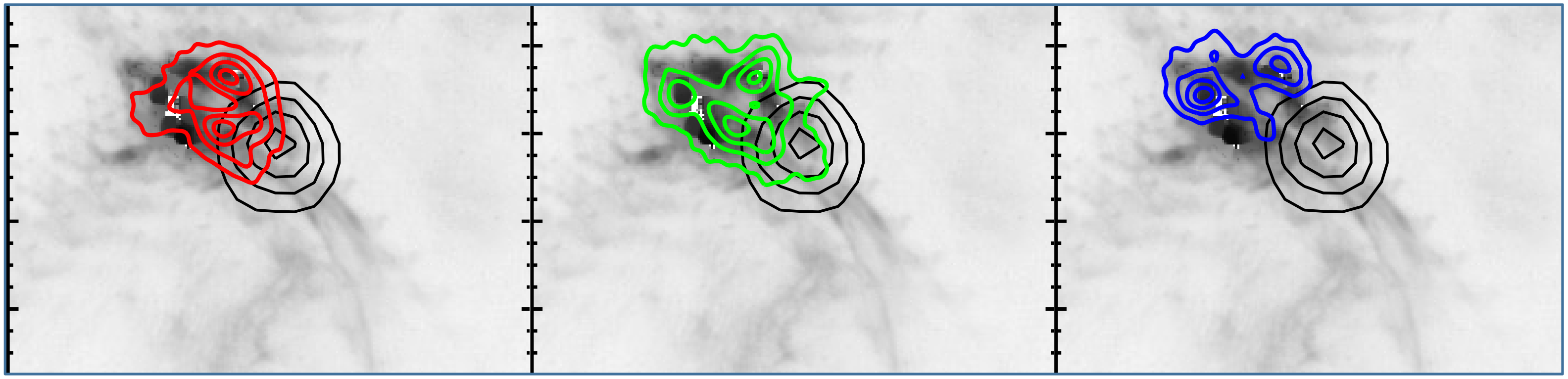


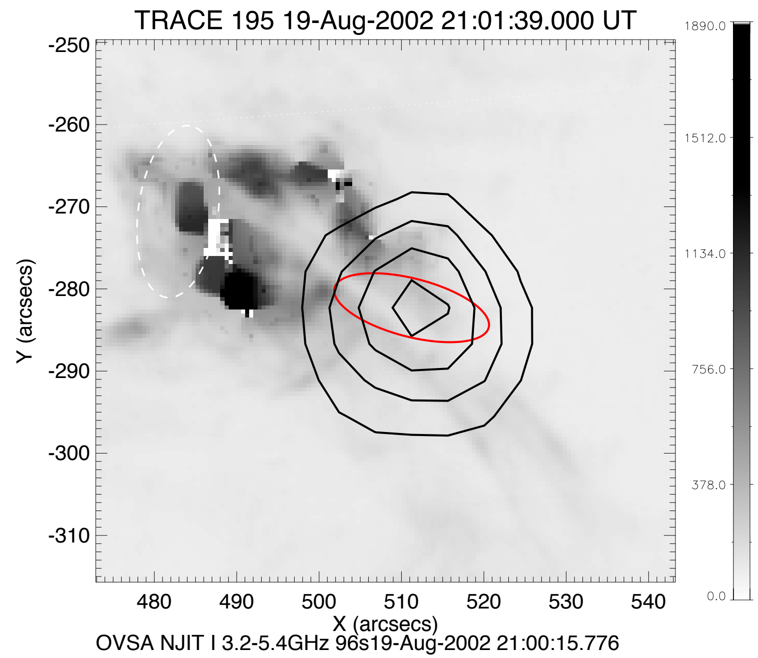
Accelerated electrons in a hard X-ray / radio jet

Lindsay Glesener (University of Minnesota) and
Gregory Fleishman (New Jersey Institute of Technology)

2016 July 27 RHESSI Workshop XV University of Graz

Outline

In this work, we combine HXR, microwave, and extreme ultraviolet (EUV) data with emission modeling to investigate flare-accelerated electrons in a coronal jet.



