The X-Ray Corona

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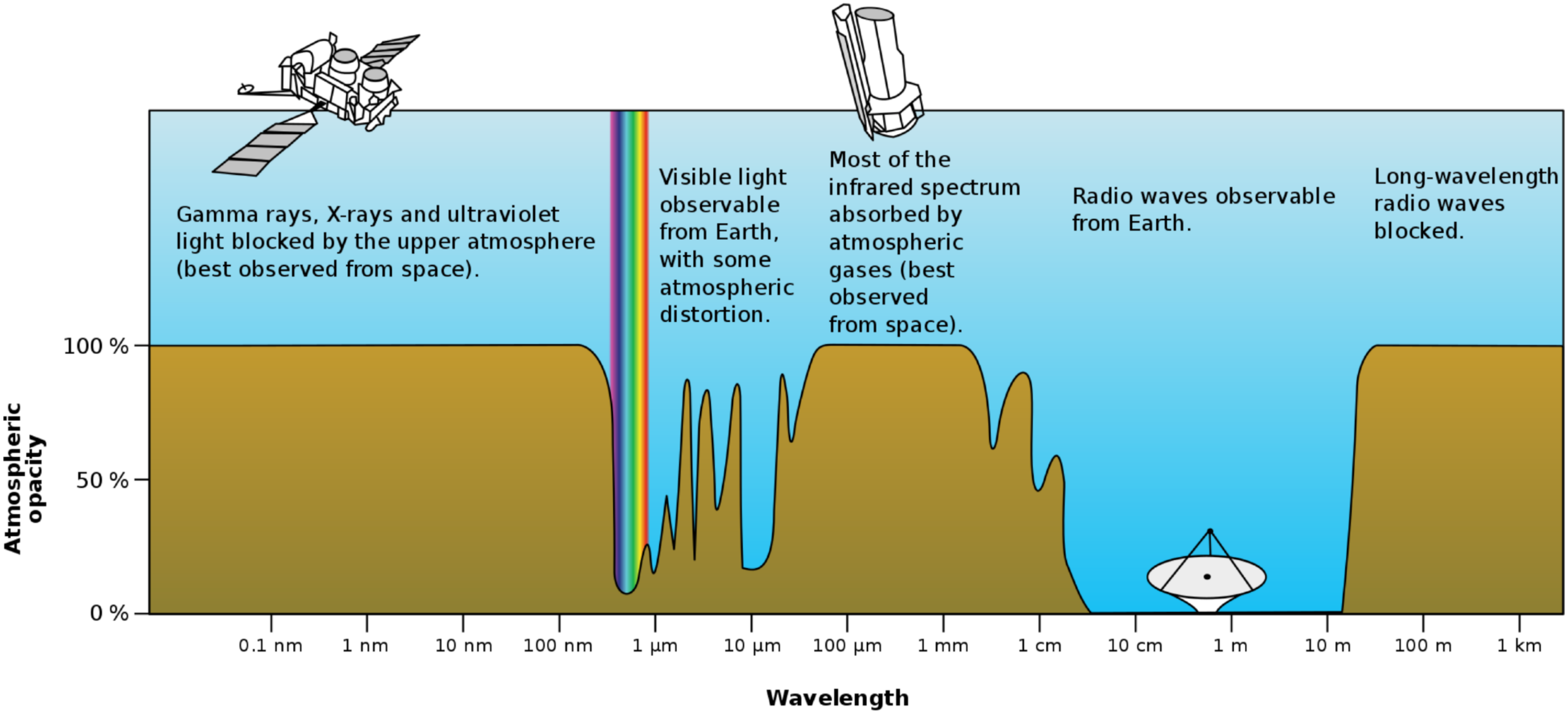
Harvard-Smithsonian CfA

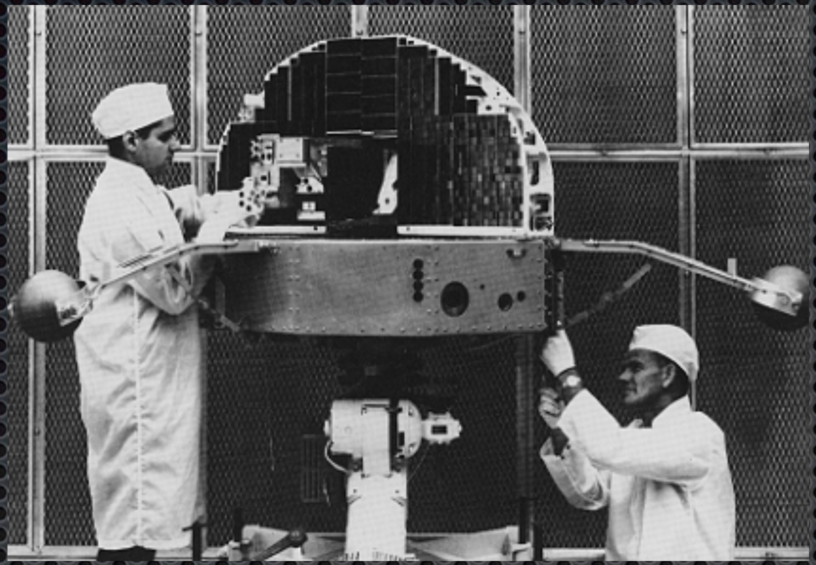
With thanks to the Hinode, RHESSI, NuSTAR, and SDO teams

Observing X-rays requires going to space!

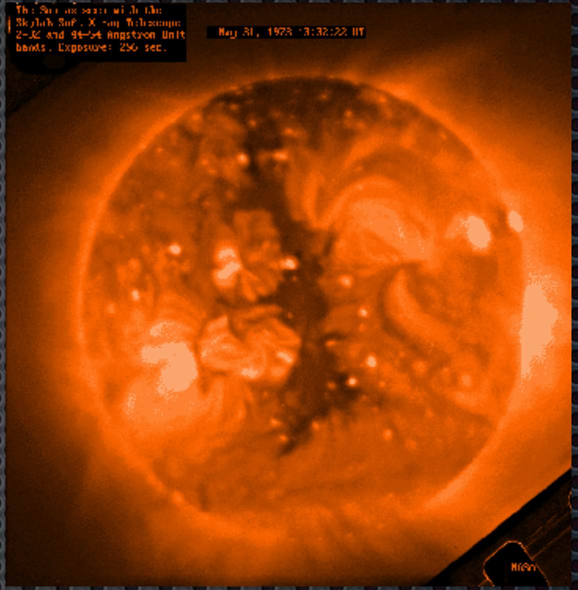


Historical X-ray instruments

Sounding Rockets
1950's and 1960's

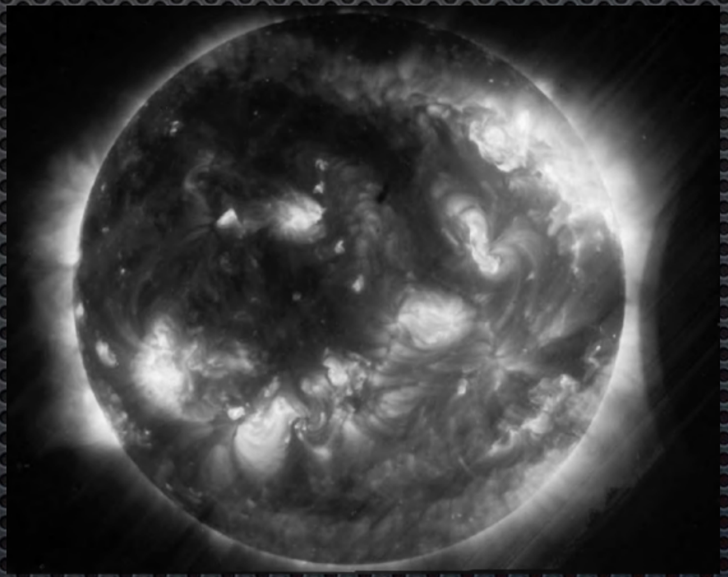


Orbiting Solar Observatory
(OSO1-8), 1962-1975



Skylab S-054 X-ray
Telescope, 1973-4

Solar Maximum
Mission (SMM)
1980-9



Normal Incidence X-ray
Telescope (NIXT) rocket
1991

Yohkoh (Solar-A)
1991-2001

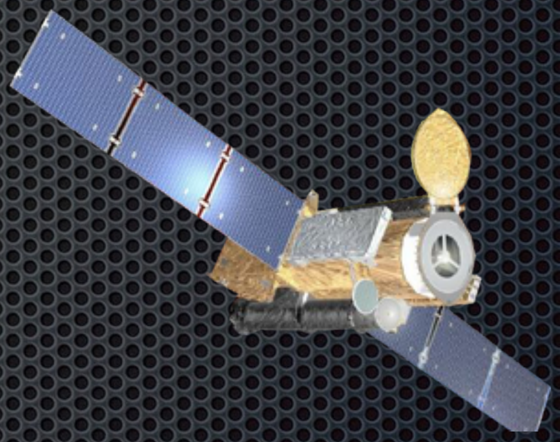
Recent X-ray Instruments

Spectrometers

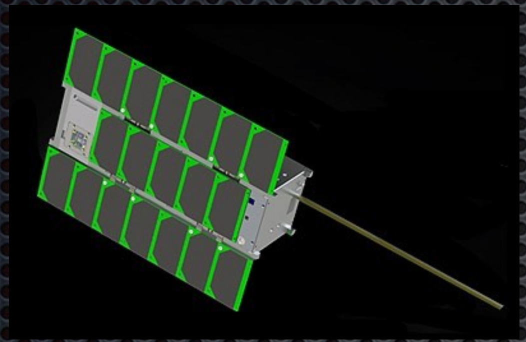
Imagers

GOES

NuSTAR

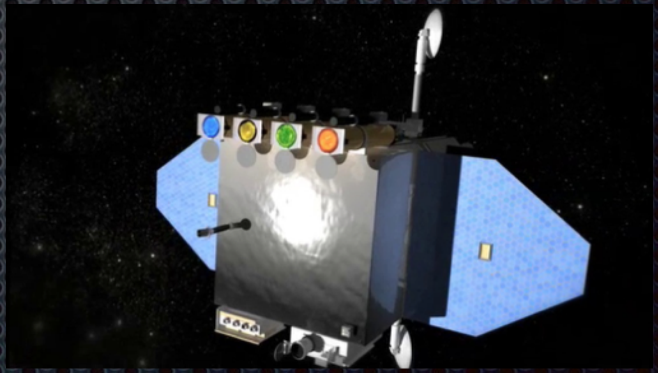


Hinode/XRT

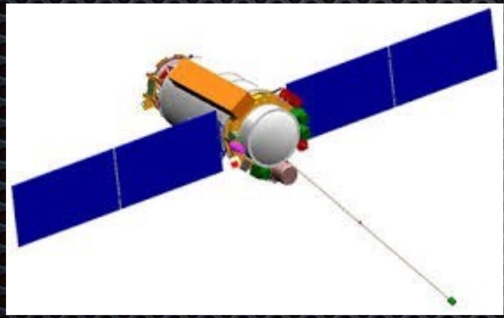


MinXSS

FOXSI Rockets



SDO/AIA 131/94 Å



Coronas-Photon/
SphinX

RHESSI

Coming soon: MaGIX, STIX   Proposed: FIERCE

X-ray Corona: Open Questions

- How is the released energy partitioned/distributed in solar eruptions?
- Is the corona heated by nanoflares?
- Sources and composition of the solar wind?

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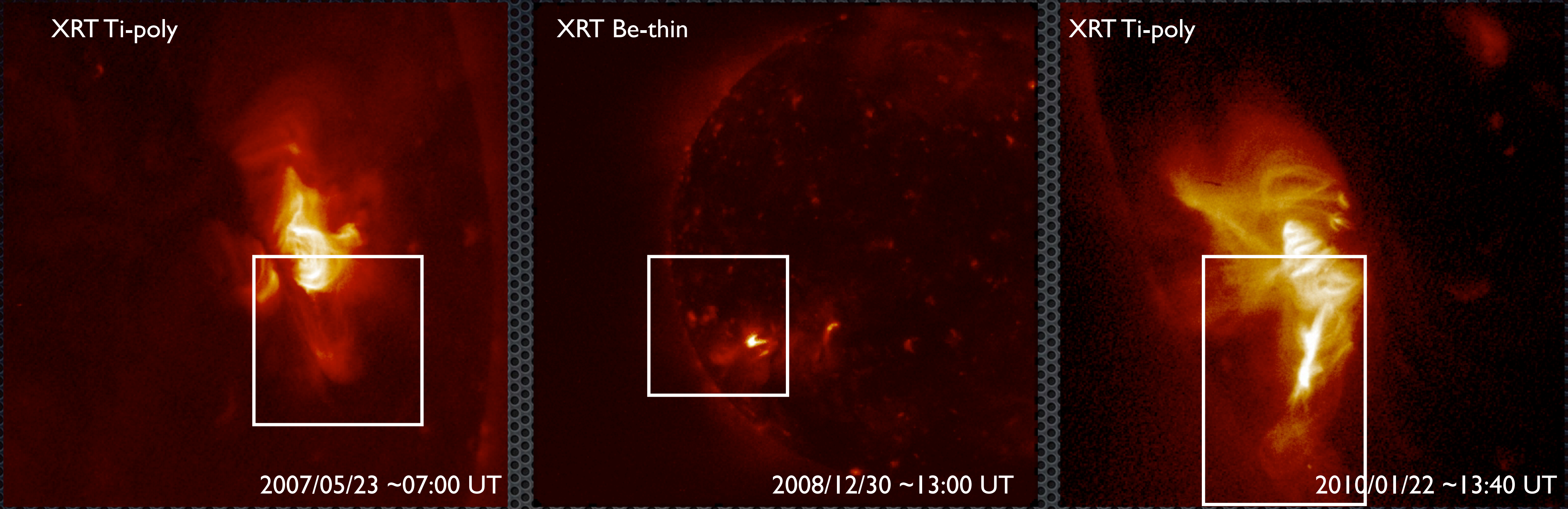
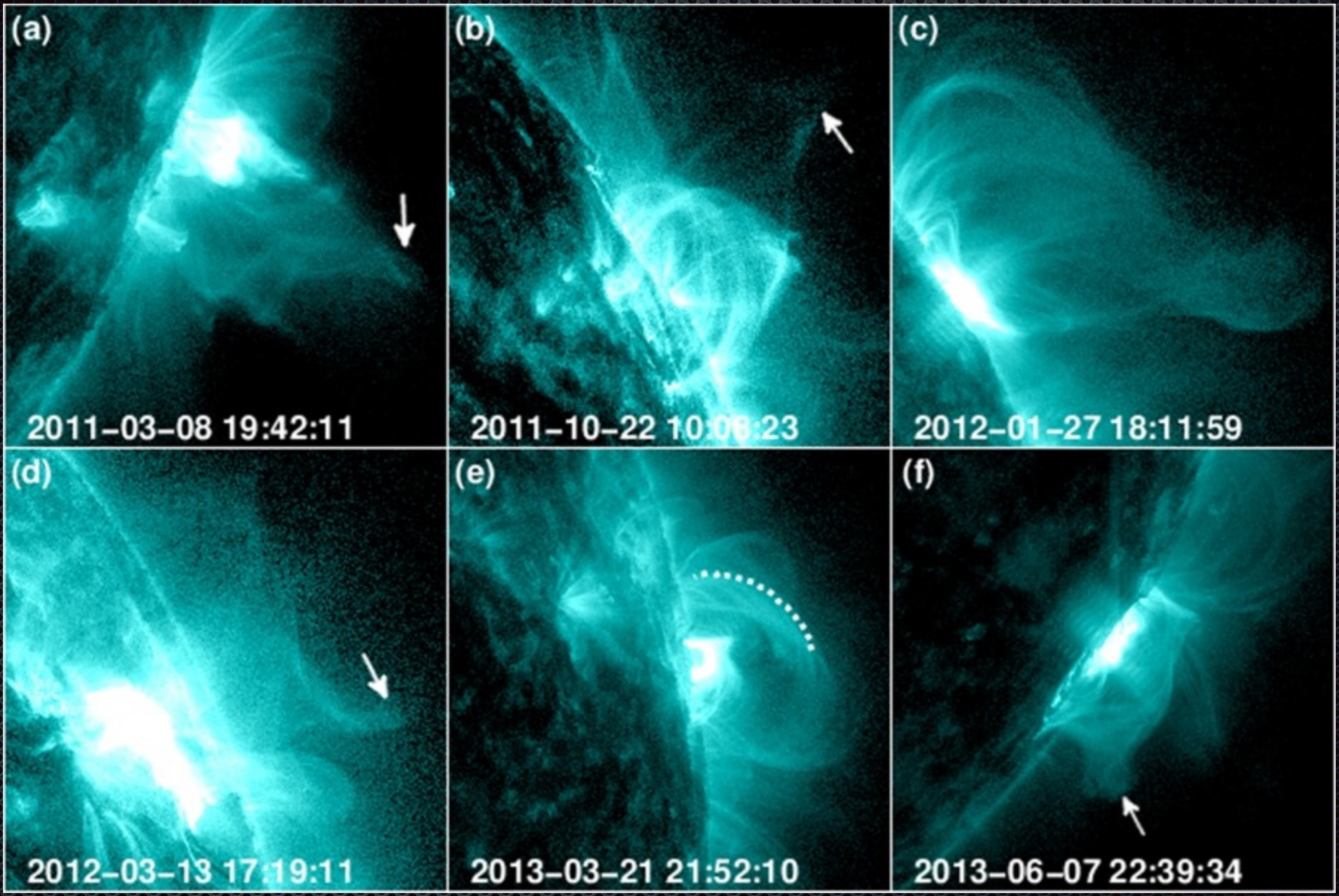
Continual CME Heating

