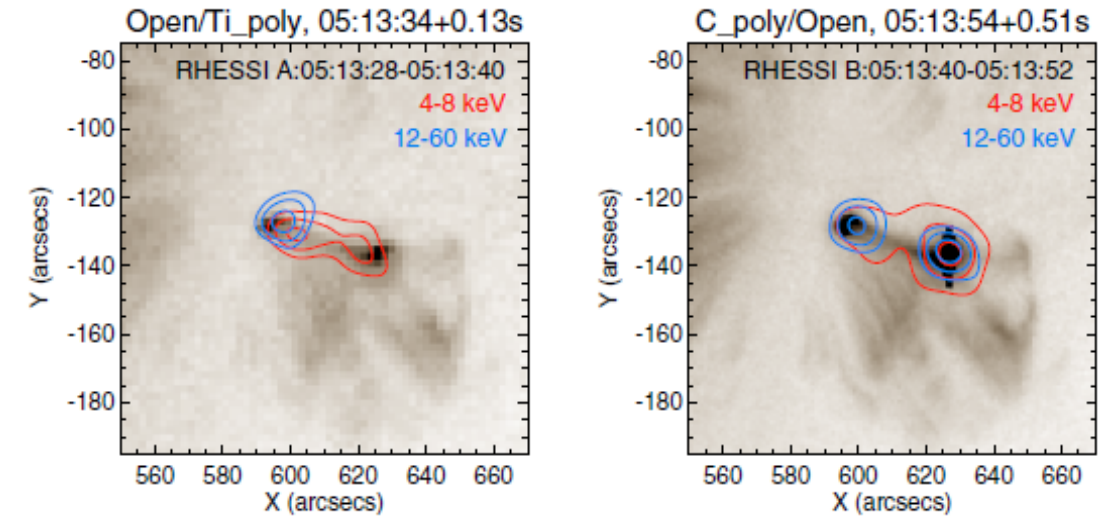


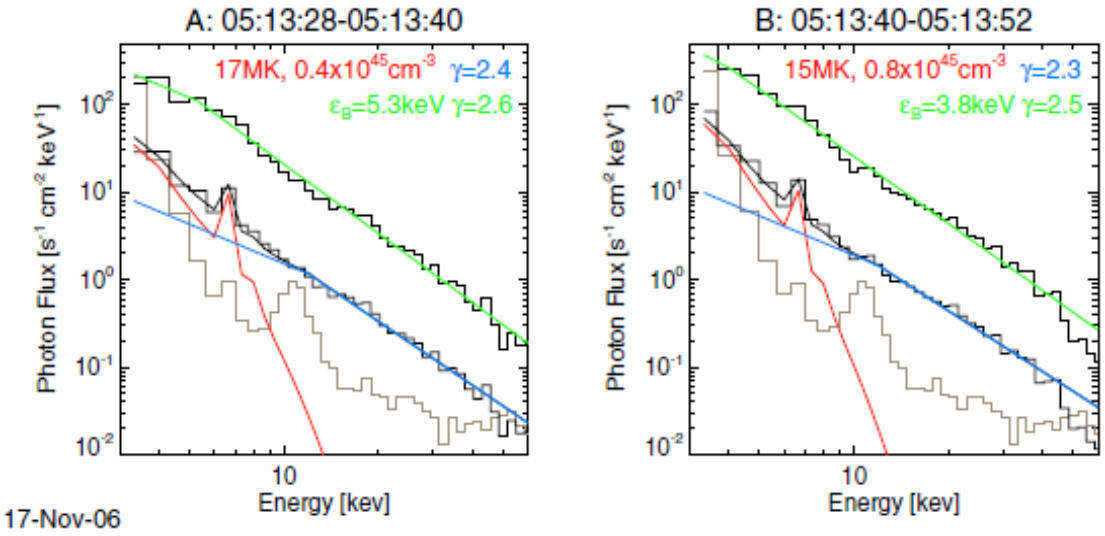
Possible Presence of Non-Thermal (Power-Law) Component below 10 keV

(Hinotori Observation)