Motivation

- What can jets tell us about particle acceleration?
- What can accelerated particles tells us about jets?

Observations of 2002 August 19 jet

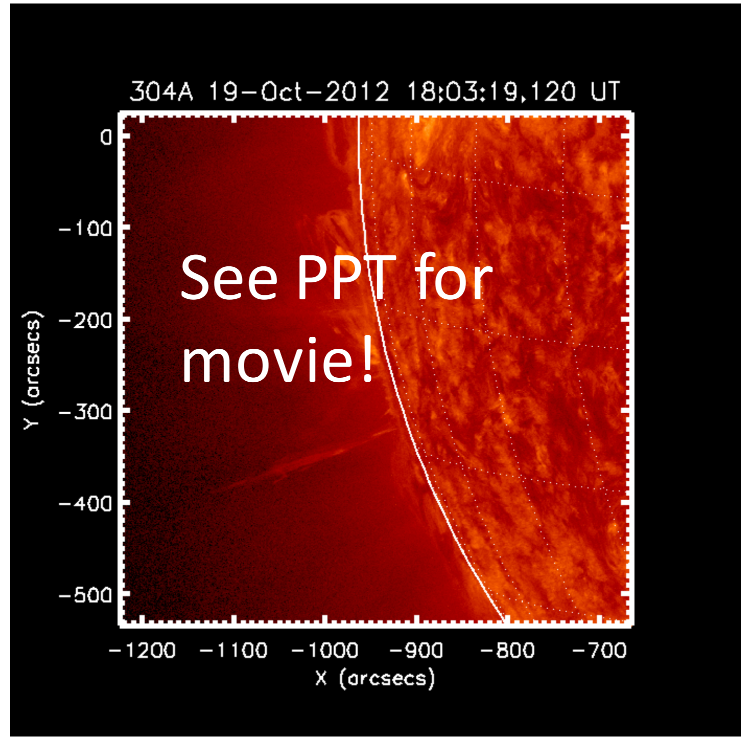
- EUV (TRACE)
- Hard X-rays (RHESSI & Konus-Wind)
- Microwaves (OVSA)

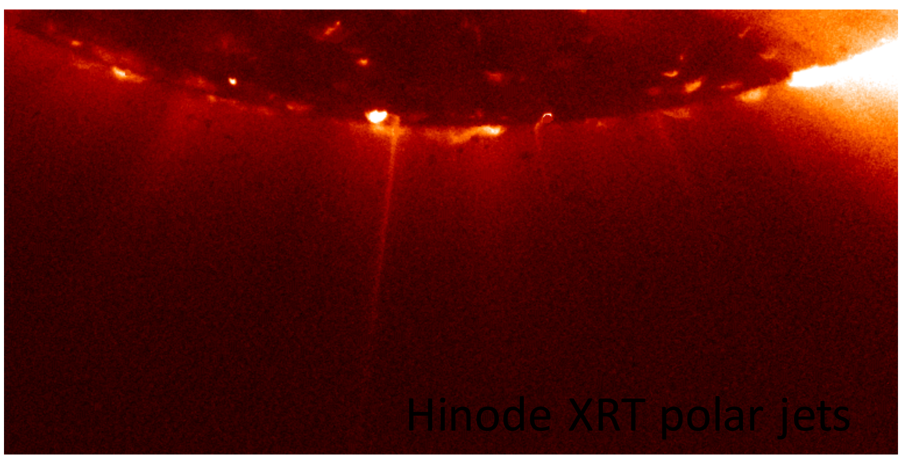
3D modeling

- Simulated electron populations with GX Simulator
- Comparison with observations

What is a solar coronal jet?

- Impulsive, collimated ejection of plasma in the corona.
- Often associated with features indicating open field:
  - Type III radio emission
  - Prompt electron events.