J.-Y. Lee et al., ApJ, 2015



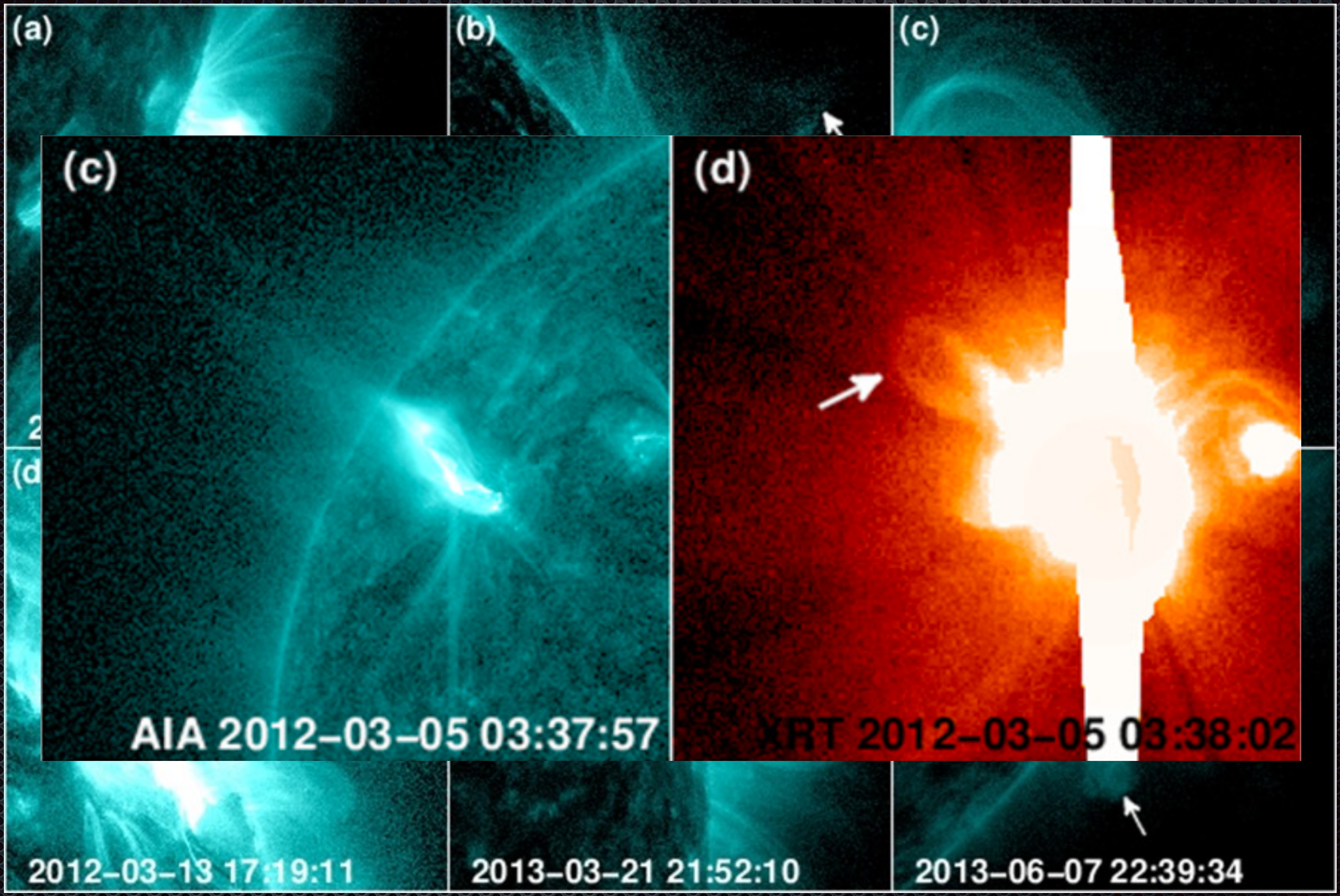
- Estimated conductive cooling time is much smaller than the lifetime of the event, indicating continual heating.
- Possible mechanisms: Rxn outflow from current sheet, kink instability, small scale reconnection, wave heating, energetic particles, ohmic heating from flux rope current (e.g. Murphy et al, ApJ 2011)

Hot flux ropes



Nindos et al., ApJ, 2015

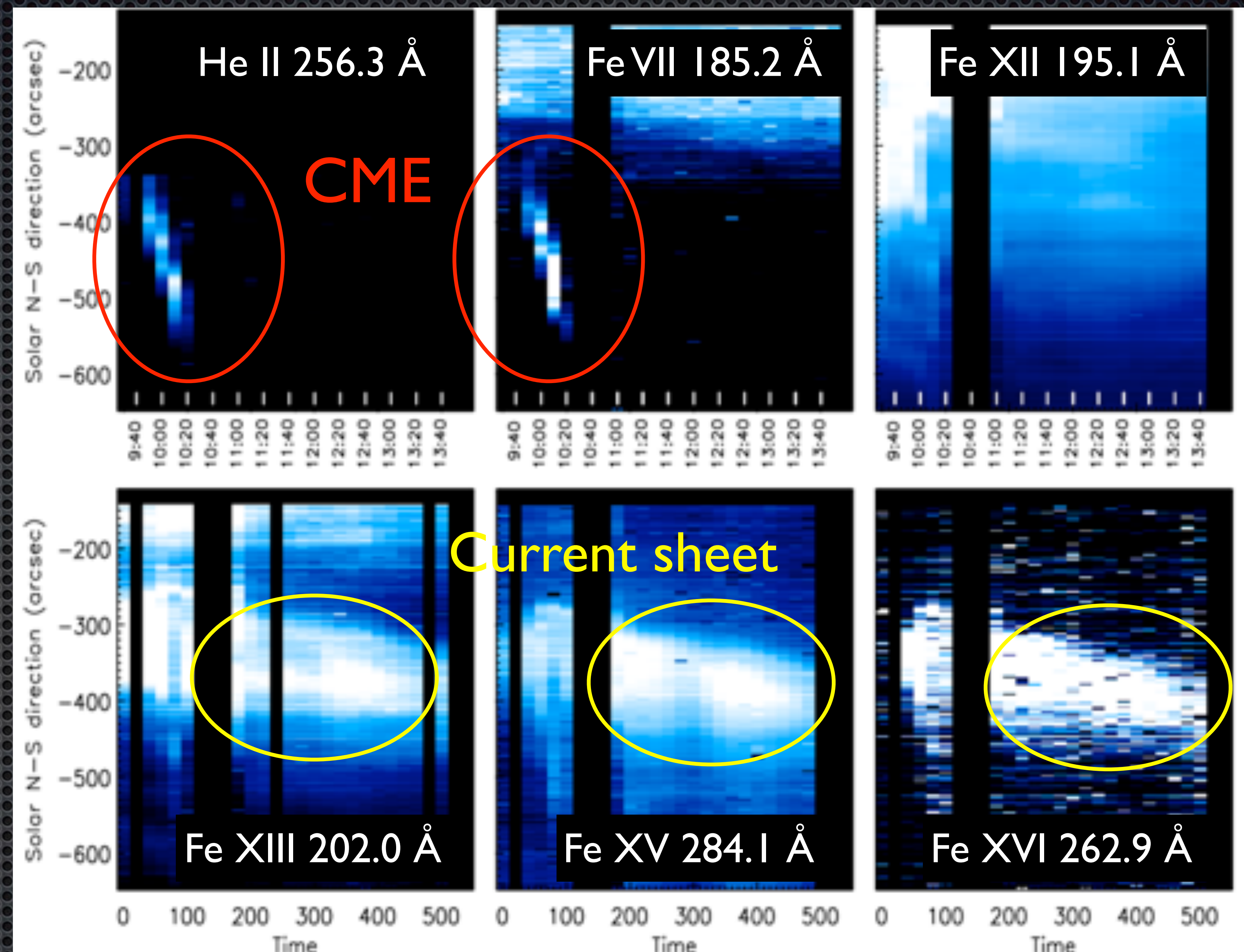
Hot flux ropes



Nindos et al., ApJ, 2015

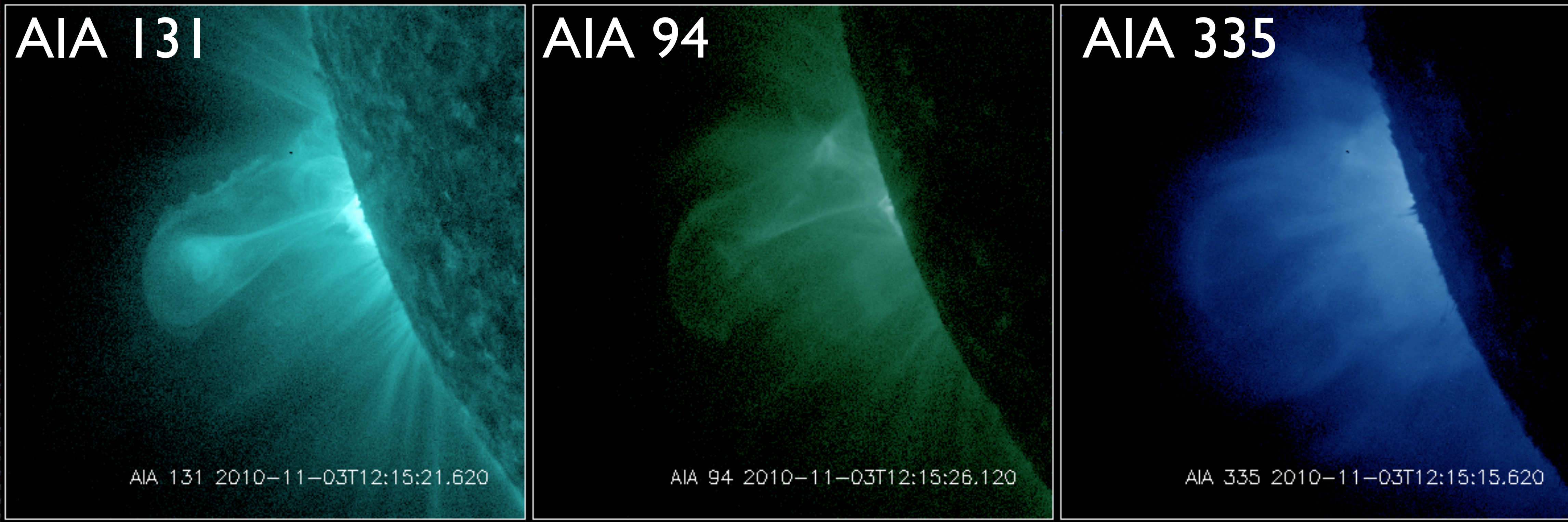
Hot current sheet observations

Current sheet flows seen in XRT (see Savage et al., ApJ, 2010)