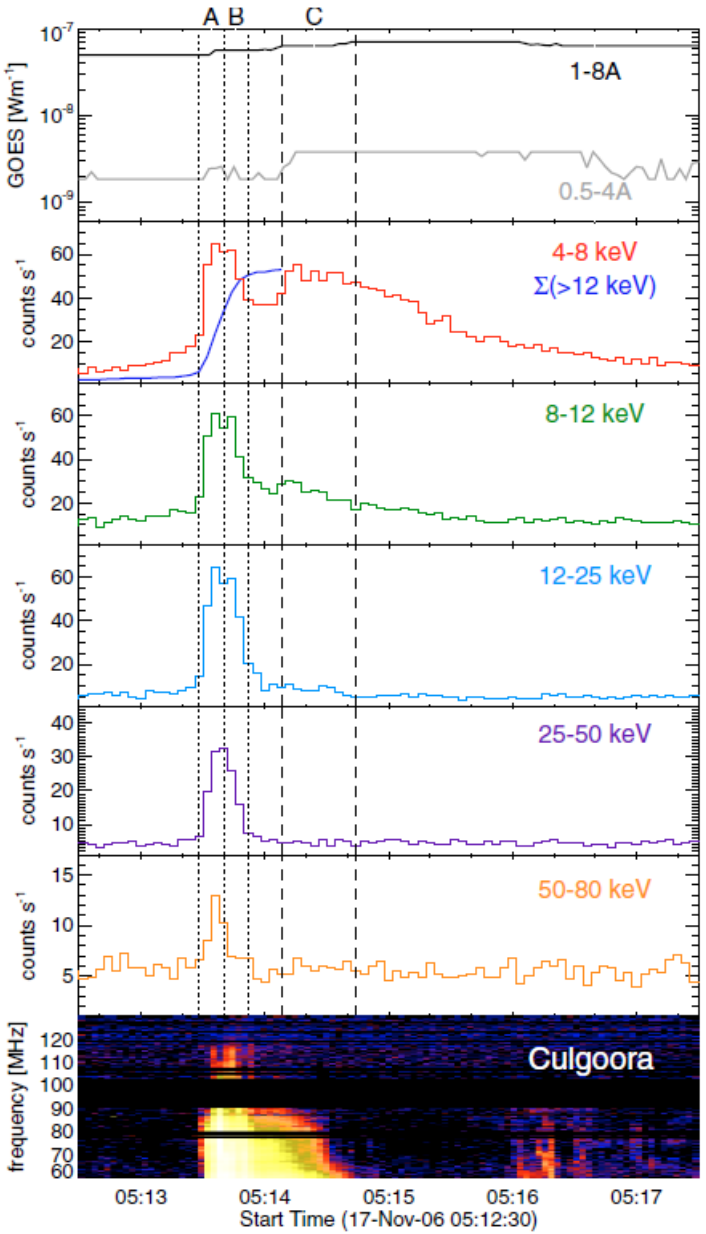
Tanaka, Watanabe, and Nitta 1984

Non-Thermal Component down to ~4 keV (RHESSI Microflare)



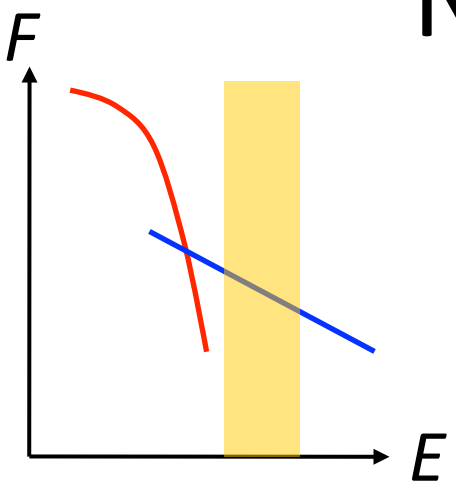


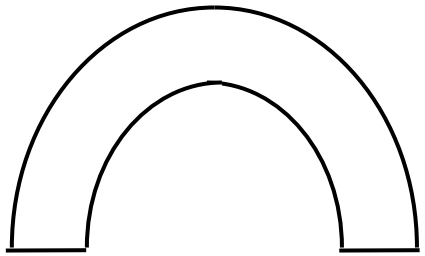
17-Nov-06



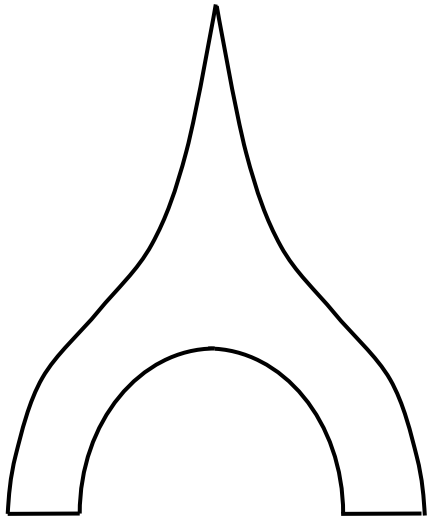
(Hannah et al. 2008)