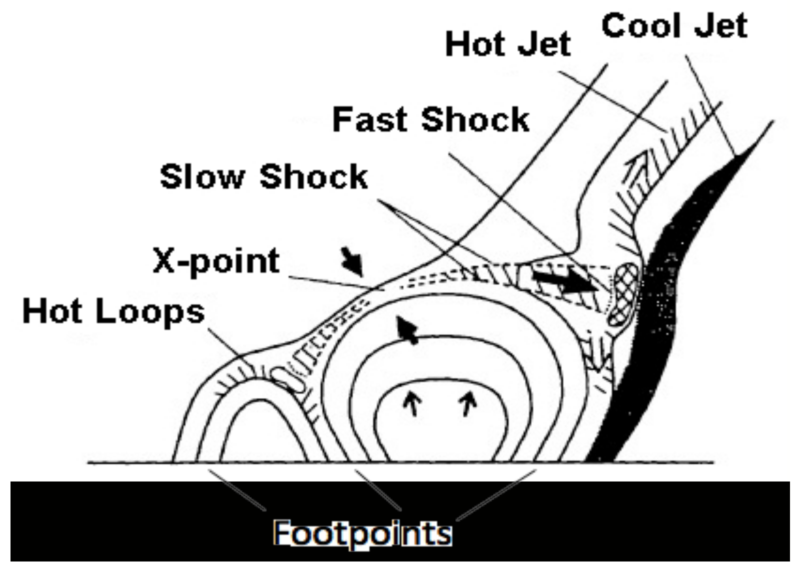




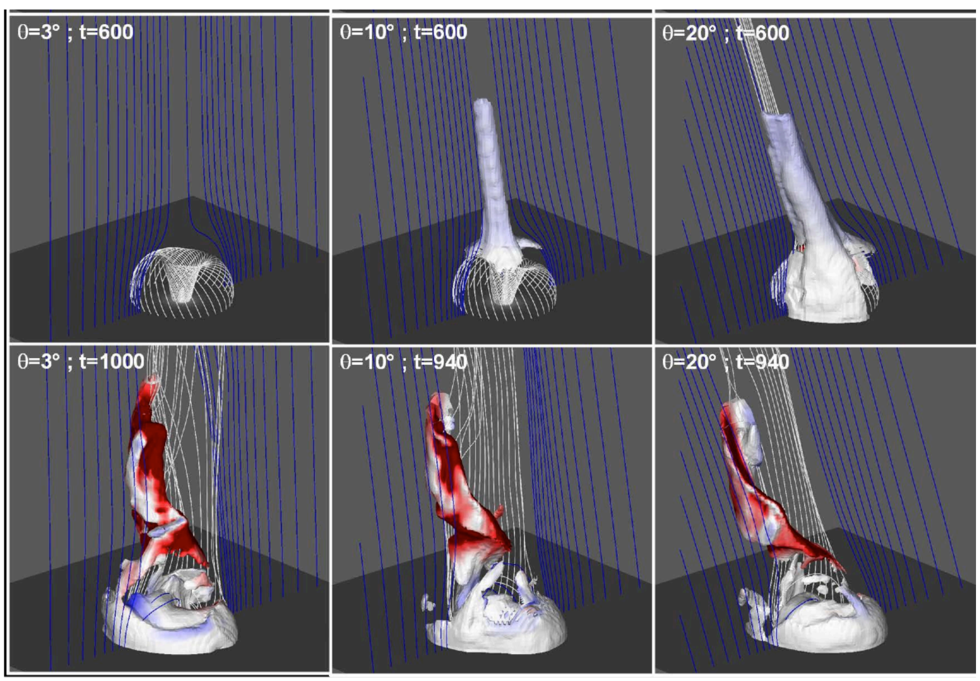
- Why study jets?
  - Relatively "simple" magnetic geometry in which to study reconnection
  - Jets are everywhere! They occur all over the Sun, and across large size scales.
  - Originator of transient heliospheric events (in-situ particle events)

How do coronal jets arise?