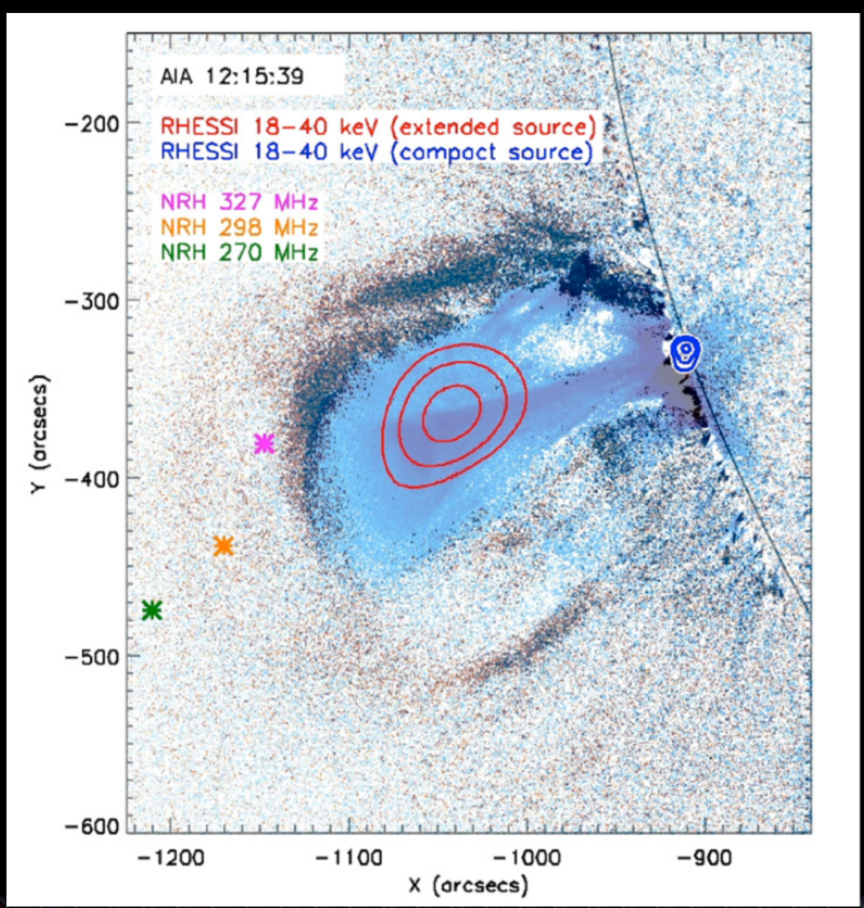


Landi et al., ApJ, 2010, 2012

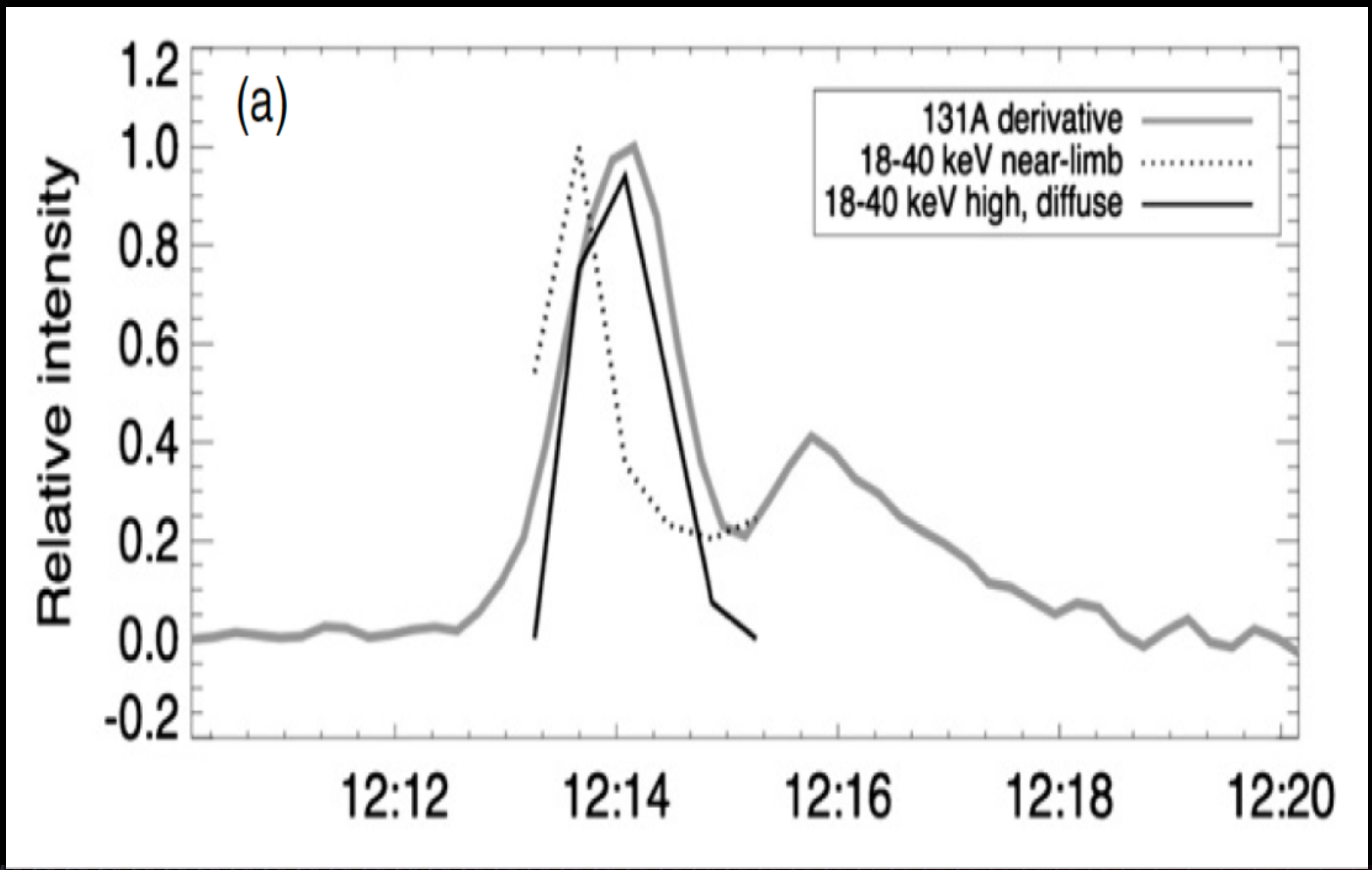
Heating by accelerated particles



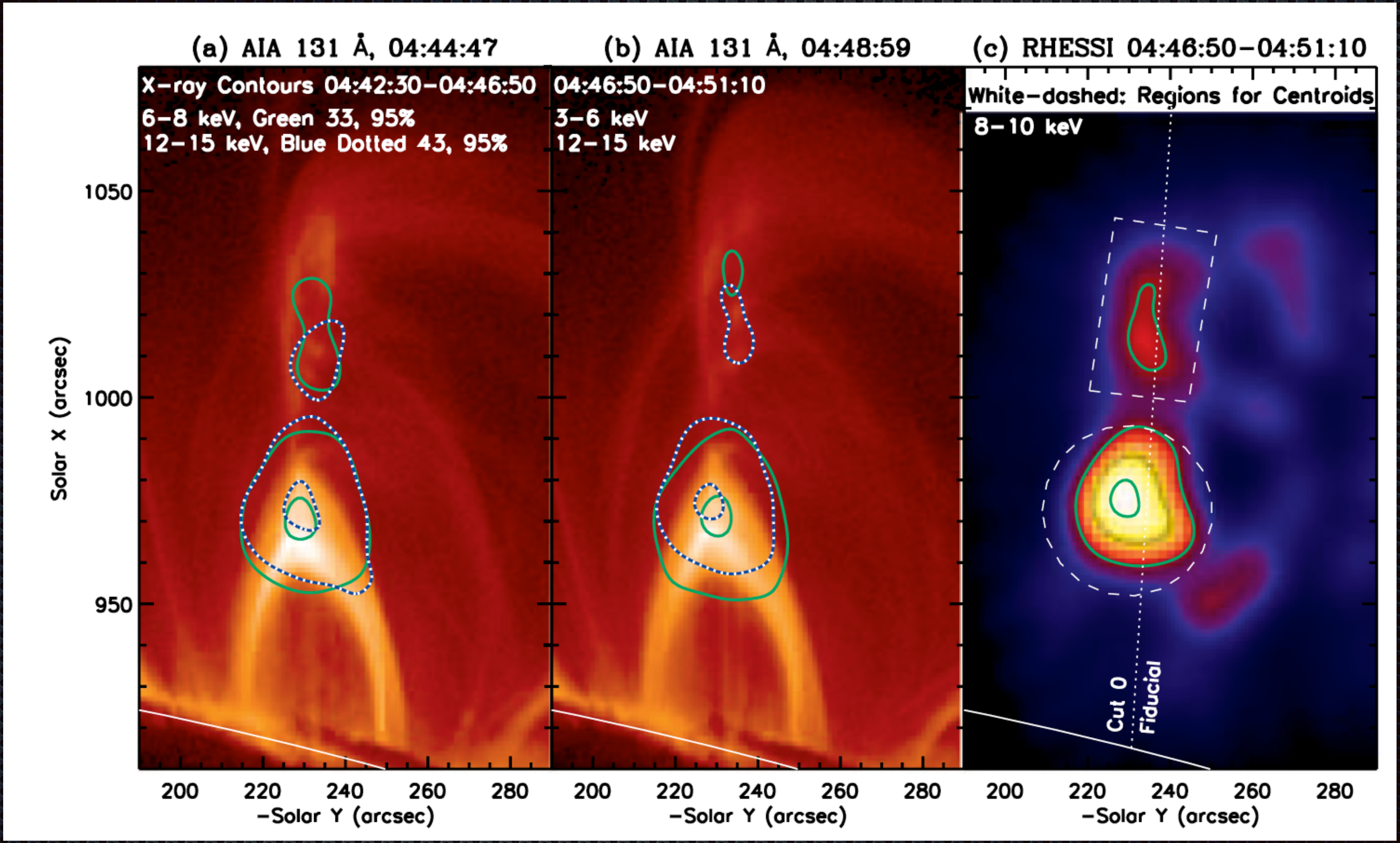
Bain et al., ApJ, 2012



Glesener, et al. ApJL, 2013

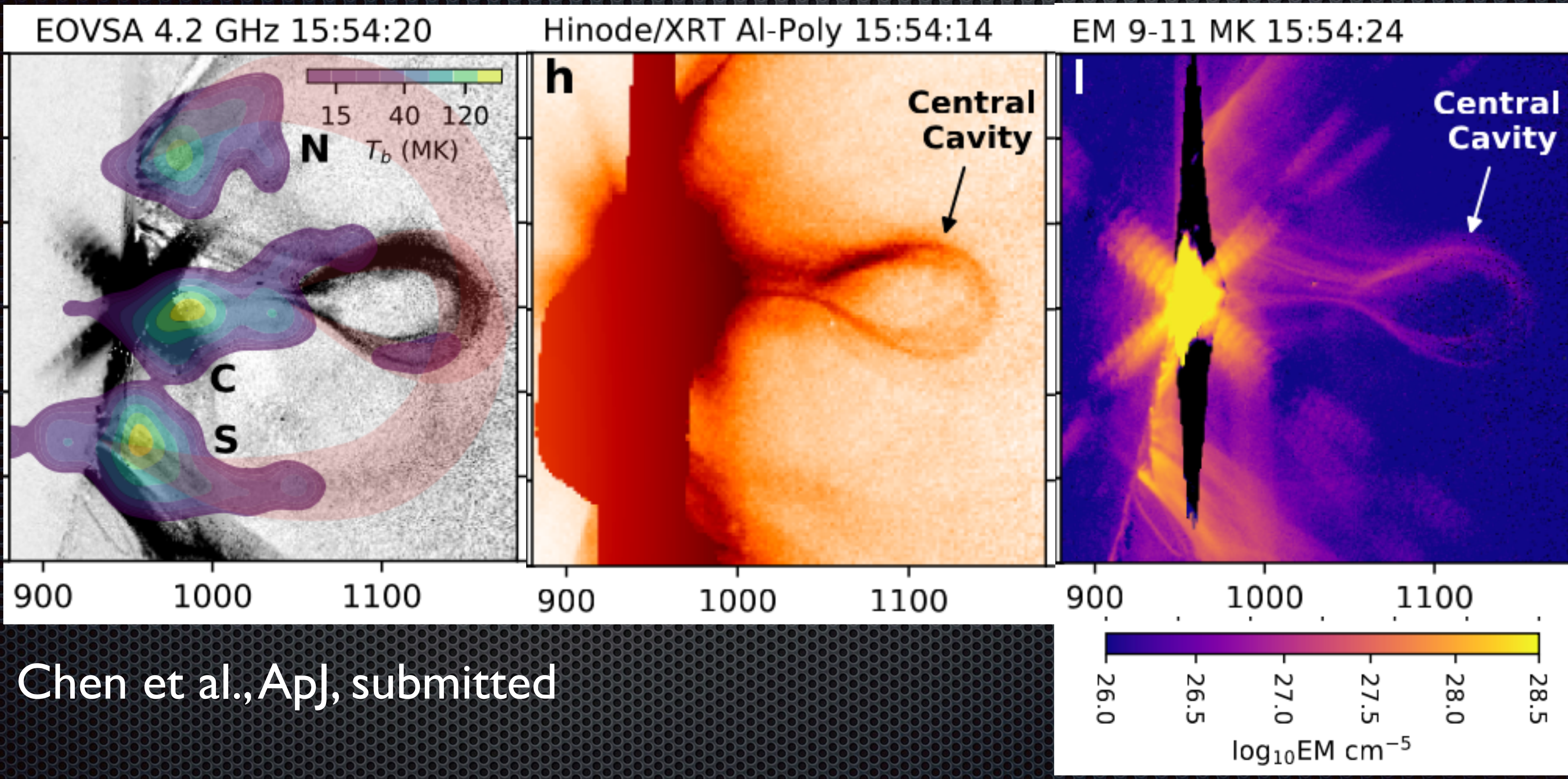


Heating in outflow region



Liu, W. et al. ApJ, 2013

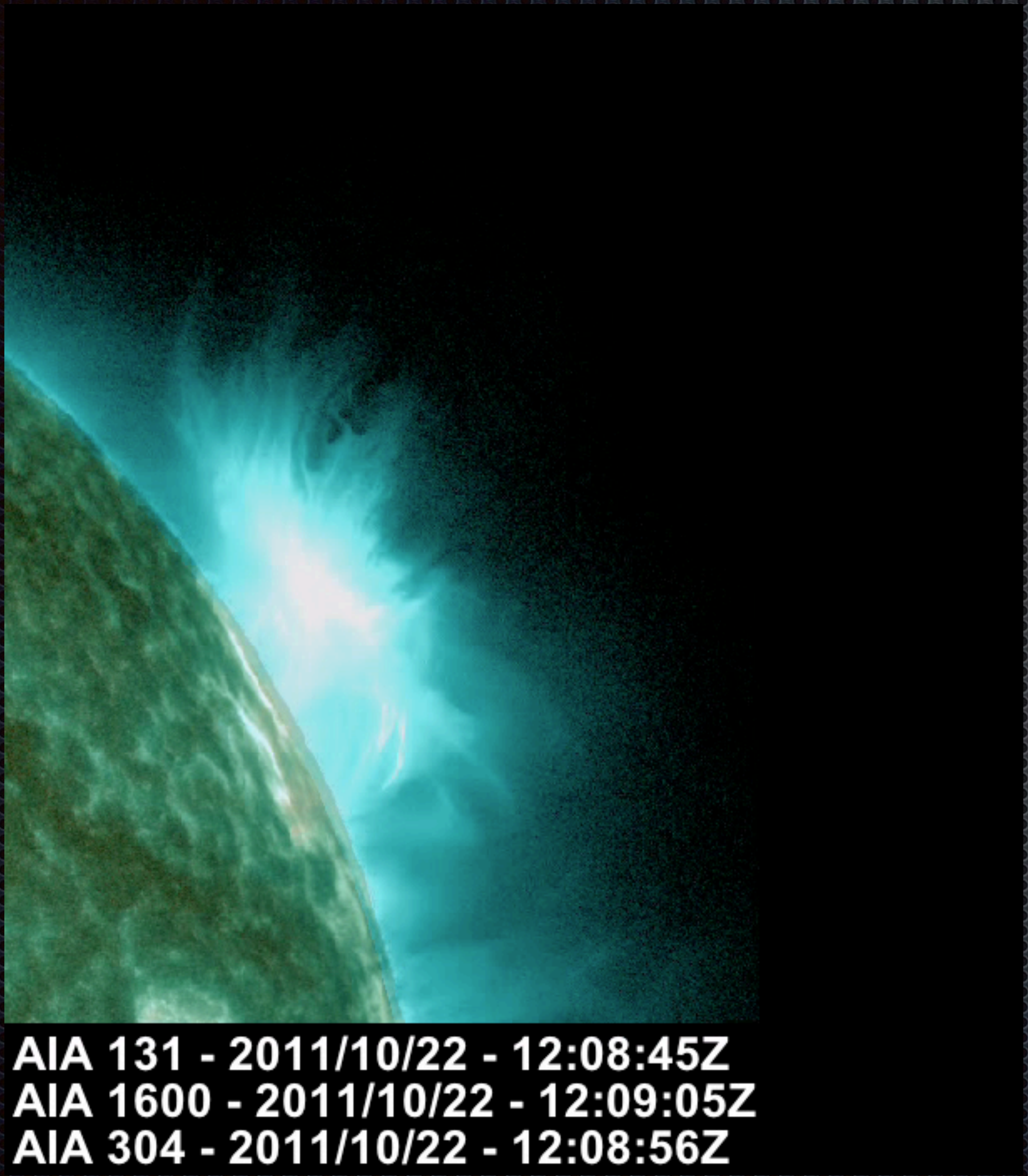
Heating & non-thermal emission

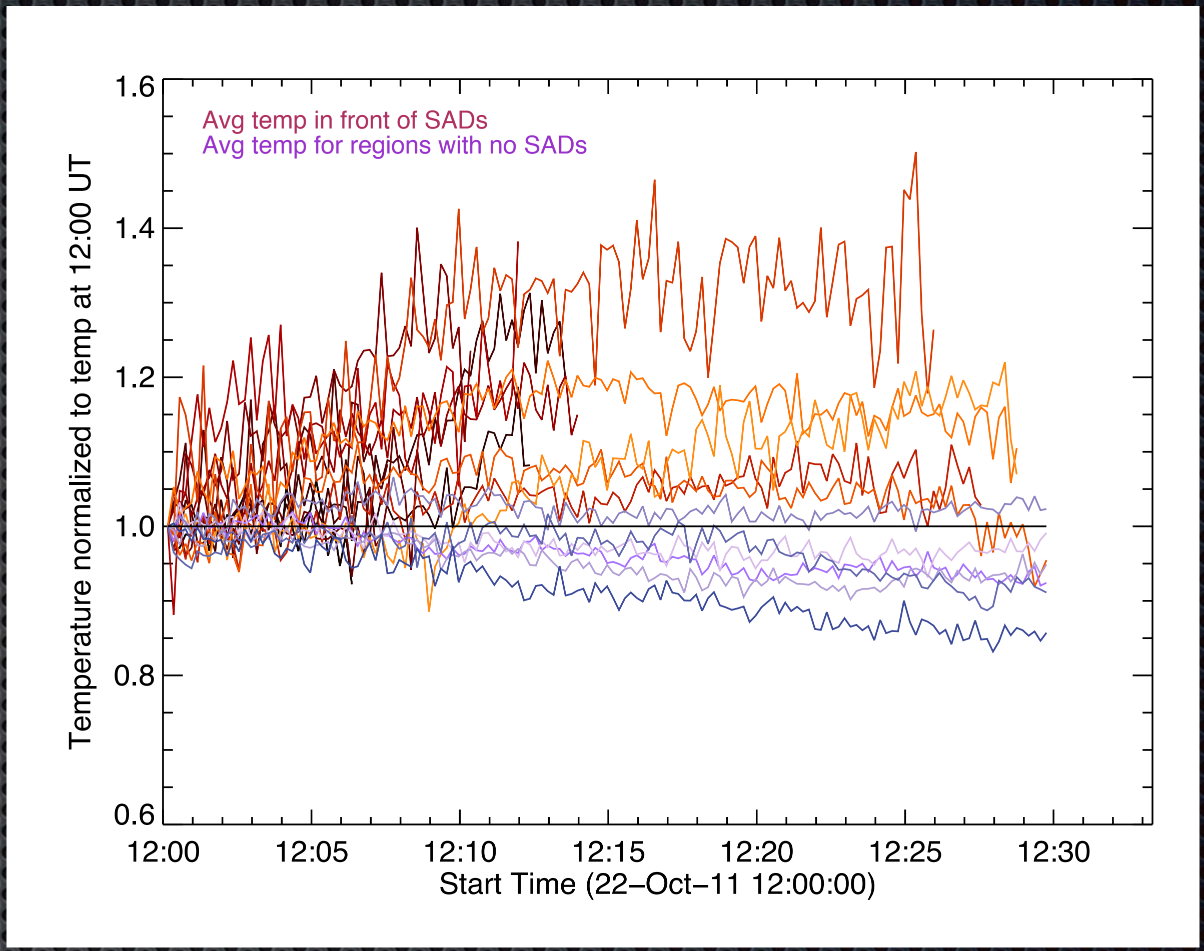


Chen et al., ApJ, submitted

Heating and turbulence

Reeves et al. ApJ, 2017





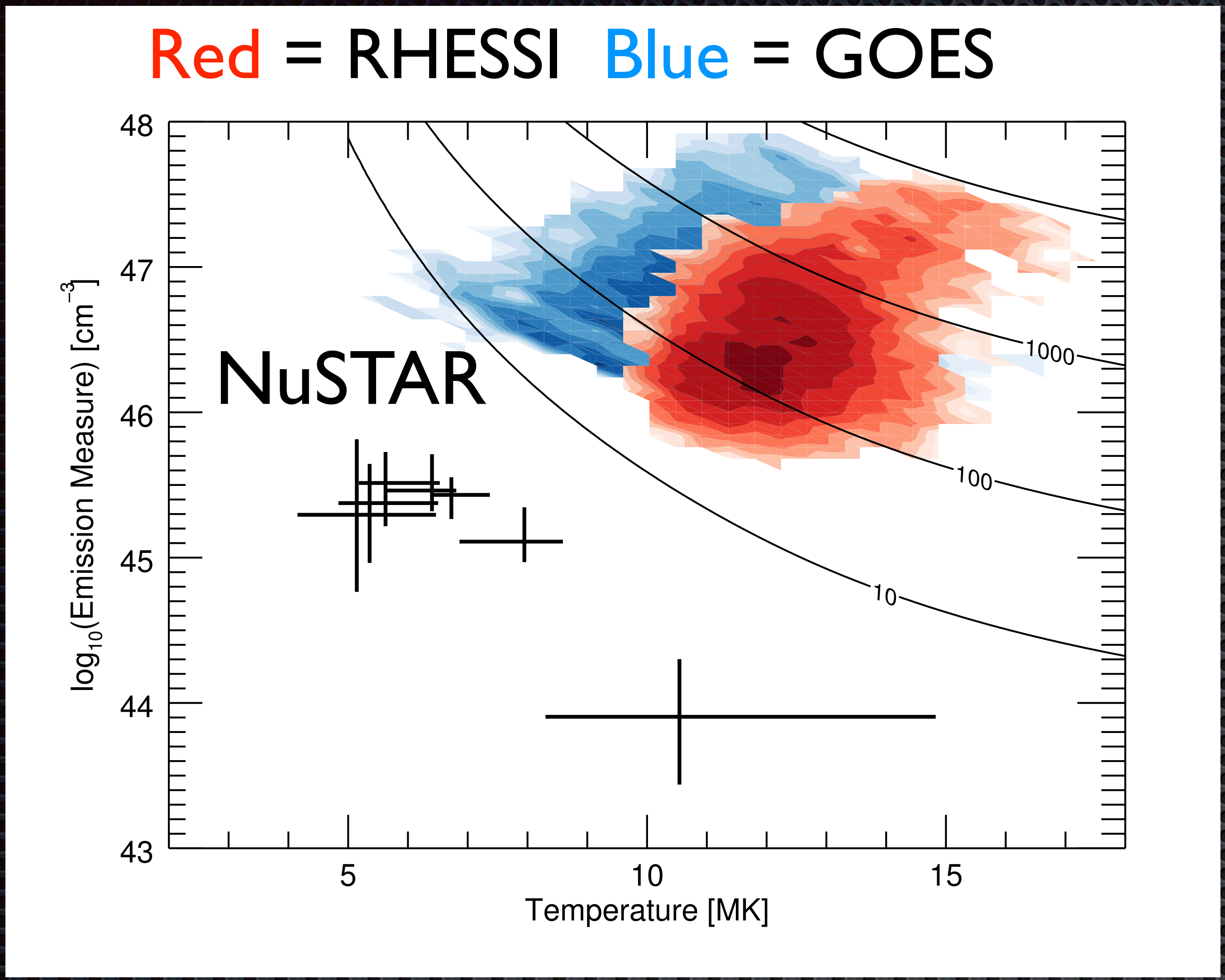
- Regions with lots of turbulence (SADs) are heated
- Viscous and adiabatic heating correlate with SADs

X-ray Corona: Open Questions

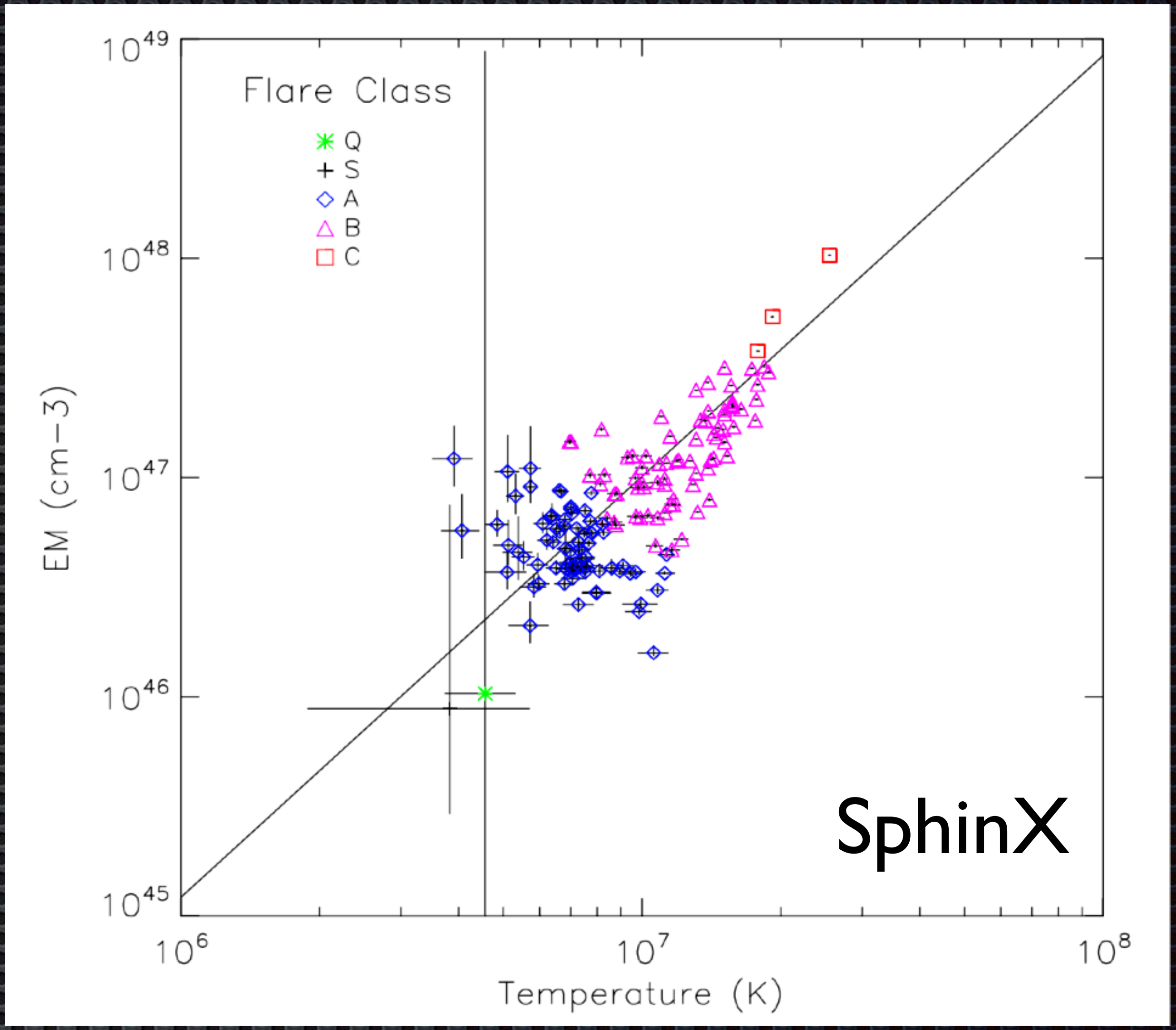
- How is the released energy partitioned/distributed in solar eruptions?
- Is the corona heated by nanoflares?
- Sources and composition of the solar wind?