Non-Thermal Imaging

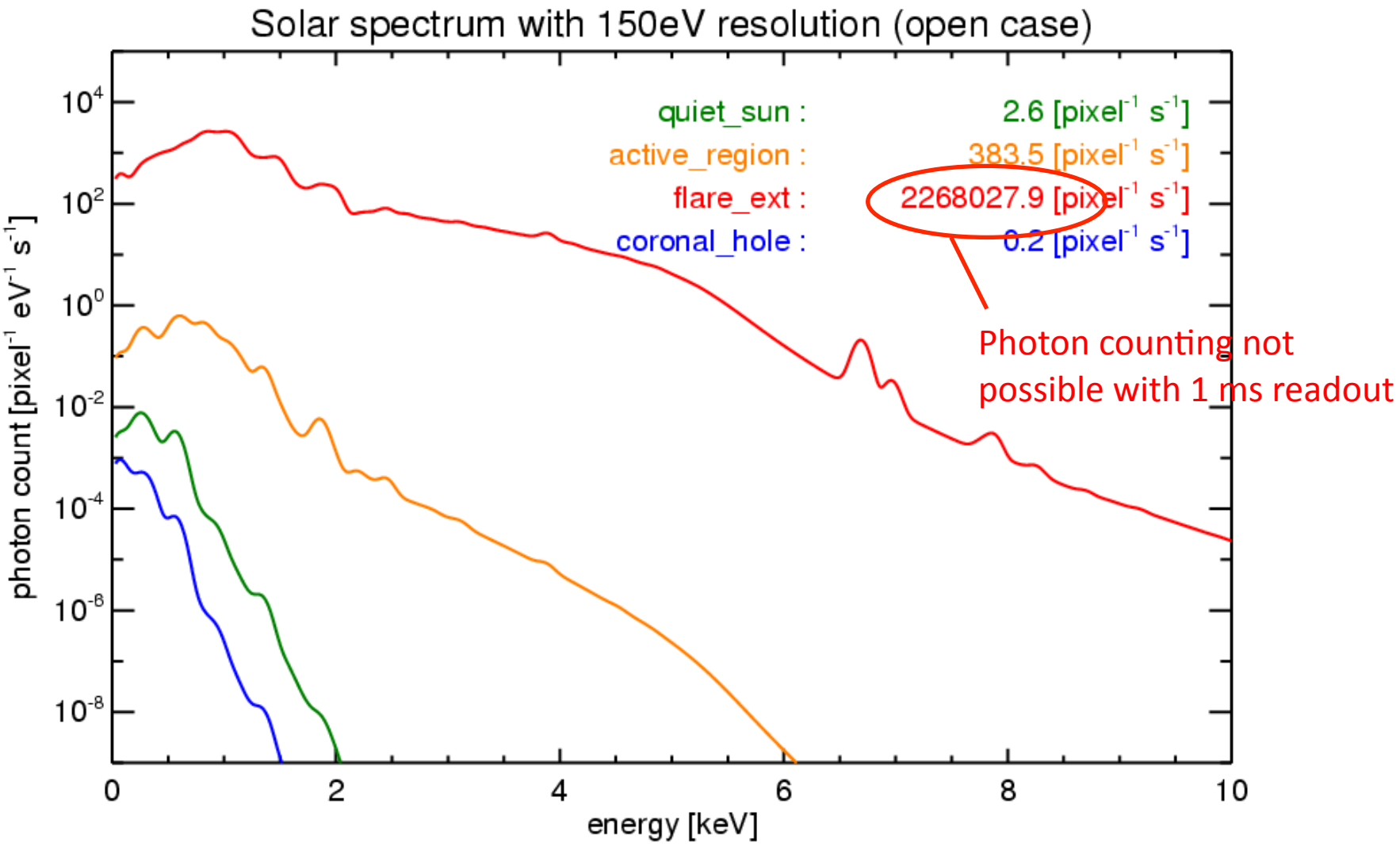




Acceleration at the loop top

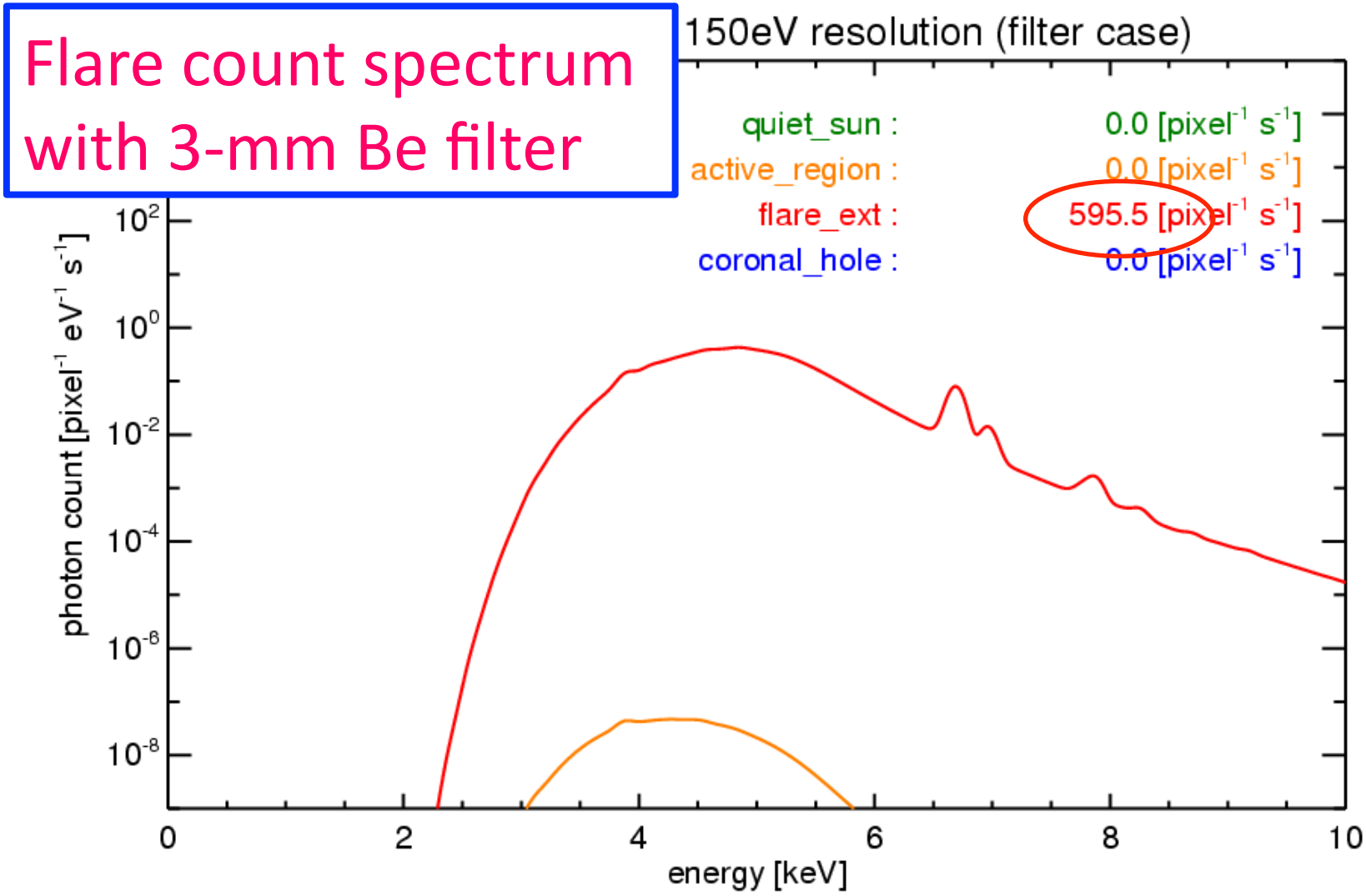


Acceleration at the reconnection point



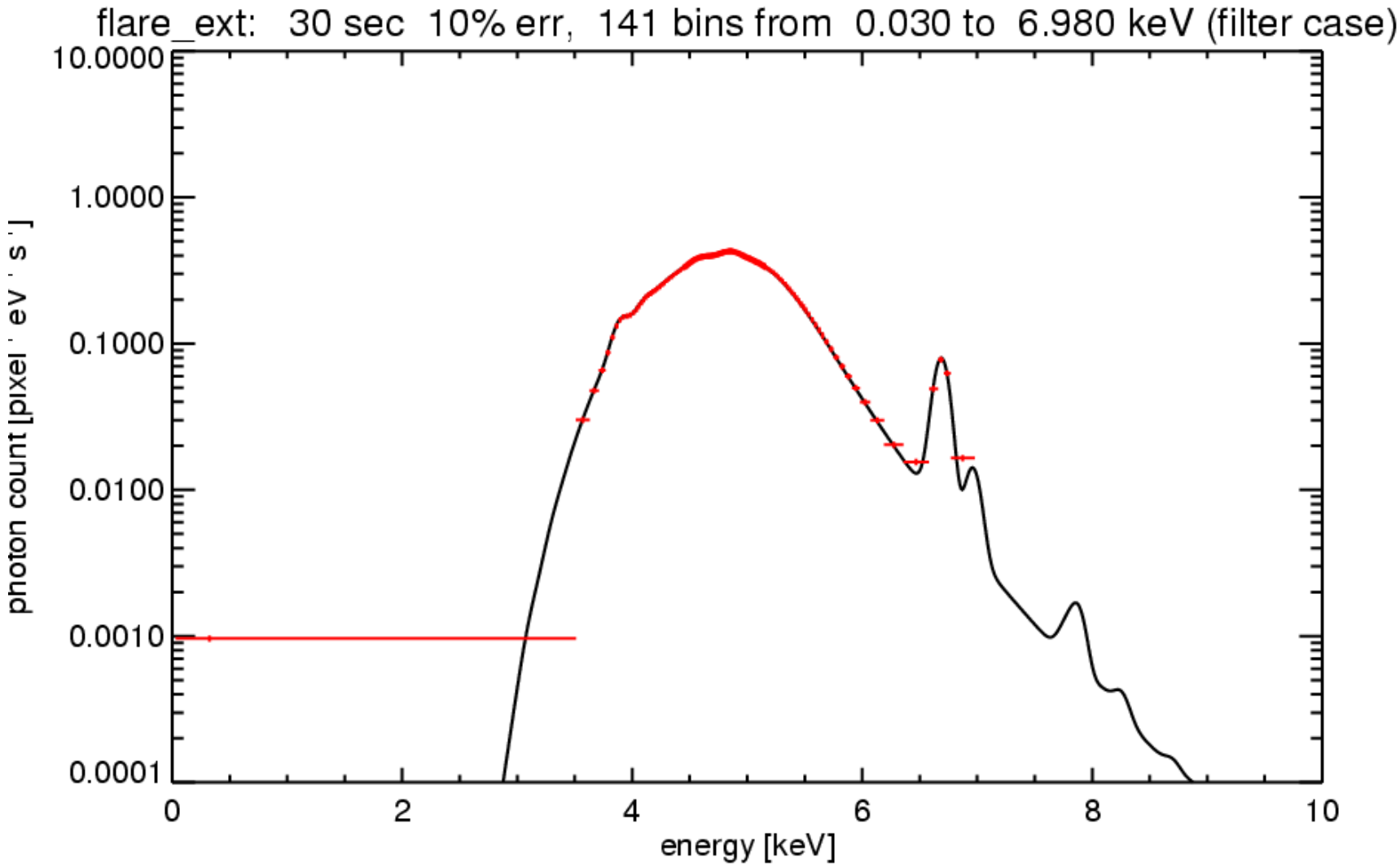
Solar spectra from various targets in the corona, convolved with assumed energy resolution of 150 eV for APS.

Flare count spectrum with 3-mm Be filter



Solar spectra from various targets in the corona, convolved with assumed energy resolution of 150 eV for APS.