- 2-D: Shibata model of interchange reconnection
- Formation of hot and cool jets within same event



Shibata et al. (1997)



Pariat et al. (2015)

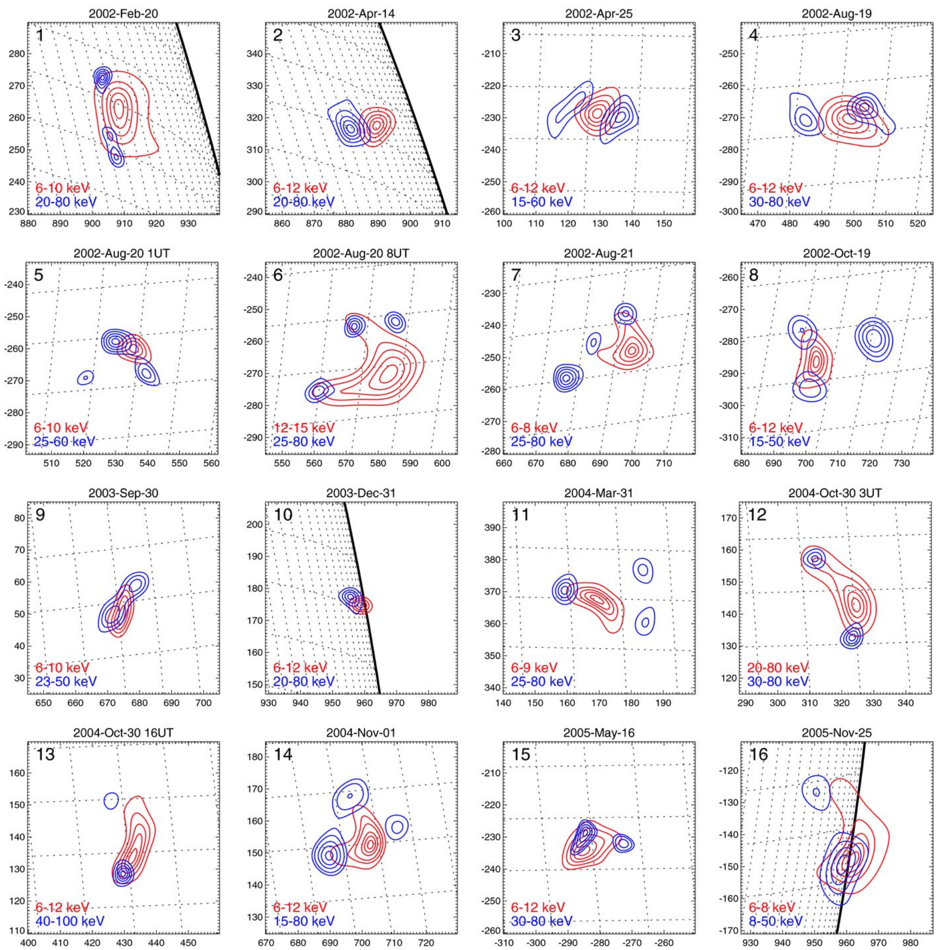
- More complex in 3-D
- e.g. Pariat et al. (2010, 2015)
- Several types of jets, including straight and helical
- **Erupting filaments?** See work by Sterling, Wyper, and others.

Why study electron acceleration in jets?

Relatively simple magnetic geometry	→	Clear context on which to study particle acceleration
Ubiquitous and multiscale phenomenon	→	Understand energy release/acceleration across scales
Clear “escape route” to interplanetary space	→	Chance to study accelerated electrons both remotely and in situ
Energy deposited by accelerated electrons can affect jet evolution	→	Learn more about how jets form and evolve

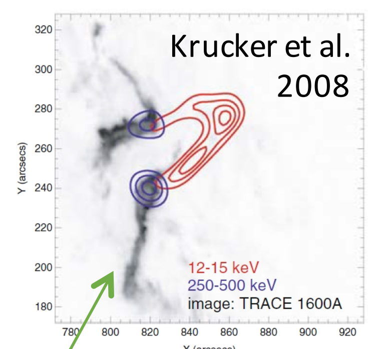
What do we learn from hard X-rays?