Microflares and nanoflares

Glesener et al., ApJ, 2017



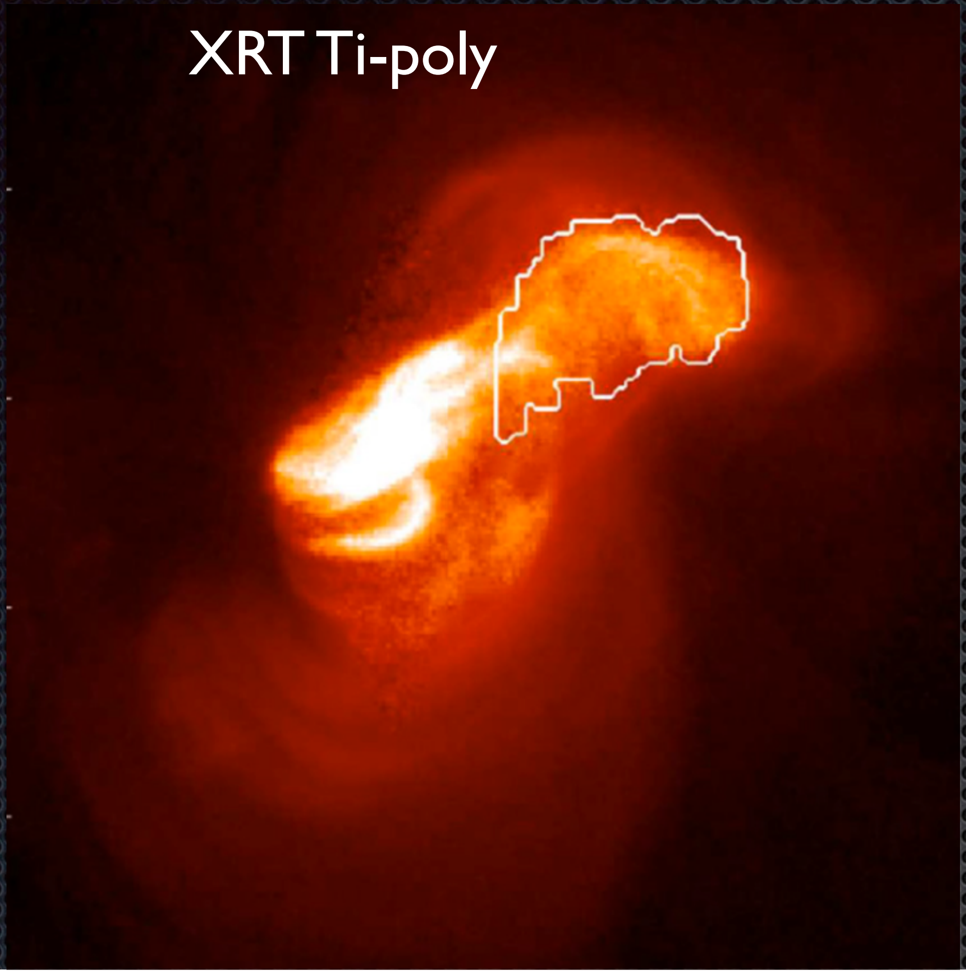
Engell et al., ApJ, 2011



(See also MinXSS results, Woods et al., ApJ, 2017)

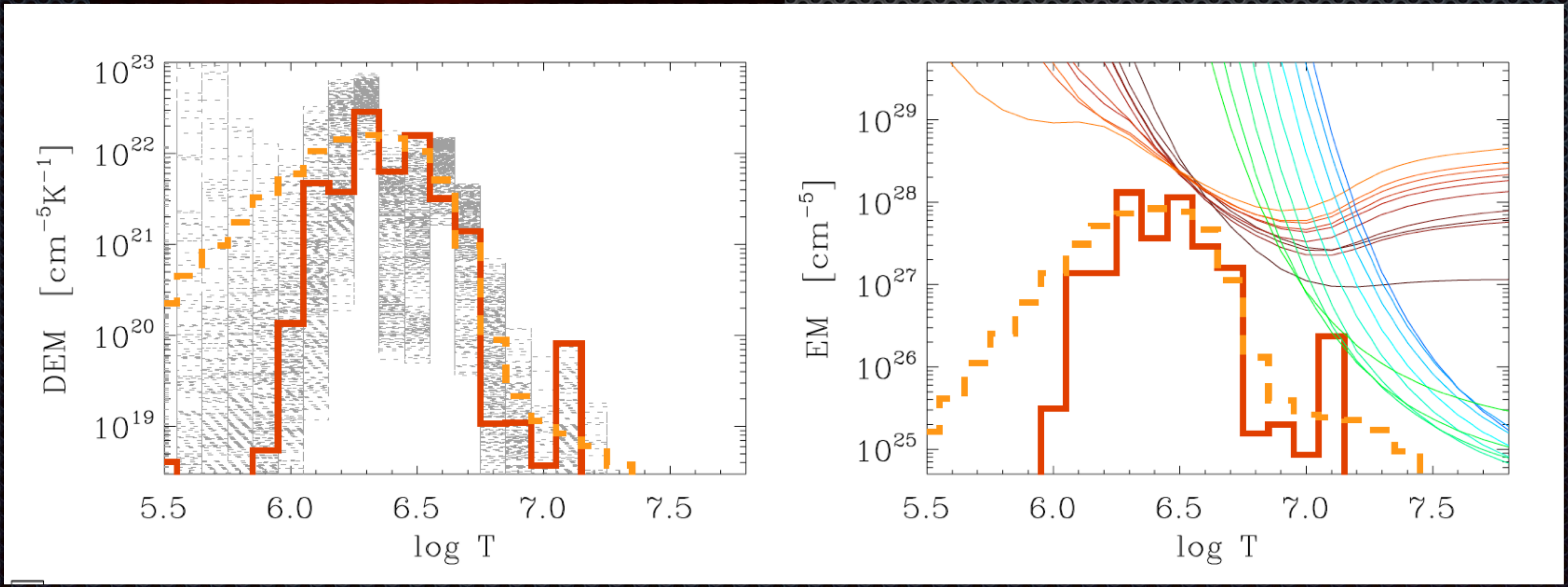
- Small flares exist below GOES & RHESSI sensitivity
- Could lots of small (nano) flares heat the corona?
- Broad distribution of hot plasma is necessary for nanoflares to contribute to coronal heating

Faint, hot AR emission?



- XRT+RHESSI DEMs show a possible faint, hot component

Schmelz et al. ApJ, 2009

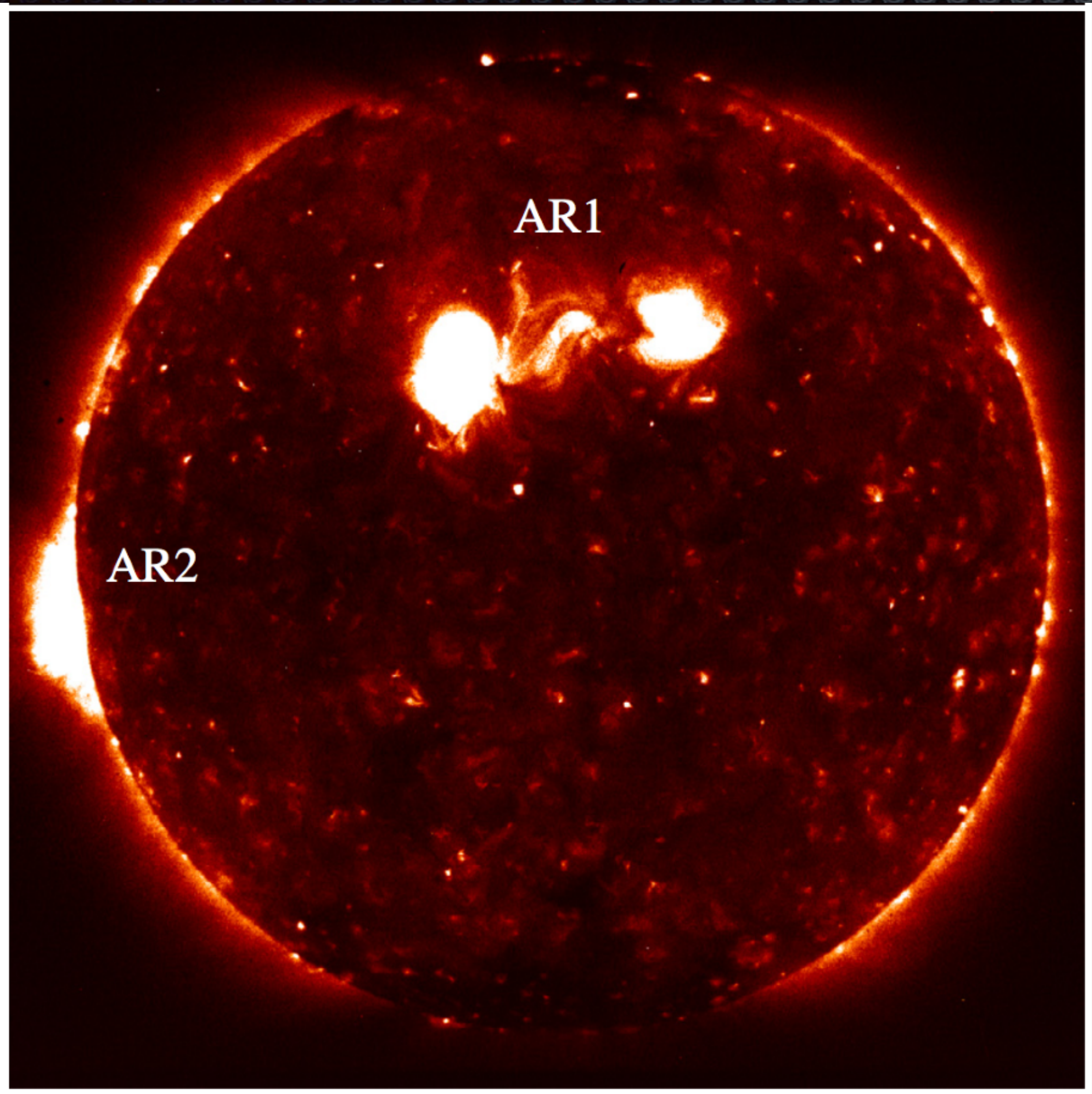


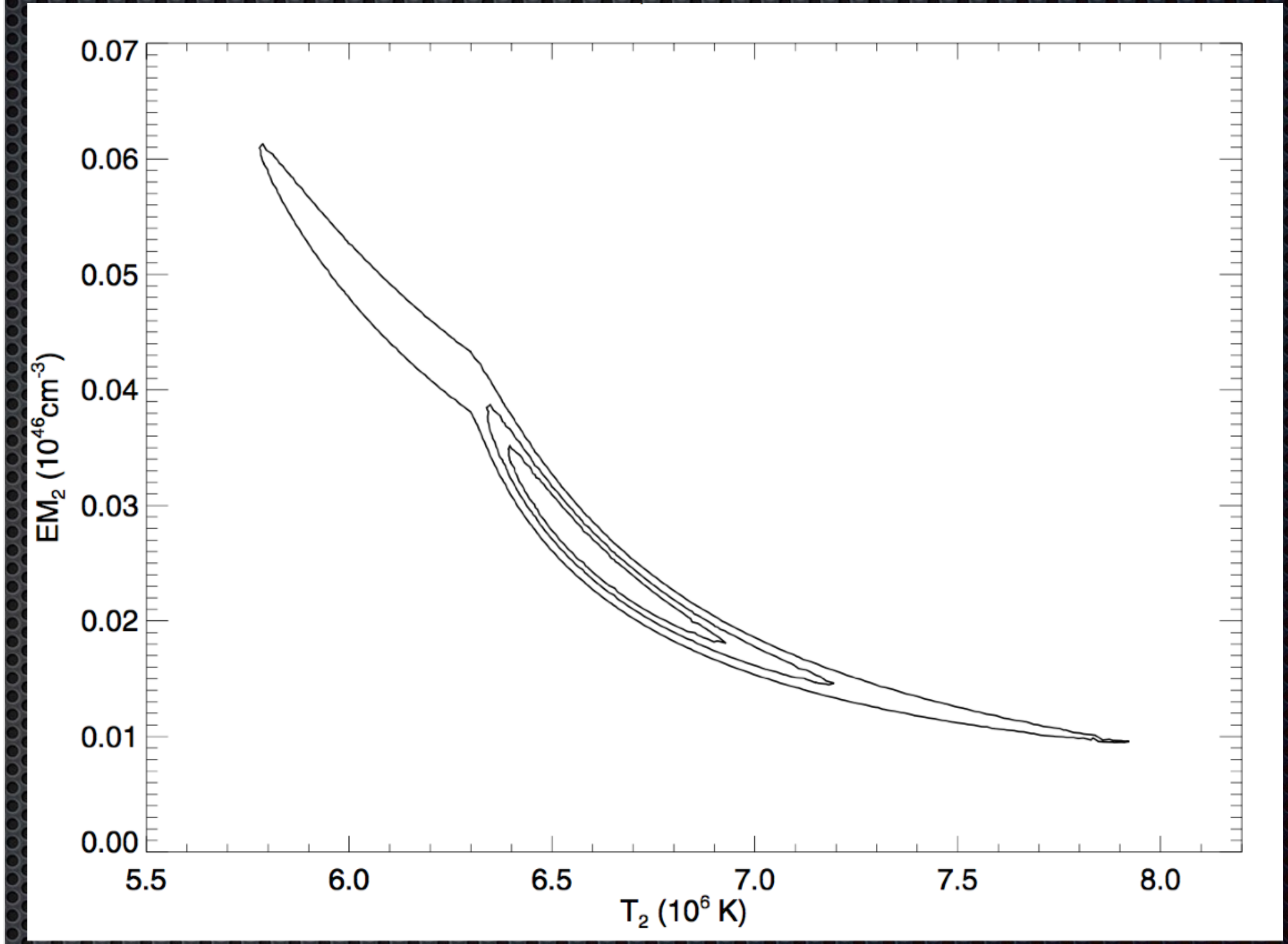
Red/orange = XRT

Blue/green = RHESSI

SphinX time averaged spectra

Miceli et al., A&A, 2012

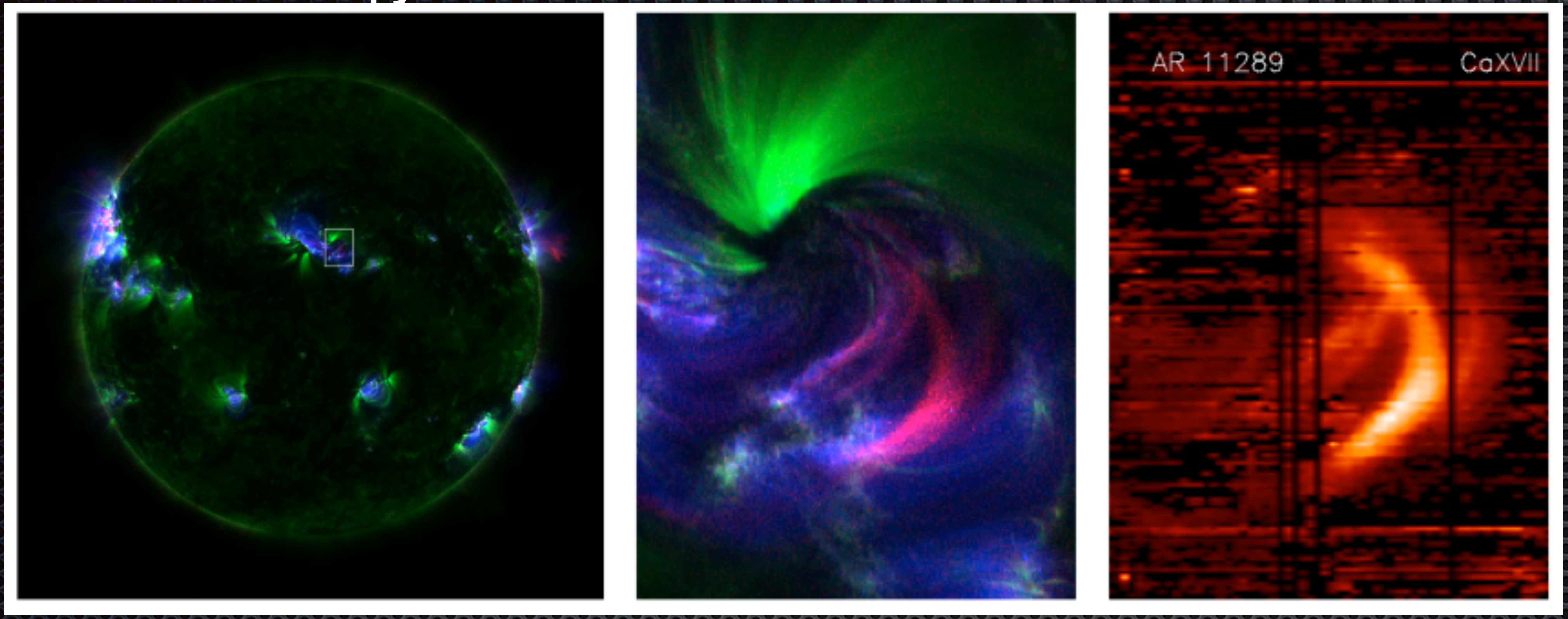




- Spectra averaged over one month show evidence for a hot component at with 3 orders of magnitude less emission measure than the 'warm' component