Flare (M2) : With Filter
30-s Integration, 1”x1”



Flare (M2) : With Filter
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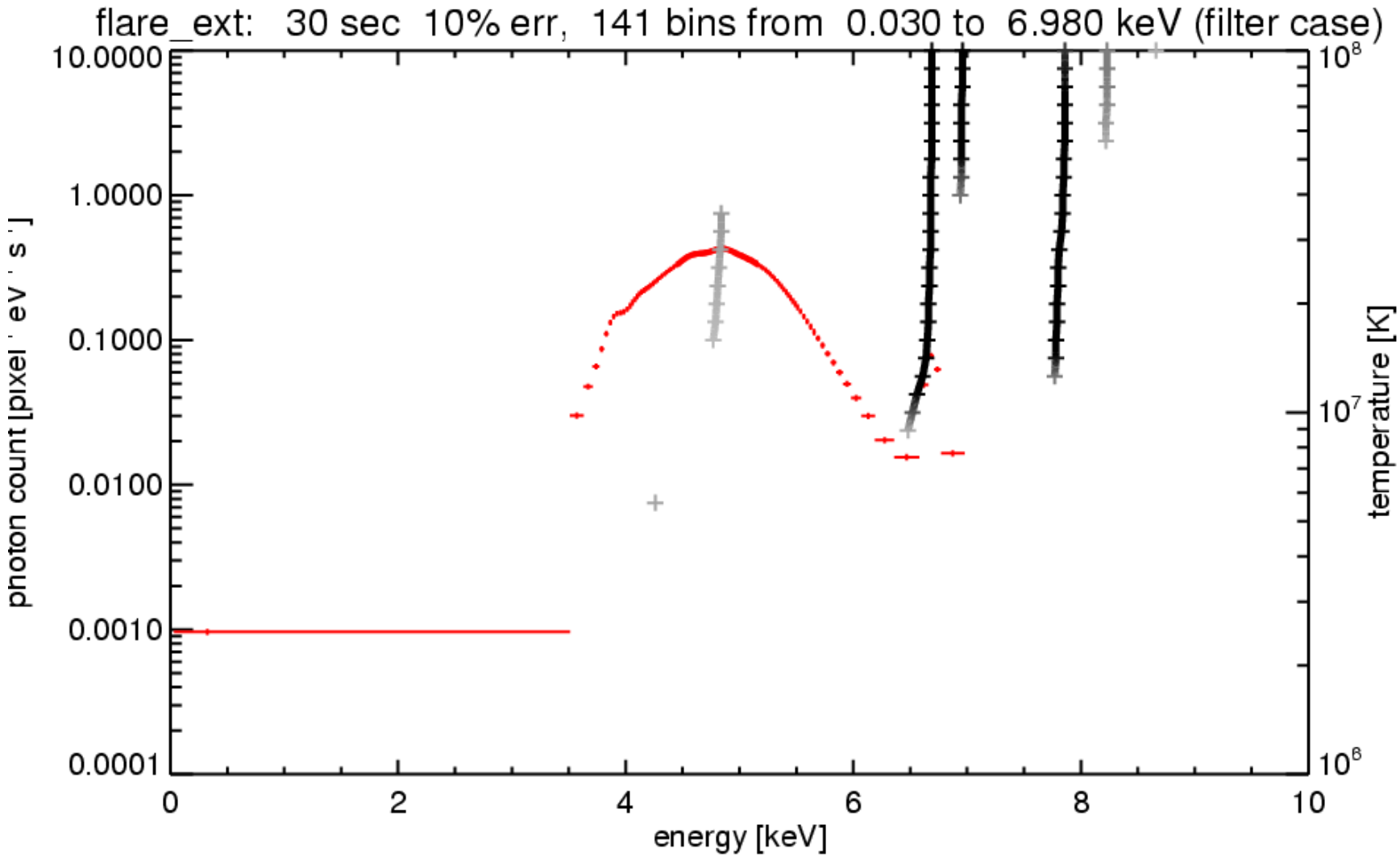
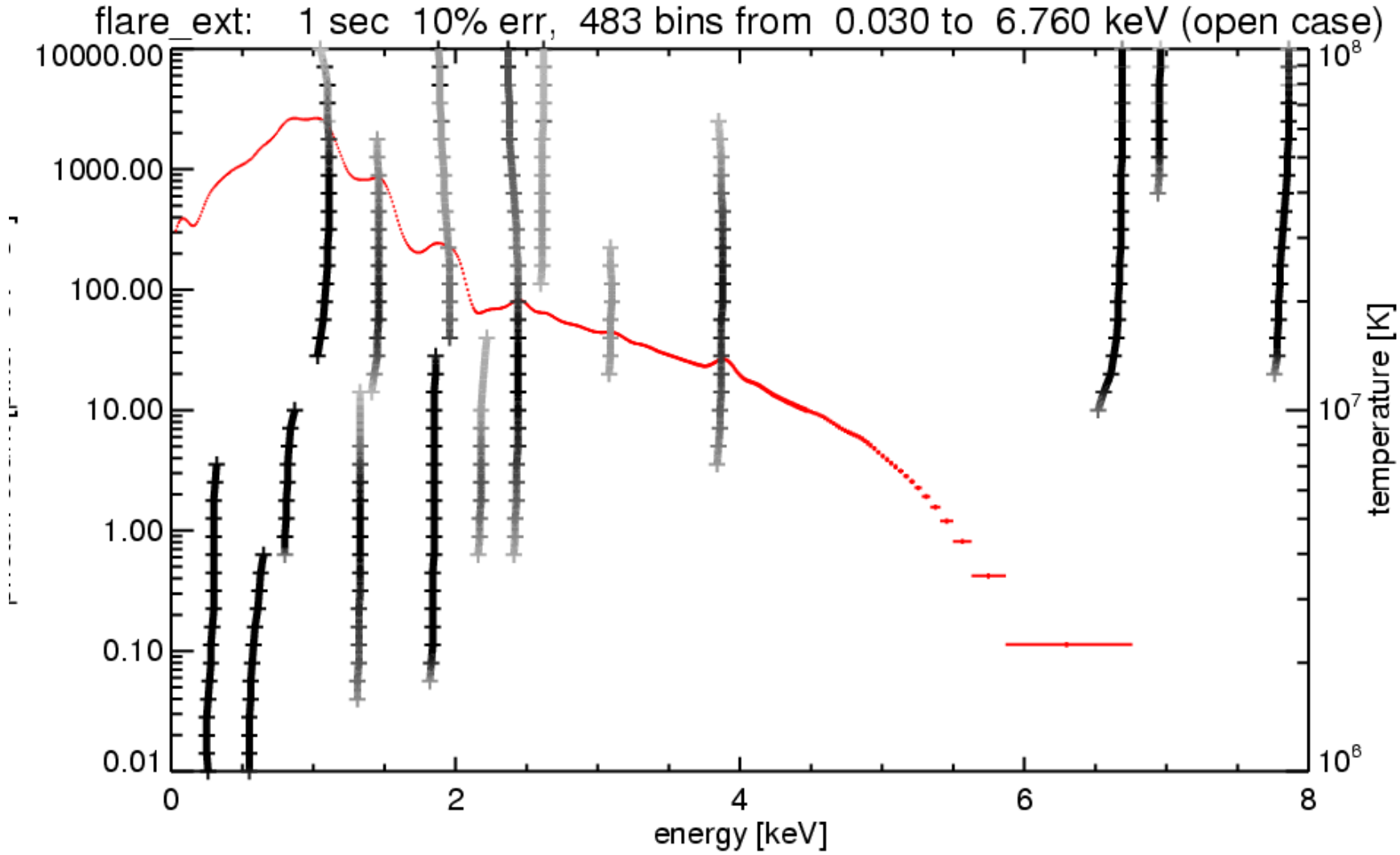
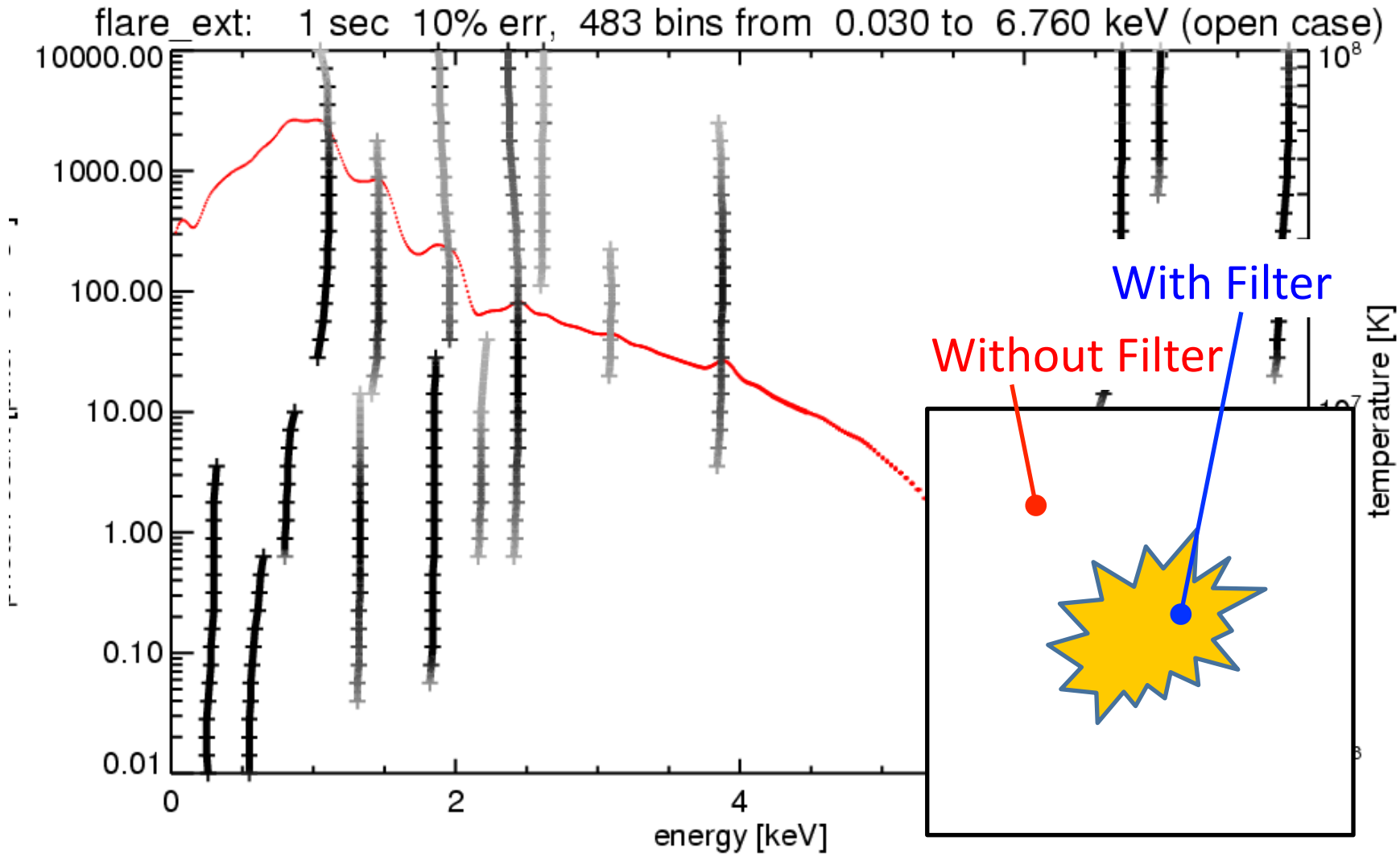