- Hard X-rays (HXRs) reveal the locations and spectra of accelerated electrons.

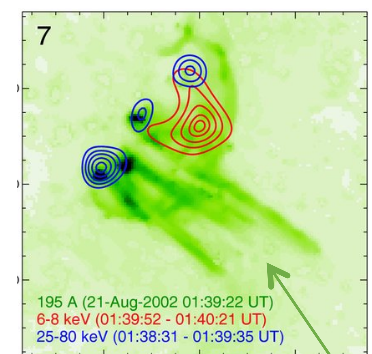


- Krucker et al. (2011) studied 16 flares and found >2 footpoints in most events.

- Results are consistent with interchange reconnection, either 2D or 3D.



Contrast with 2-ribbon flare



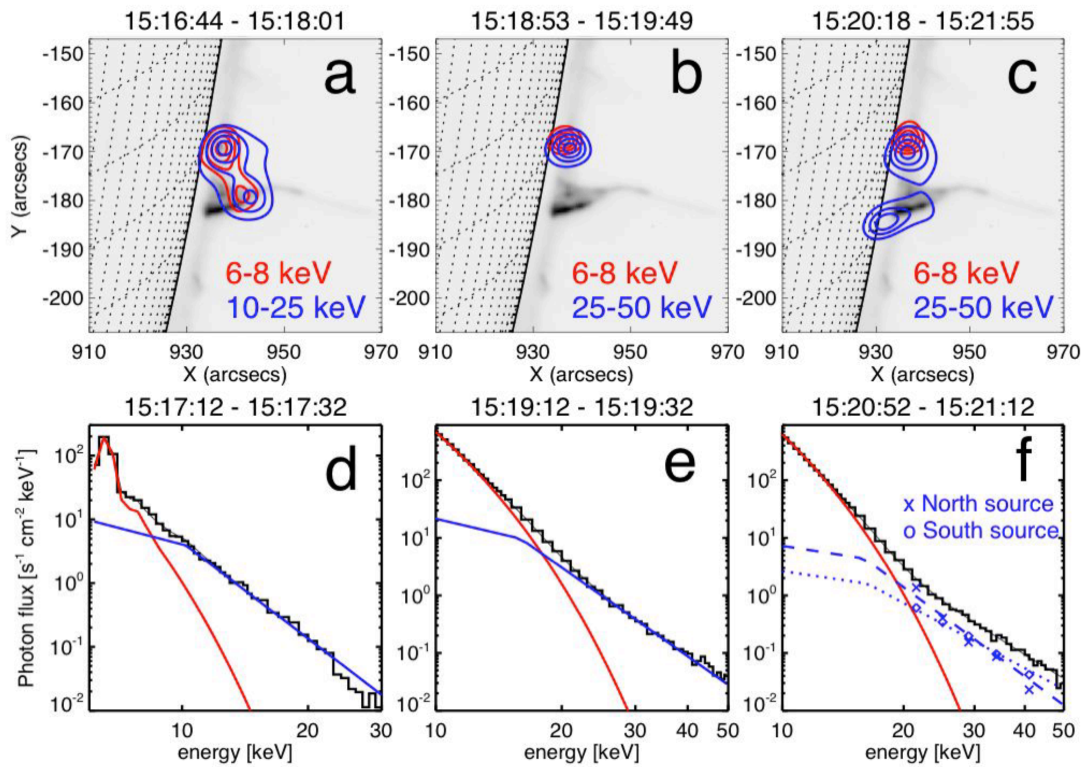
RHESSI HXR overlay on TRACE EUV jet

Partly occulted flares reveal coronal sources

- Jet/flare on 2003 Aug 21 showed multiple coronal sources.
  - Double coronal source, thermal + nonthermal
  - Accelerated electrons within the emerging jet itself.