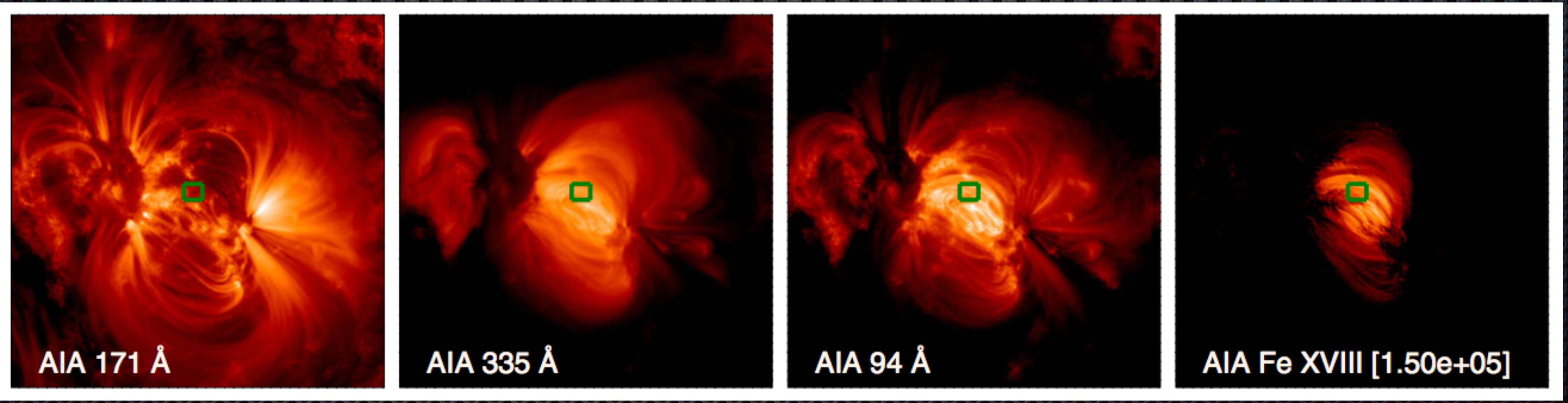
Hot AR emission in AIA/EIS

Testa & Reale, ApJL, 2012



Red = 94 Å
Blue = 335 Å
Green = 171 Å

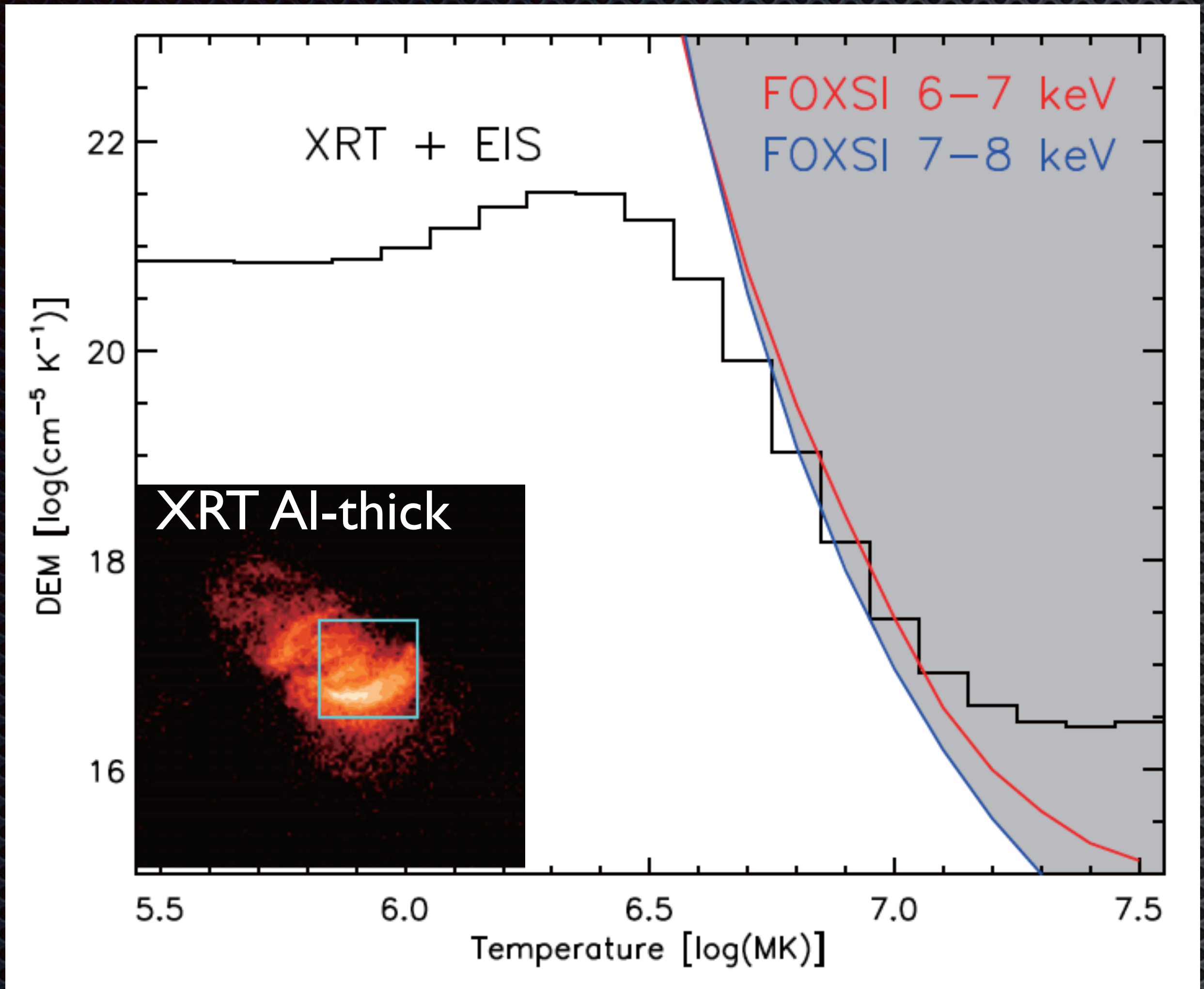
Warren et al. ApJ, 2012



- AR DEMs strongly peaked at 4 MK for strong B fields, more broad for weaker B fields

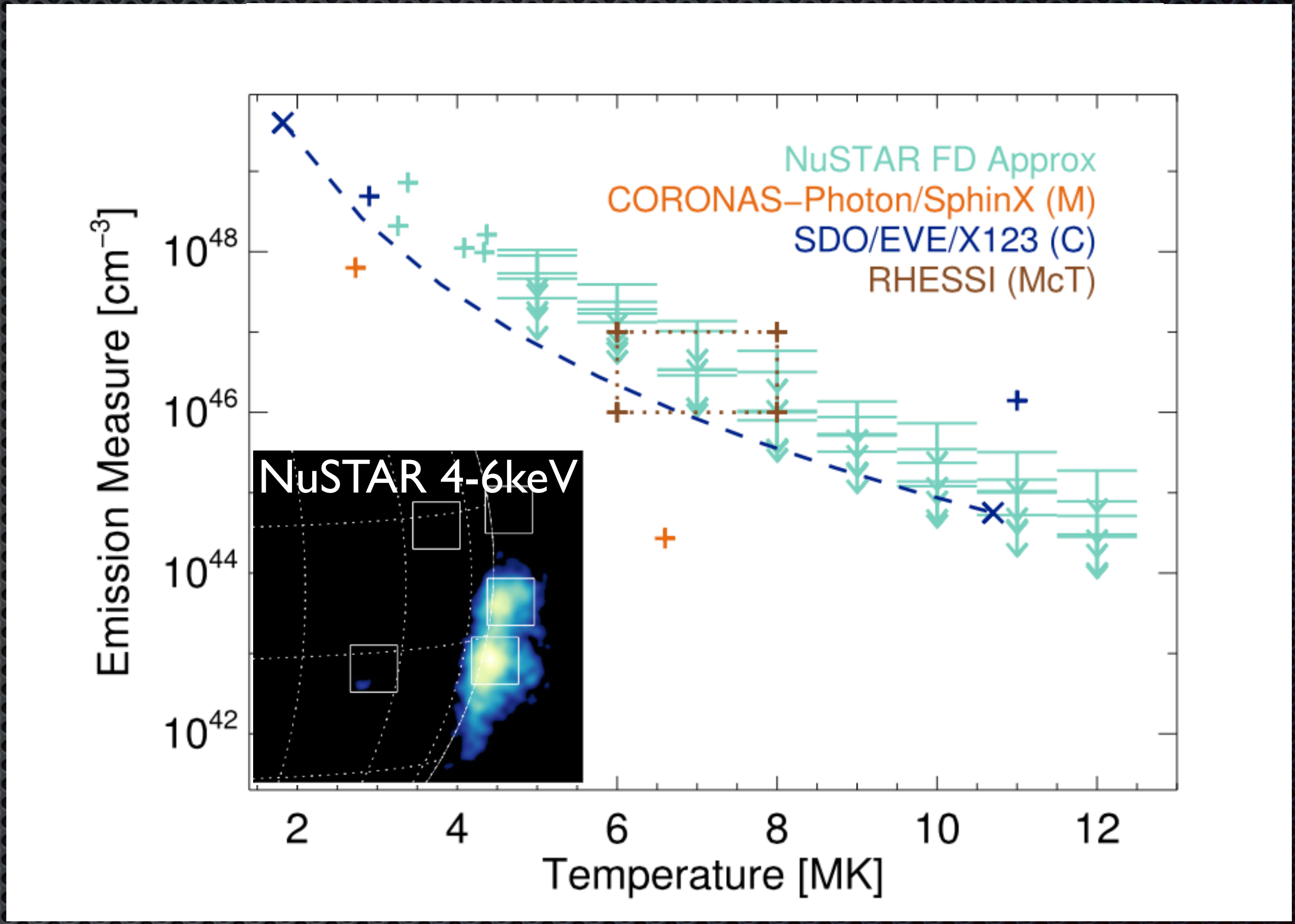
Constraints from HXRs

FOXSI 1 Rocket



Ishikawa et al. PASJ, 2014

NuSTAR

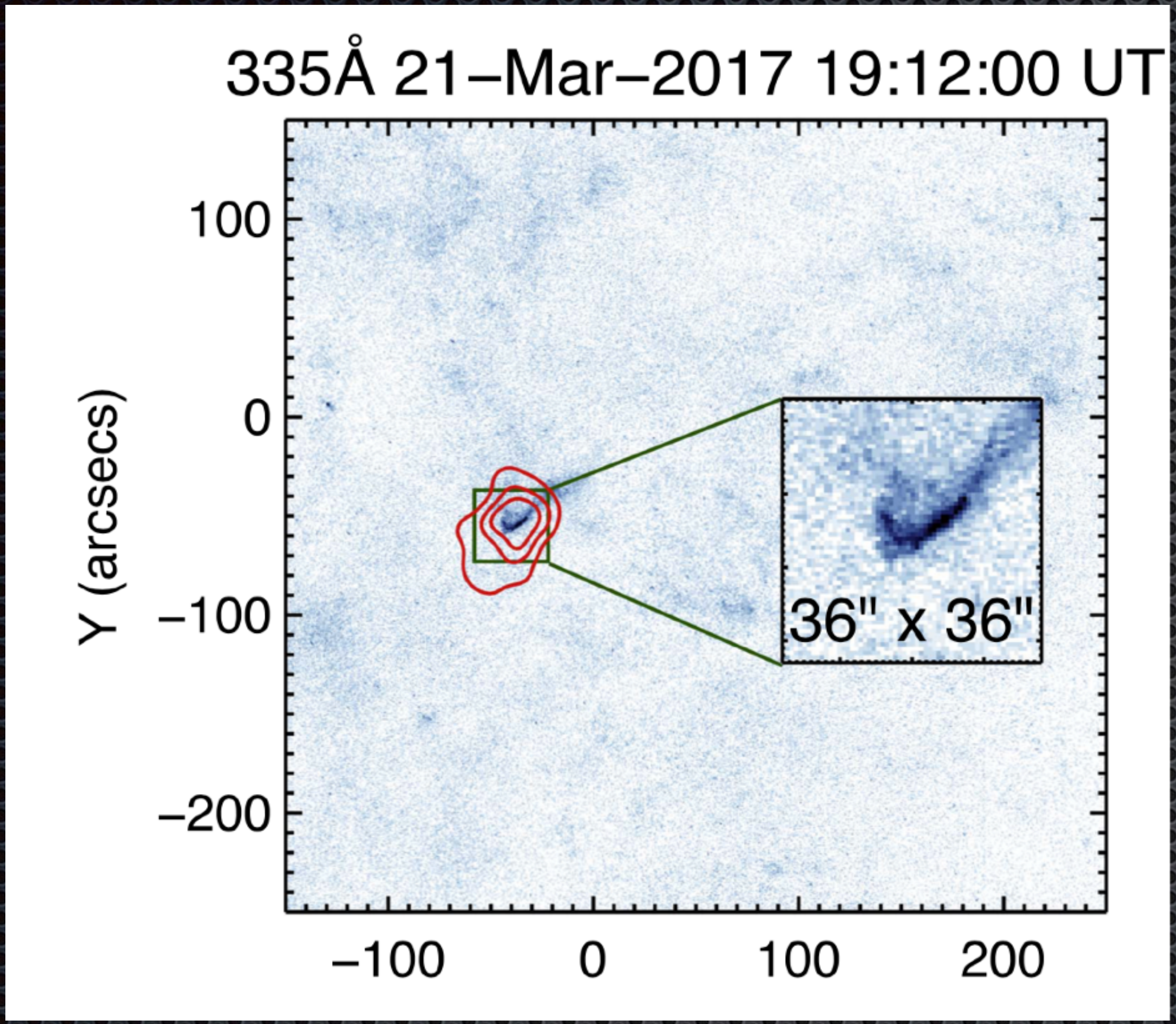


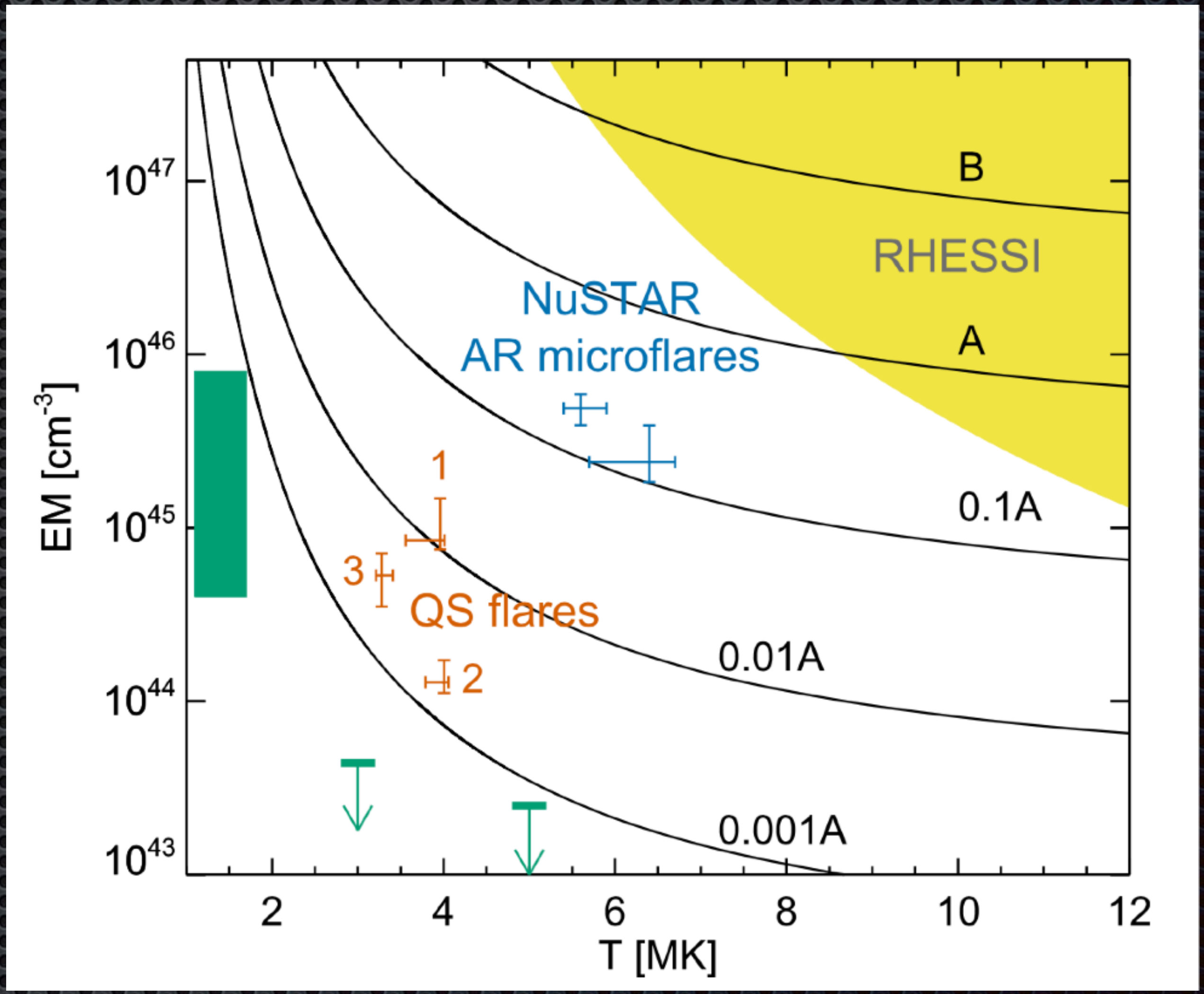
Hannah et al. ApJ, 2016

- Sensitive HXR telescopes put limits on high temperature components in quiescent ARs
- No evidence from FOXSI or NuSTAR for non-thermal particles

Quiet Sun X-rays

Kuhar et al., ApJL, 2018





- First imaging spectroscopy observations of small eruptions in the quiet Sun with NuSTAR