Flare (M2) : Without Filter
1-s Integration, 1”x1”

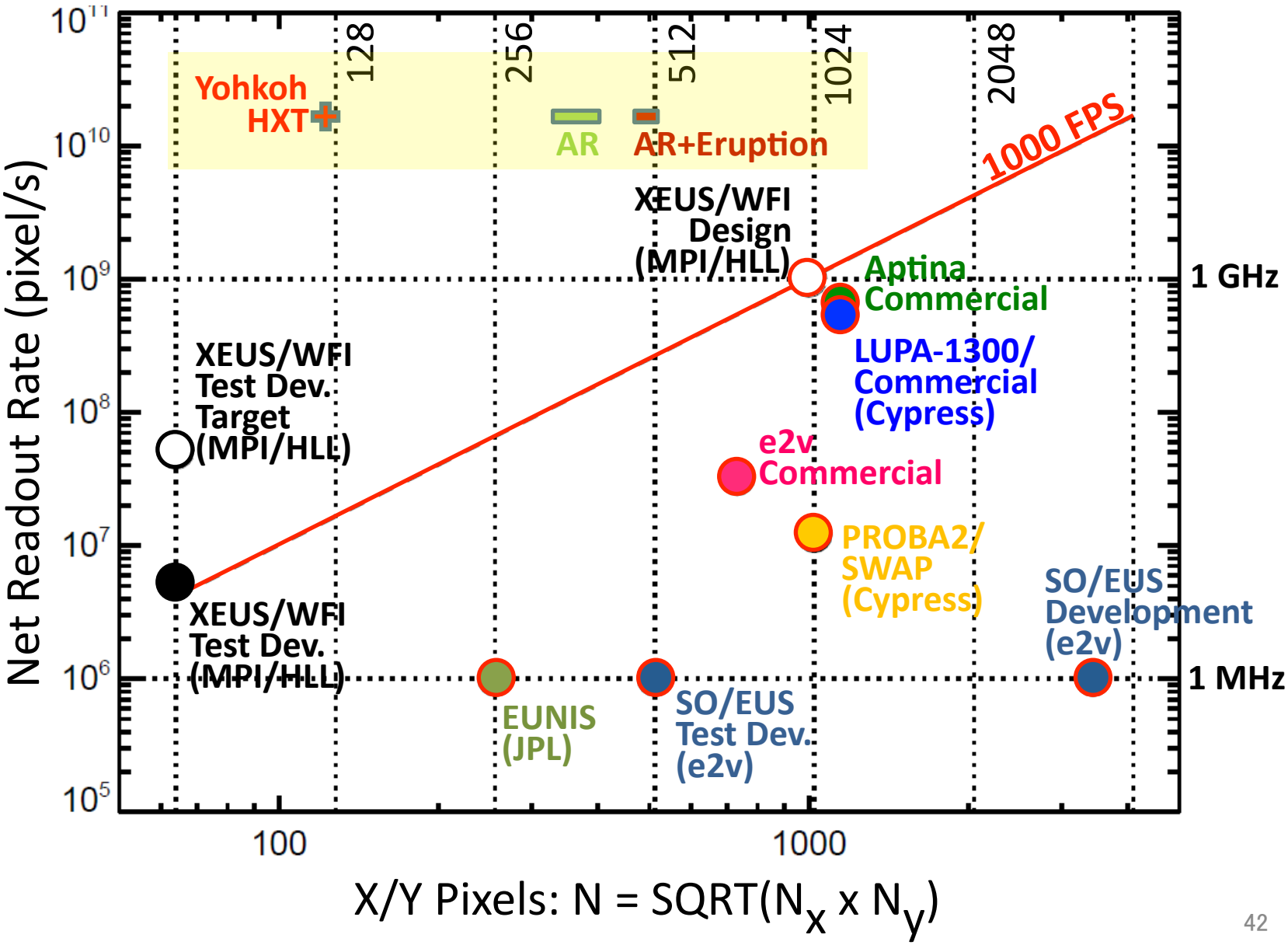


Flare (M2) : Without Filter
1-s Integration, 1”x1”