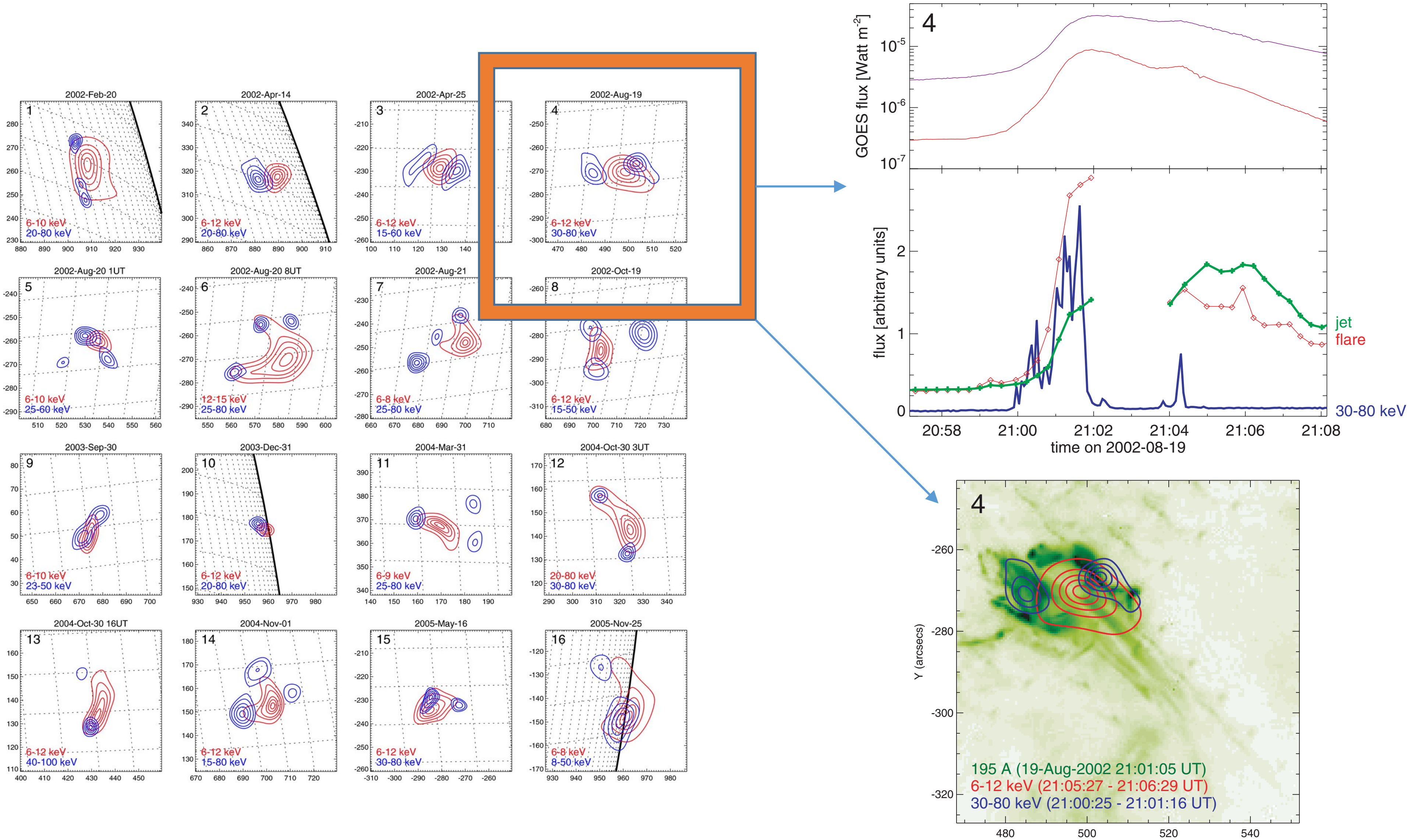
- Interpretation: HXRs show
  - Sites of reconnection or reconnection outflow
  - Postflare loop

- How do accelerated electrons access the jet?