X-ray Corona: Open Questions

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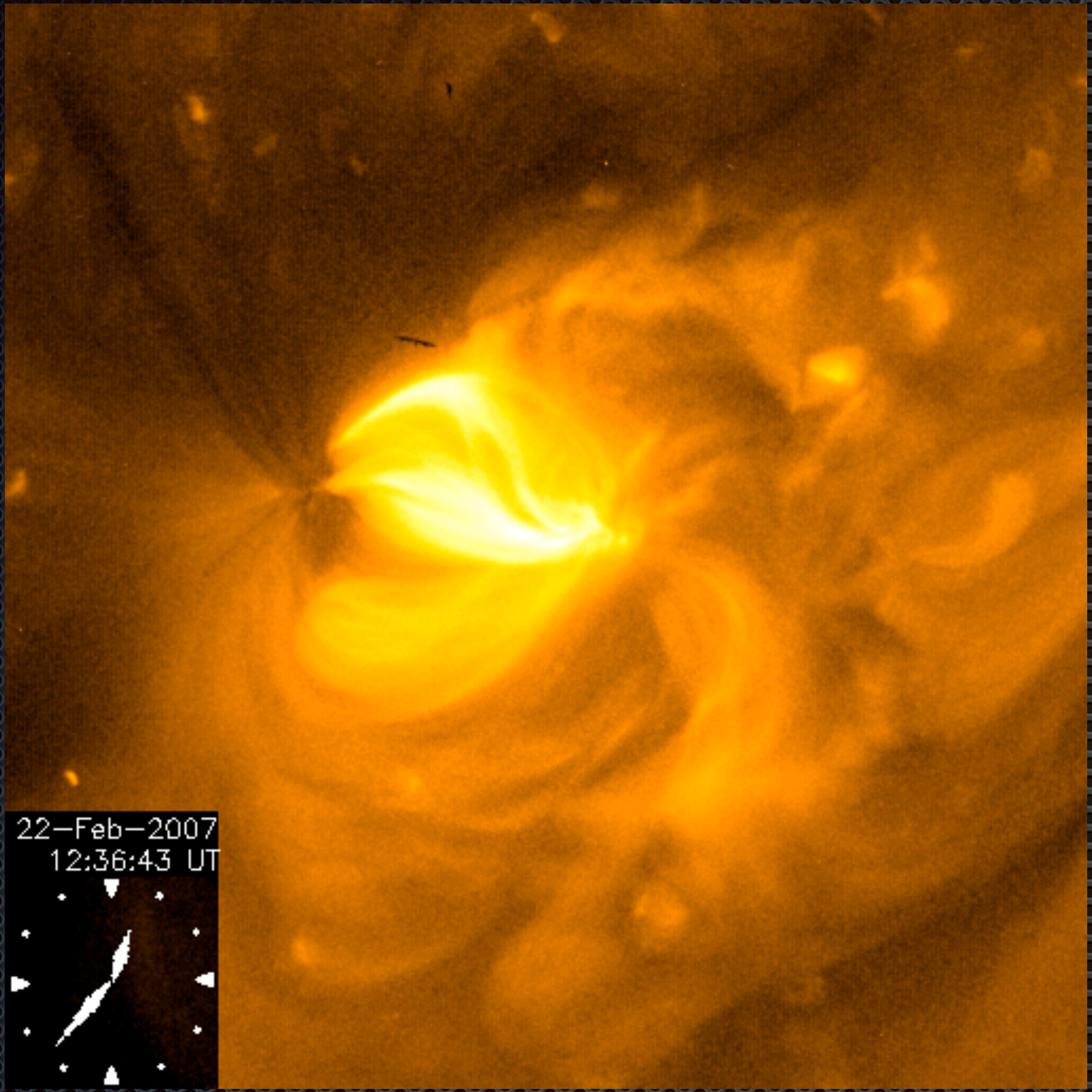
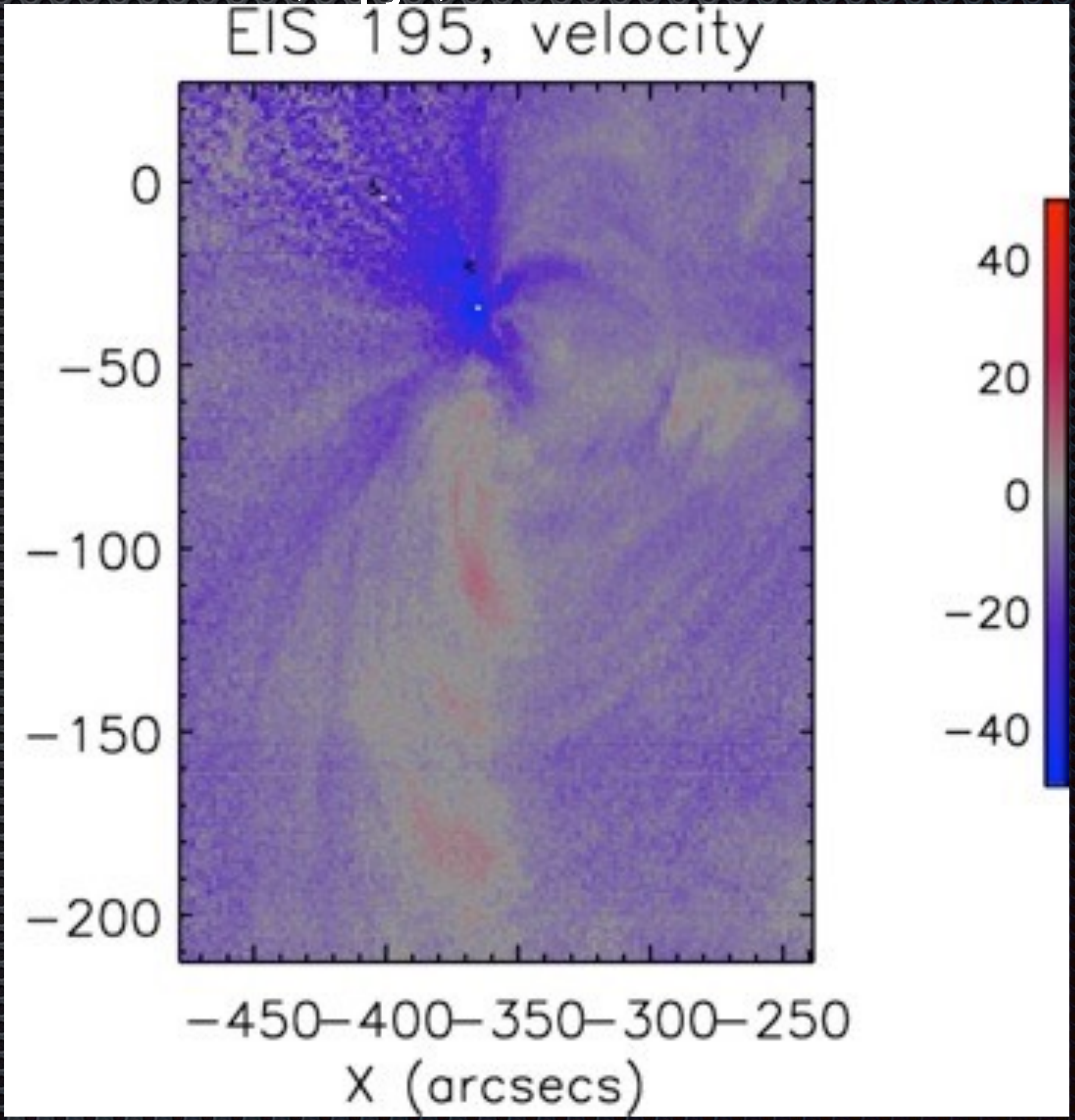
Outflows Near ARs

Sakao et al., Science, 2007

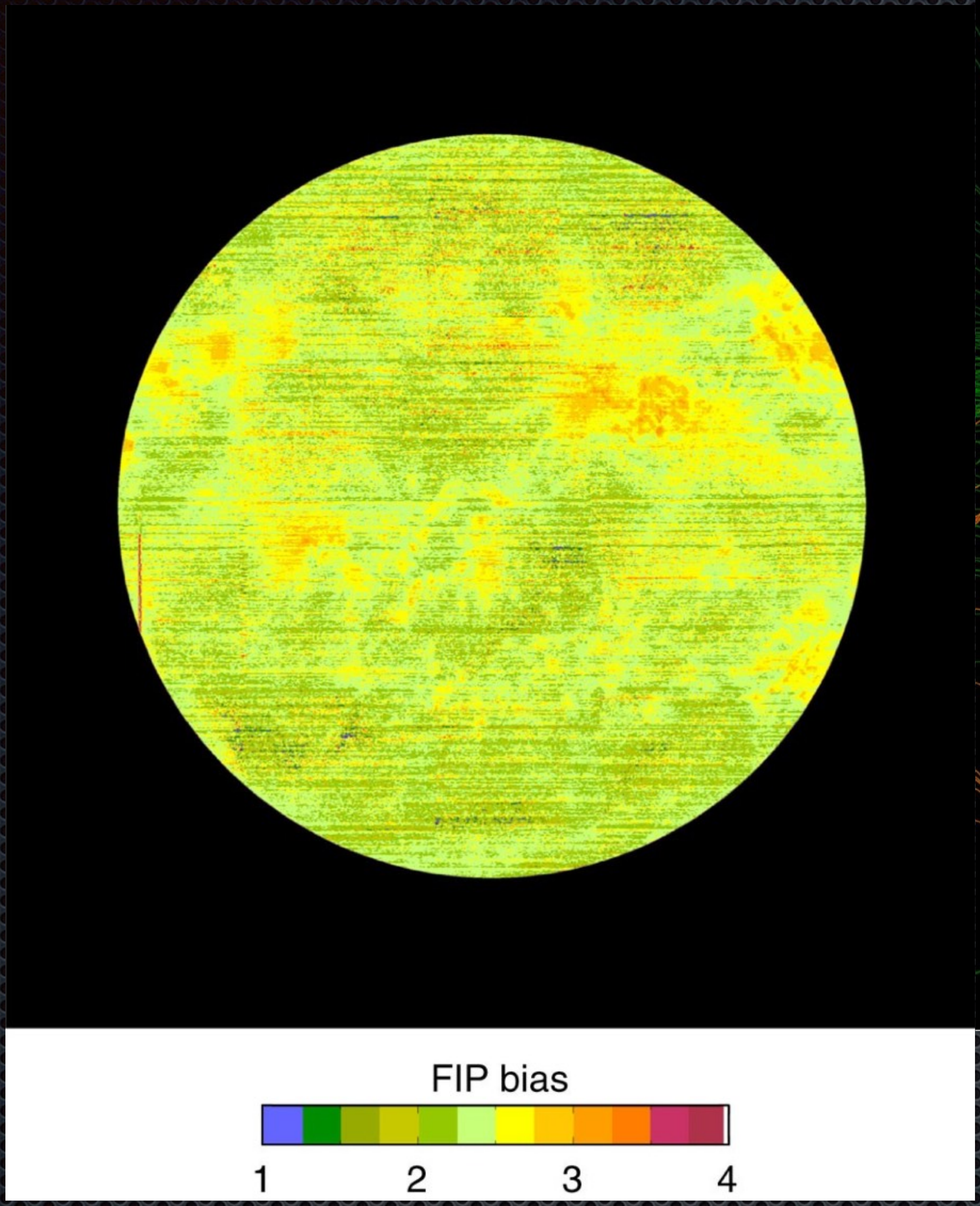


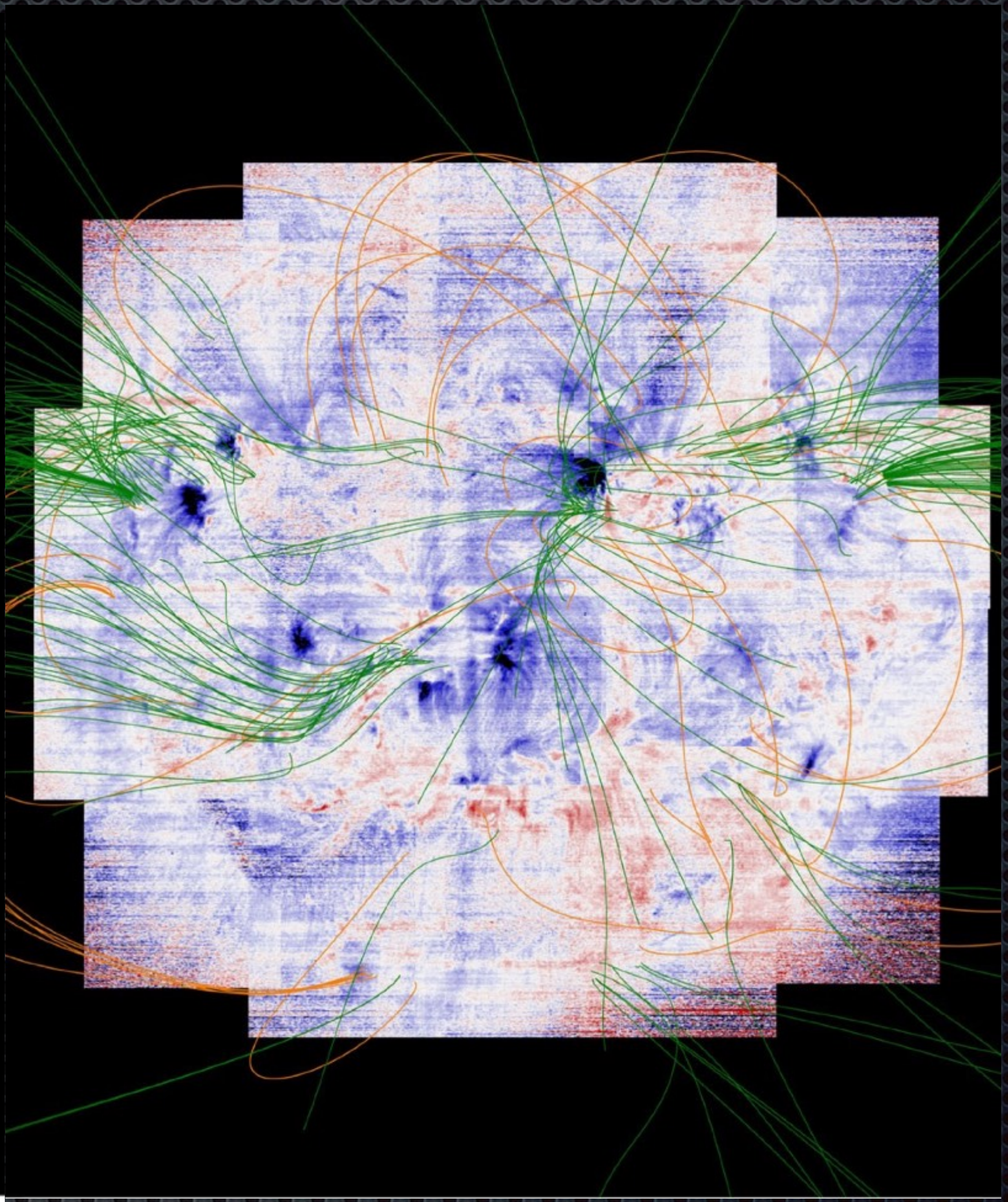
Harra et al., ApJL, 2008



- Possible source for the slow solar wind

Abundances of outflows



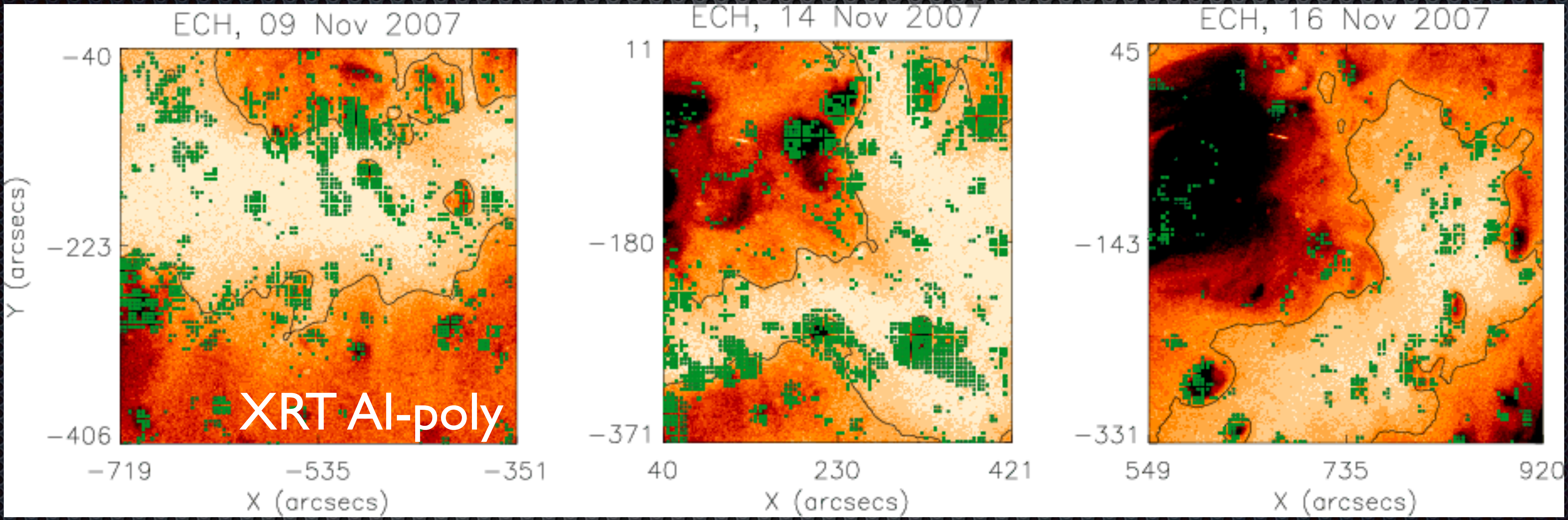


Red = inflow
Blue = outflow

- Abundances enhanced 3-4 times over photospheric (Brooks et al., 2011, 2015)

Bright points at coronal hole boundaries

Subramanian et al., A&A, 2010



- Relative to quiet sun, coronal hole boundaries are abundant with brightenings, indicating frequent reconnections

X-ray Jets

Statistics (from Savcheva et al., PASJ, 2007):