Detector

CMOS/APS Status

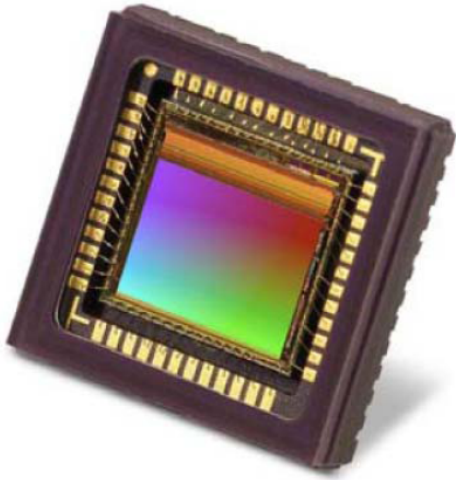


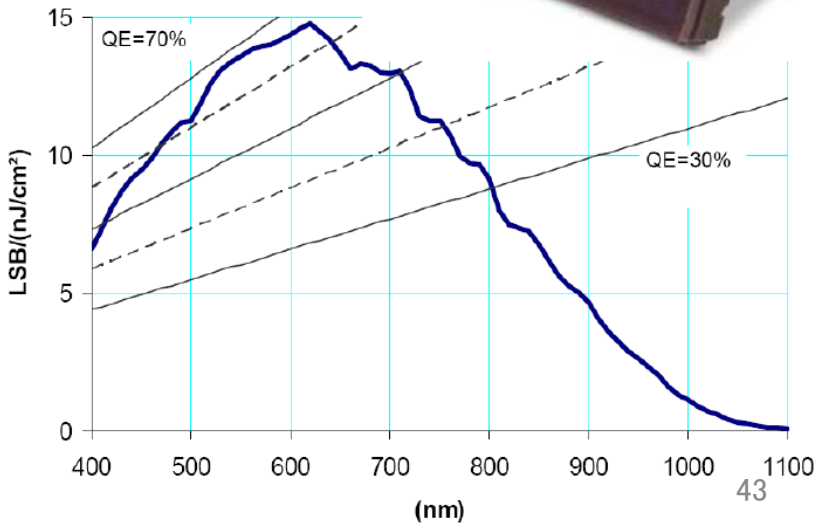
Example of Commercially-Available APS (For Reference Purpose Only)

Jade devices are currently available with the following performance

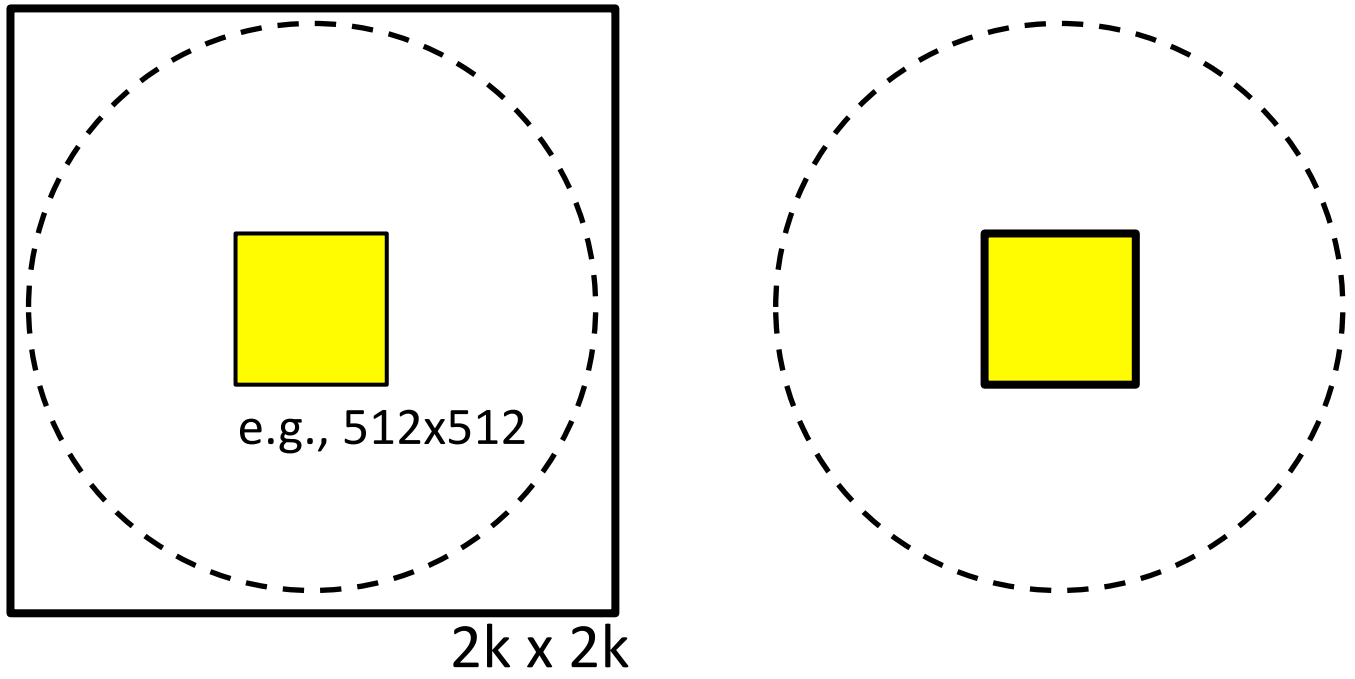
- ➲0.5Mpixes sensor
- ➲5.8µm square pixels with microlens
- ➲Global shutter
- ➲60 frames per second at full resolution (838 x 640)
- ➲Good responsivity
- ➲8 bit parallel output

➲Commercial devices but potentially could be qualified for space use





Photon-Counting Area



Summary

- Imaging spectroscopy with photon-counting CMOS/APS has potential to open up a new frontier in coronal physics, particularly for particle acceleration/plasma heating in flares.
- Photon counting for, say, 512”x512” area would comfortably cover targets of interest. Even smaller area size still has scientific significance. Photon counting for this pixel format can be reasonably assumed.
- Photon-counting imagery of the X-ray corona is likely within reach.