60-100 jets per day

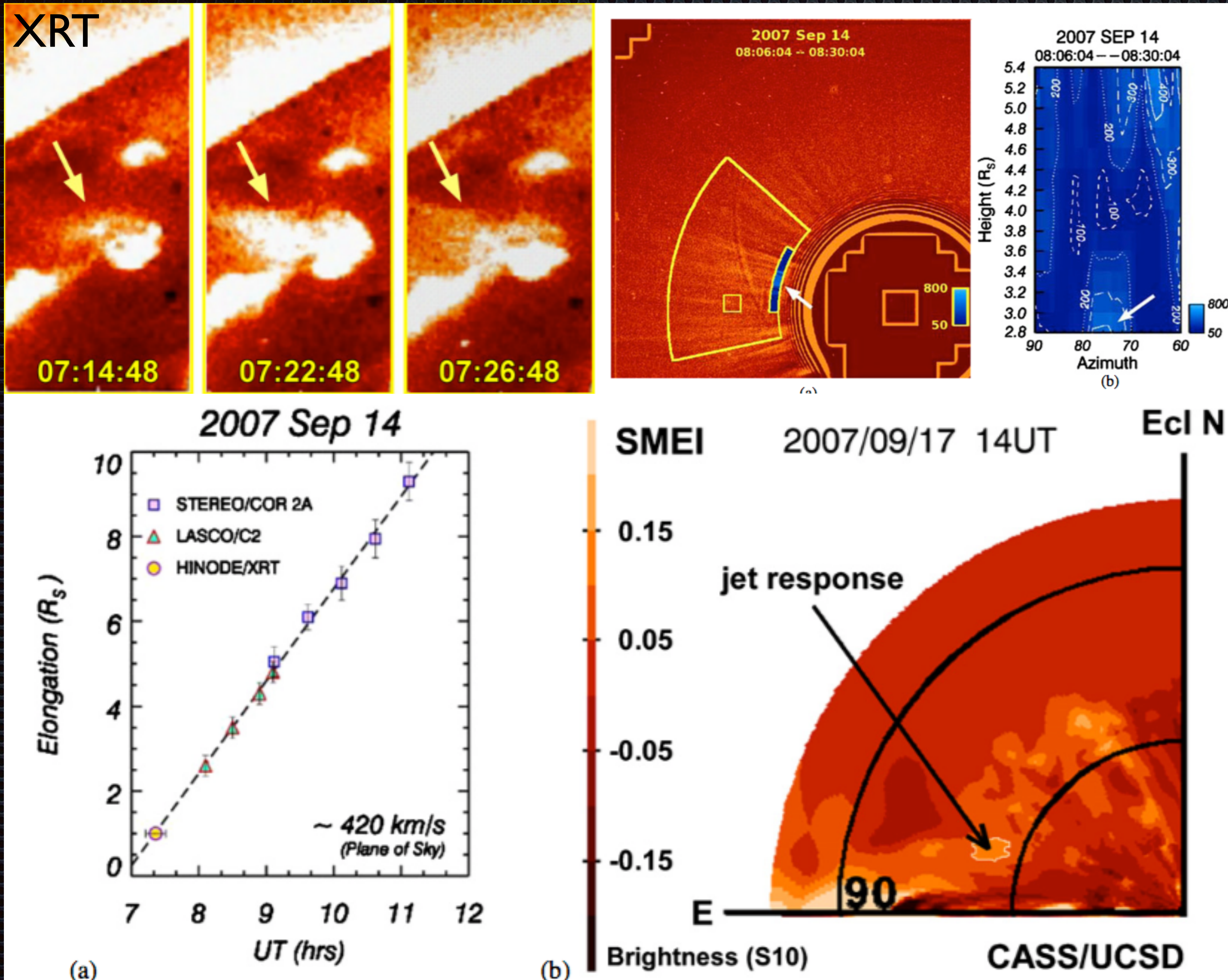
mean velocity 160 km/s,

velocities up to 1000 km/s observed

mean height 5 x10^4 km

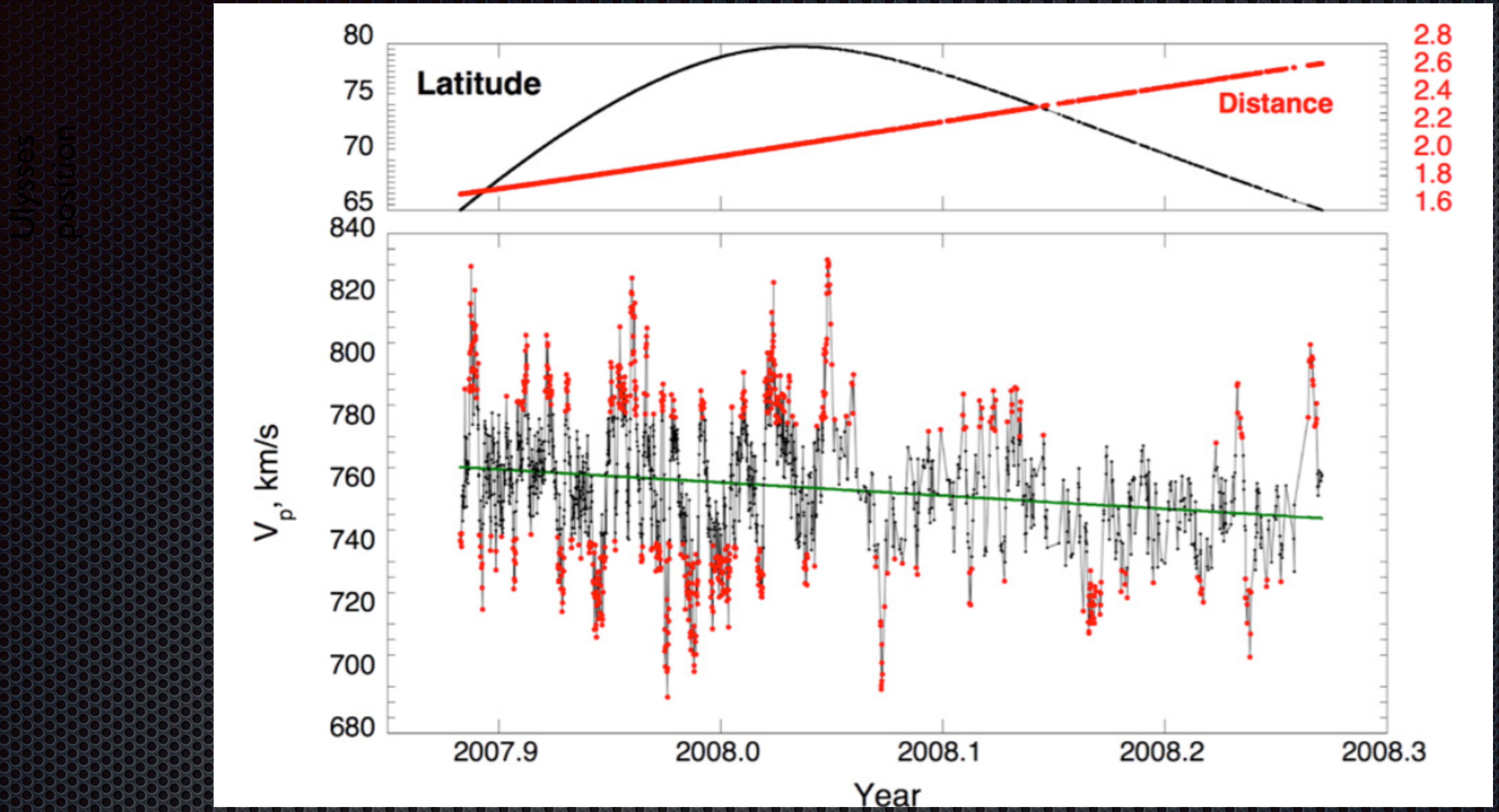
mean lifetime 10 mins

Jets traced into solar wind



Yu et al., ApJ, 2014

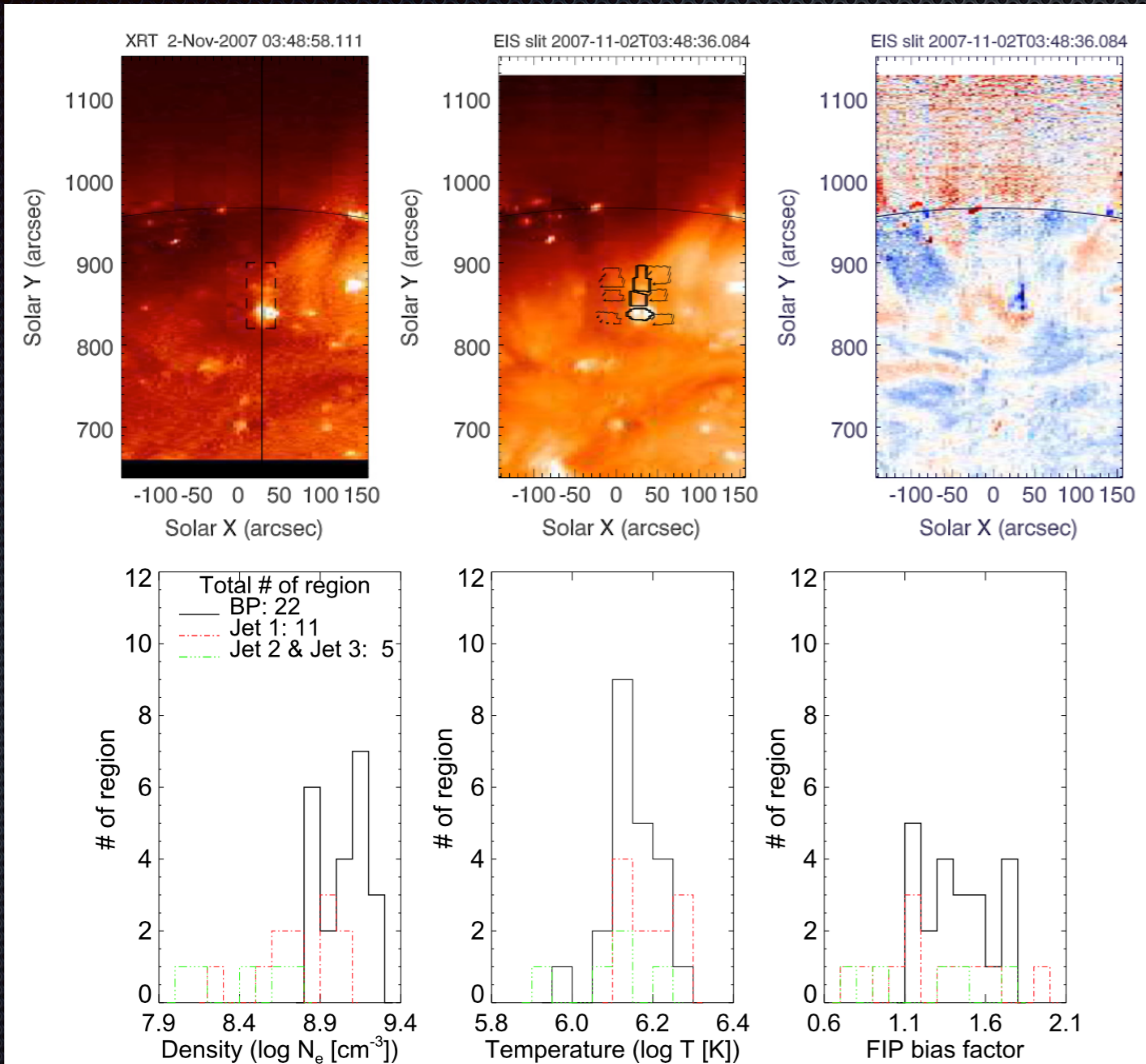
Jets and microstreams



Neugebauer et al., ApJ, 2012

- Proton temperature and normalized flux are greater in peaks, consistent with density, temperature and high speeds of X-ray jets

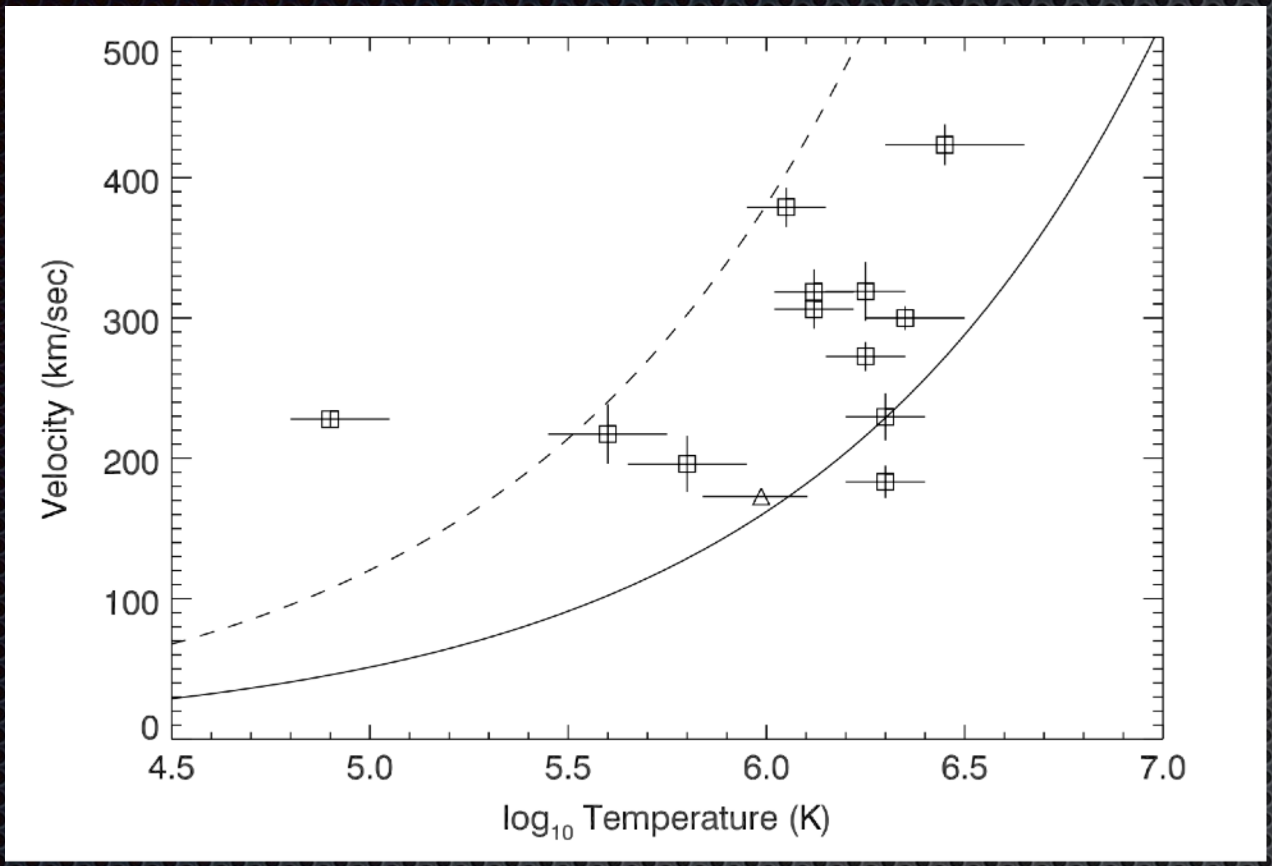
Jets composition from EIS



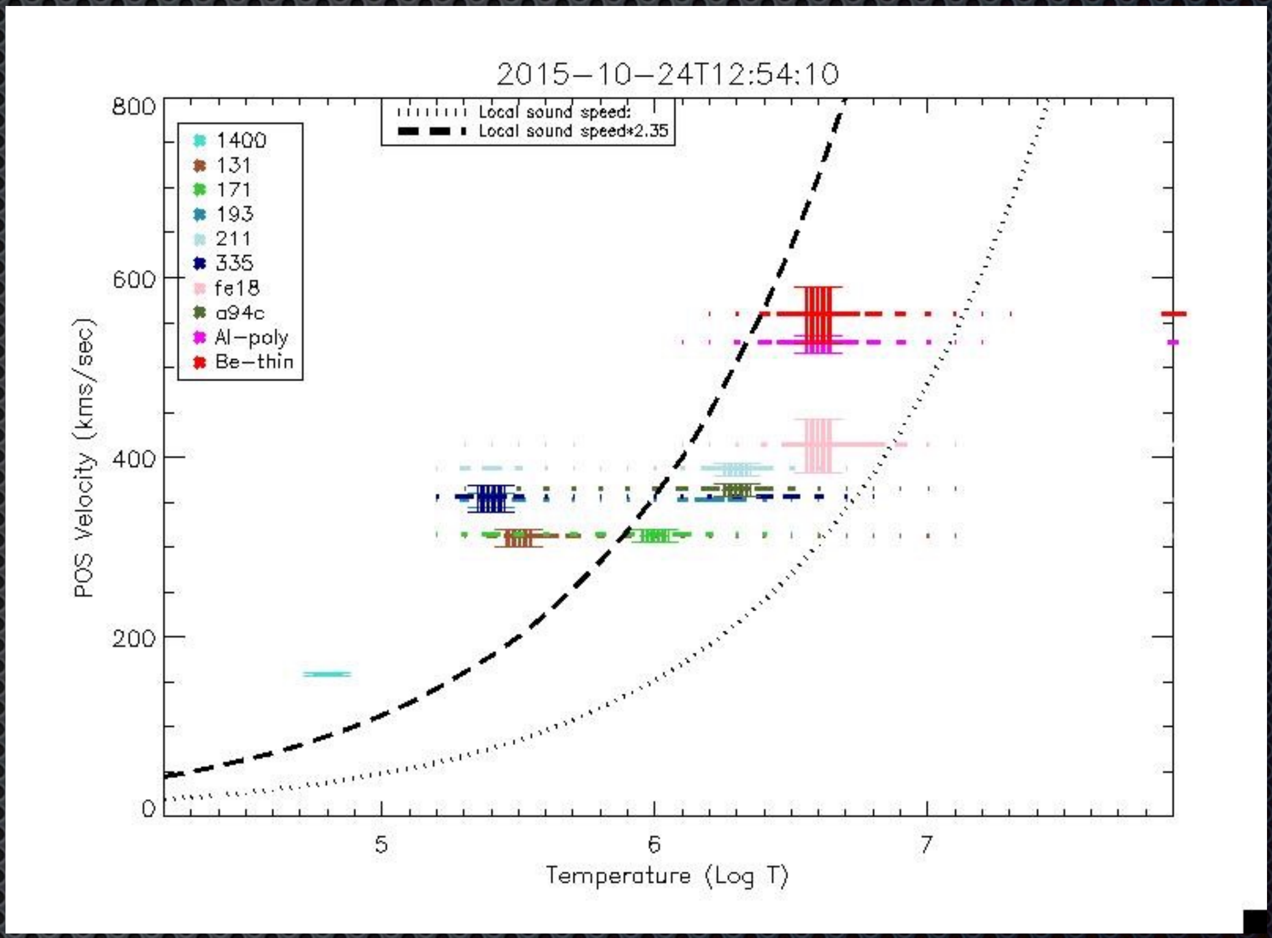
- Abundances in jets are close to photospheric

Lee et al, ApJ, 2015

Chromospheric evaporation in jets



Matsui et al., ApJ, 2012

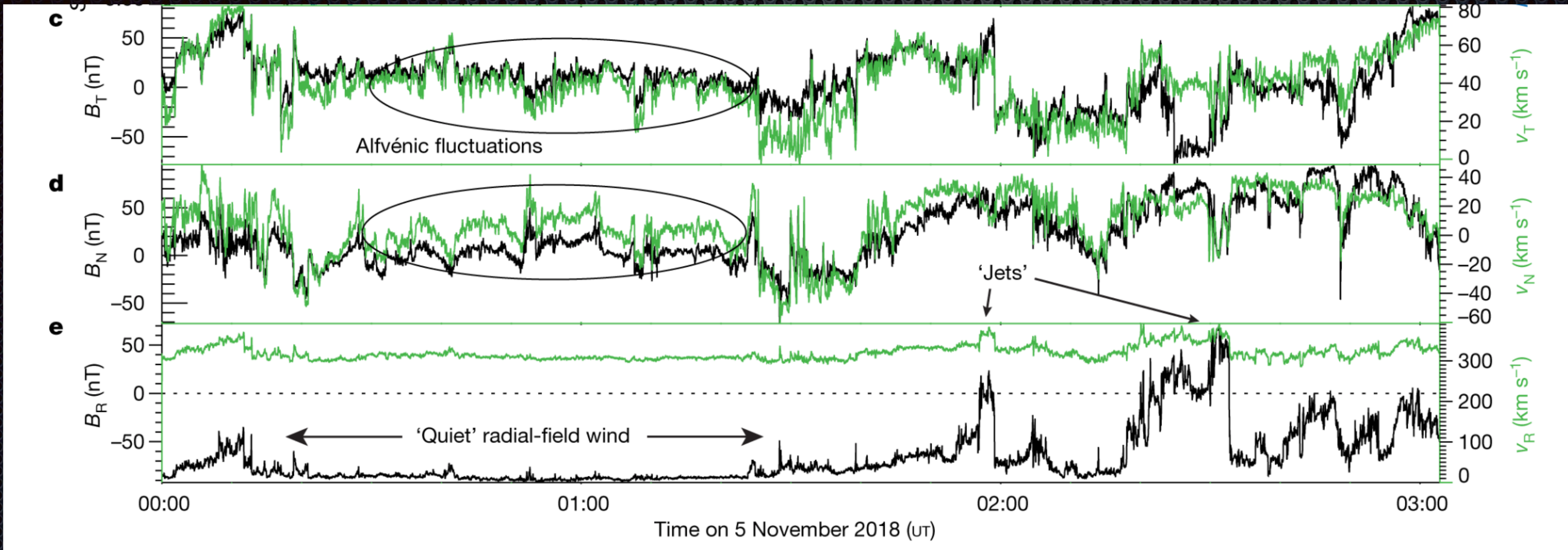


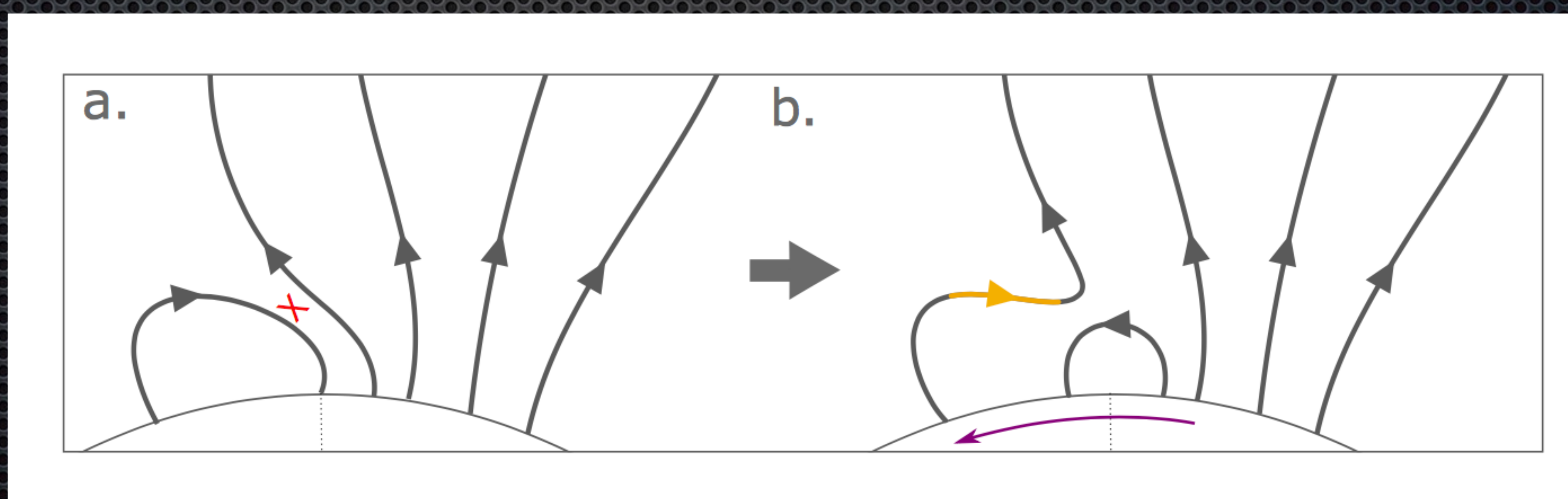
Farid et al., ApJ, submitted

- Increasing velocity with temperature is an indication of chromospheric evaporation, which implies photospheric abundances
- However, not all jets show this relationship (Farid et al. 2020)

Recent PSP Results

Bale et al., Nature, 2019



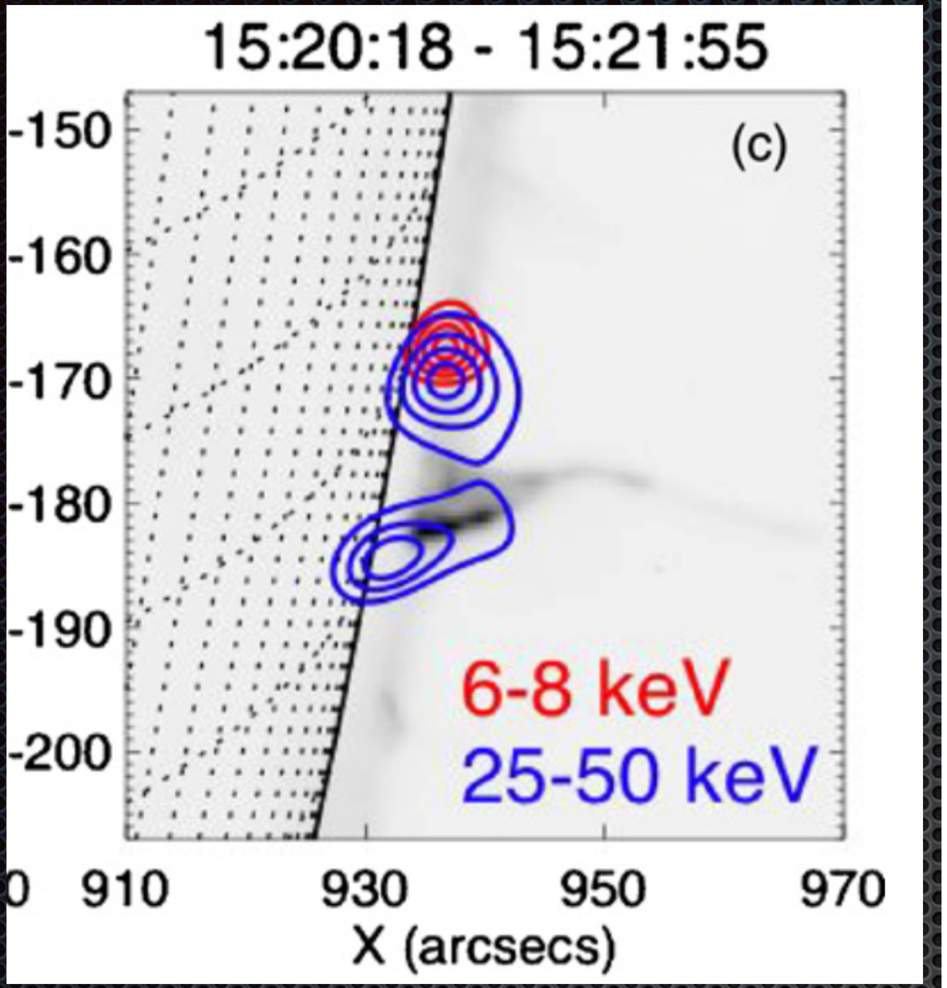


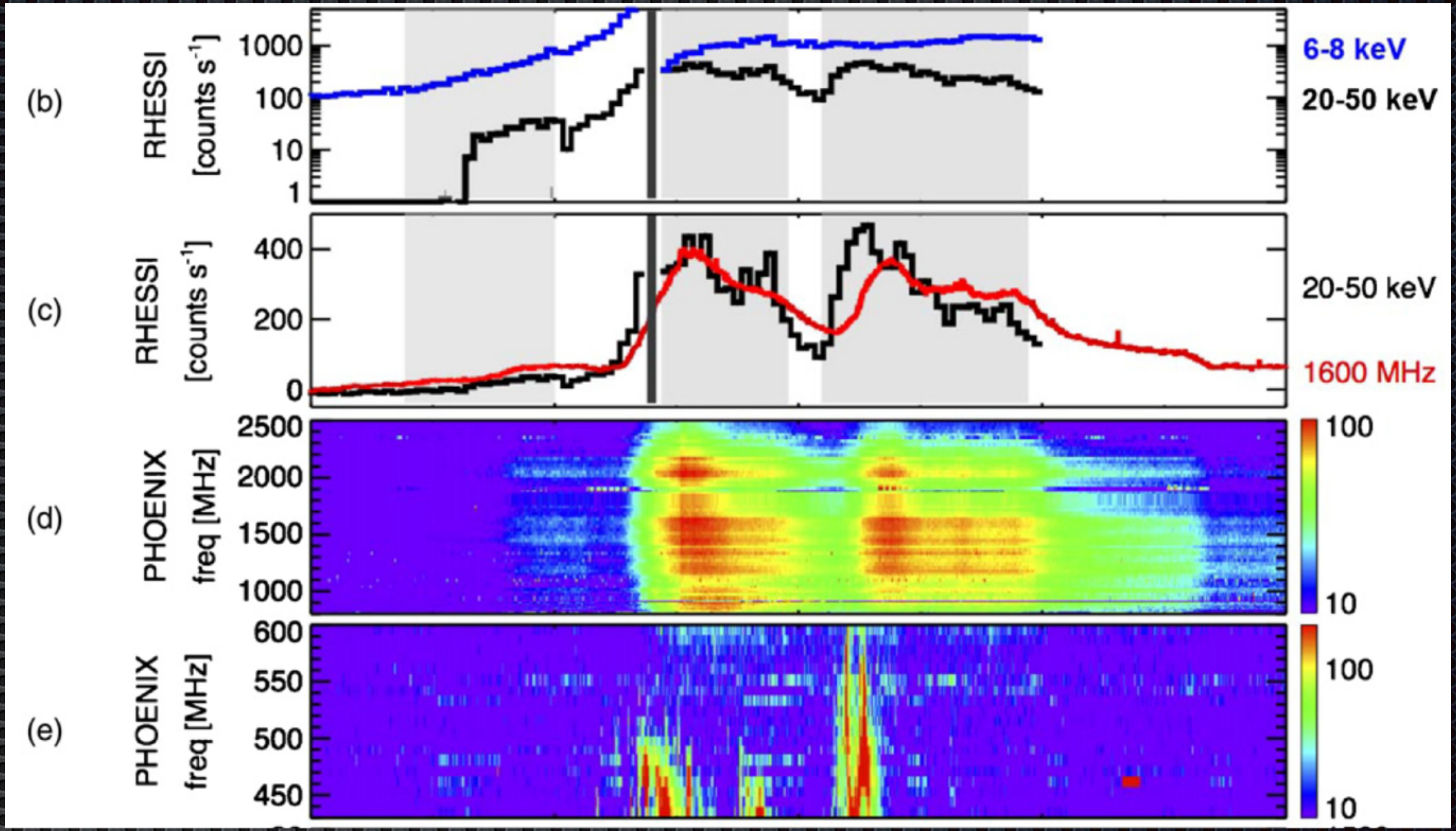
Macneil, MNRAS, 2020

- Rapid Alfvénic fluctuations in heliospheric magnetic field may be remnants of coronal jets

Hard X-rays in Jets

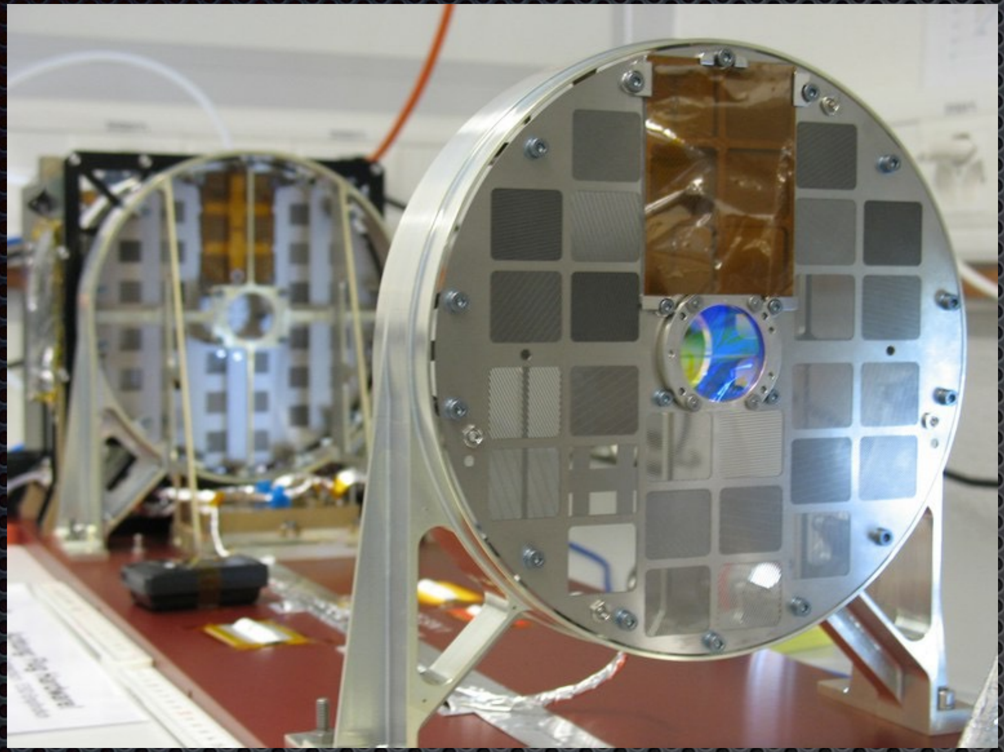
Glesener et al., ApJ, 2012, see also Musset et al., ApJ, 2020



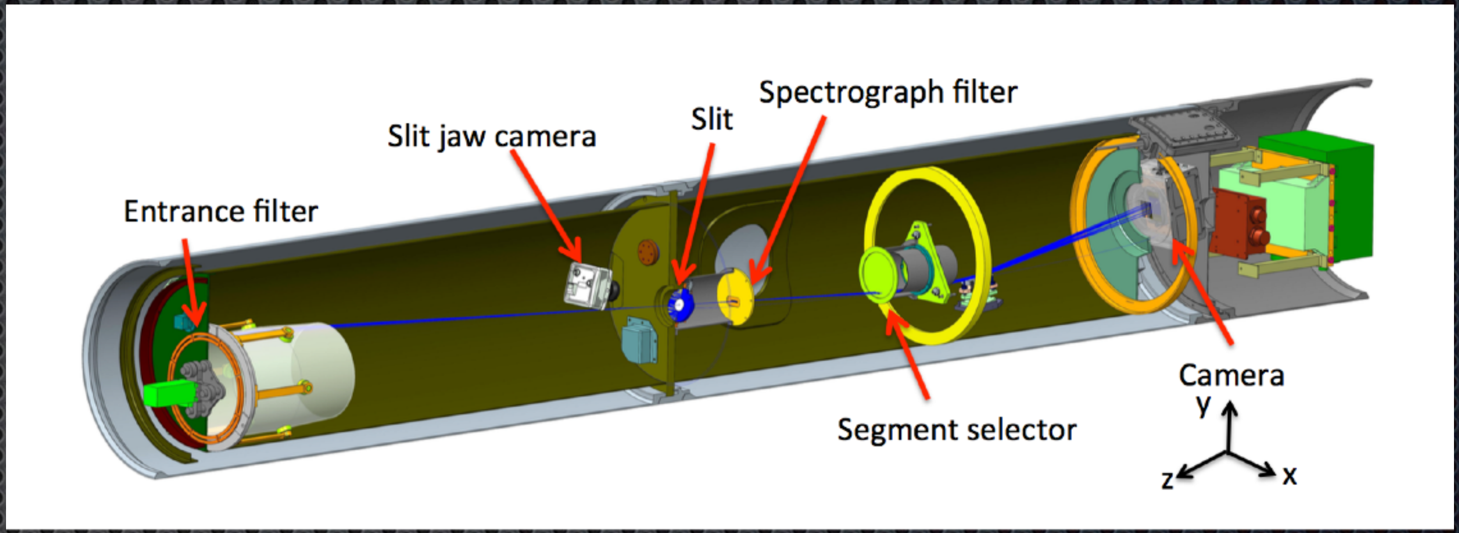


- Elongated HXR source in an AR jet
- Corresponds with a Type III burst in radio, indicating open field for the accelerated elections to travel along

Future X-ray Instruments



Spectrometer/Telescope for Imaging X-rays (STIX) on Solar Orbiter
Launched Feb 9, 2020
Turned on April 14, 2020



Marshall Grazing Incidence X-ray Spectrometer (MaGIX)
Launch delayed by COVID19 until 2021

Future X-ray Instruments

FIERCE Fundamentals of Impulsive Energy Release in the Corona Explorer

Deducing how solar energy is suddenly released and transformed:
- Physical origins of space weather?
- Particle acceleration and energy transport at the Sun?
- Heating of the solar corona?

X-ray imaging spectroscopy and EUV imaging at high angular resolution, fast cadence, and high sensitivity:
- Focusing Optics X-ray Solar Imager (FOXSI)
- Thermal and Dynamic Imager for the Sun (THADIS)
- Spectrometer for Temperature and Composition (STC)

If selected, FIERCE will launch in 2025, near the peak of solar activity