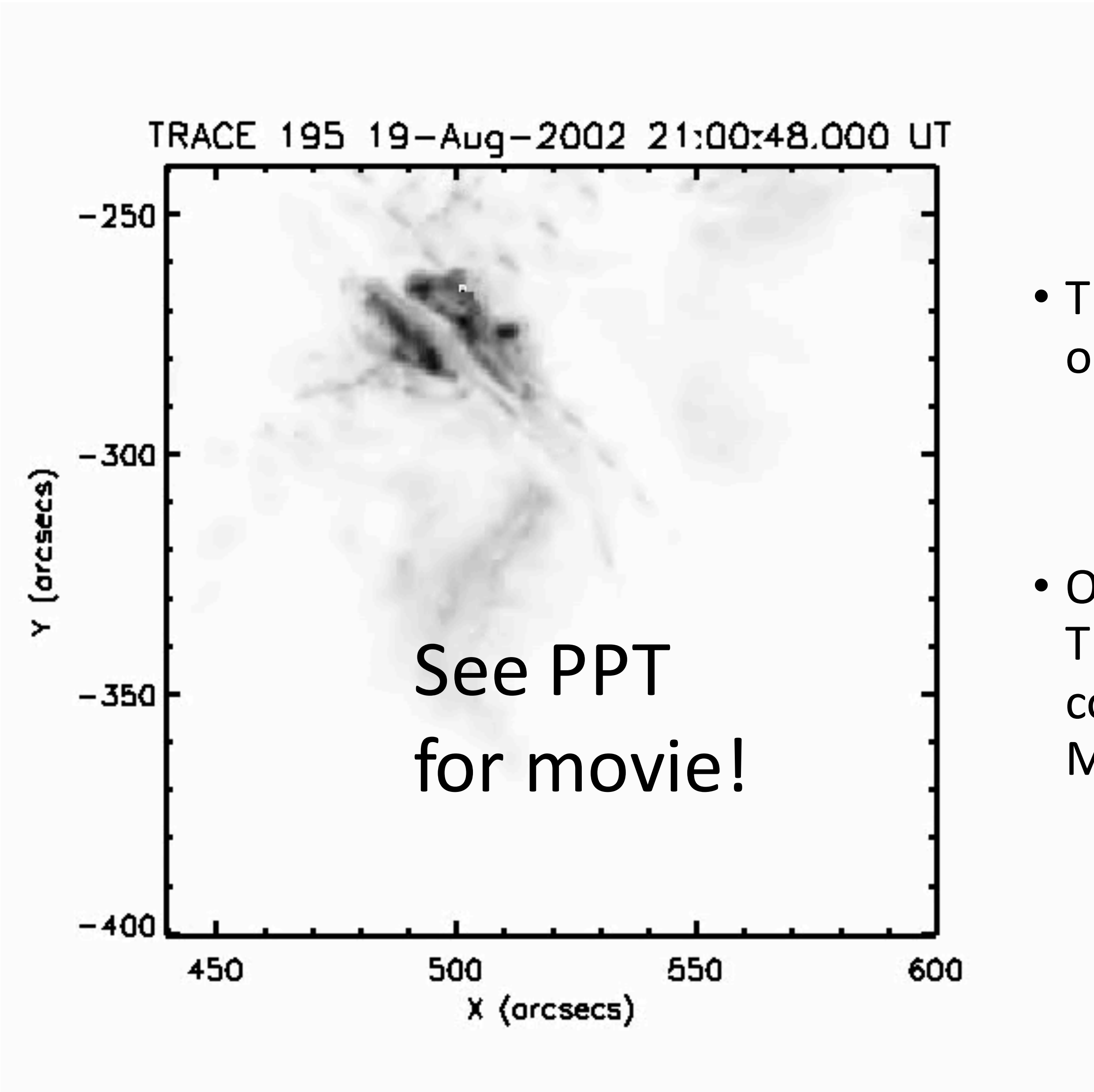


Glesener, Krucker, & Lin, Ap.J., 2012

For the starting point for this work, we go back to Krucker et al. (2011):



Flare/jet on 2002 August 19 as seen by TRACE



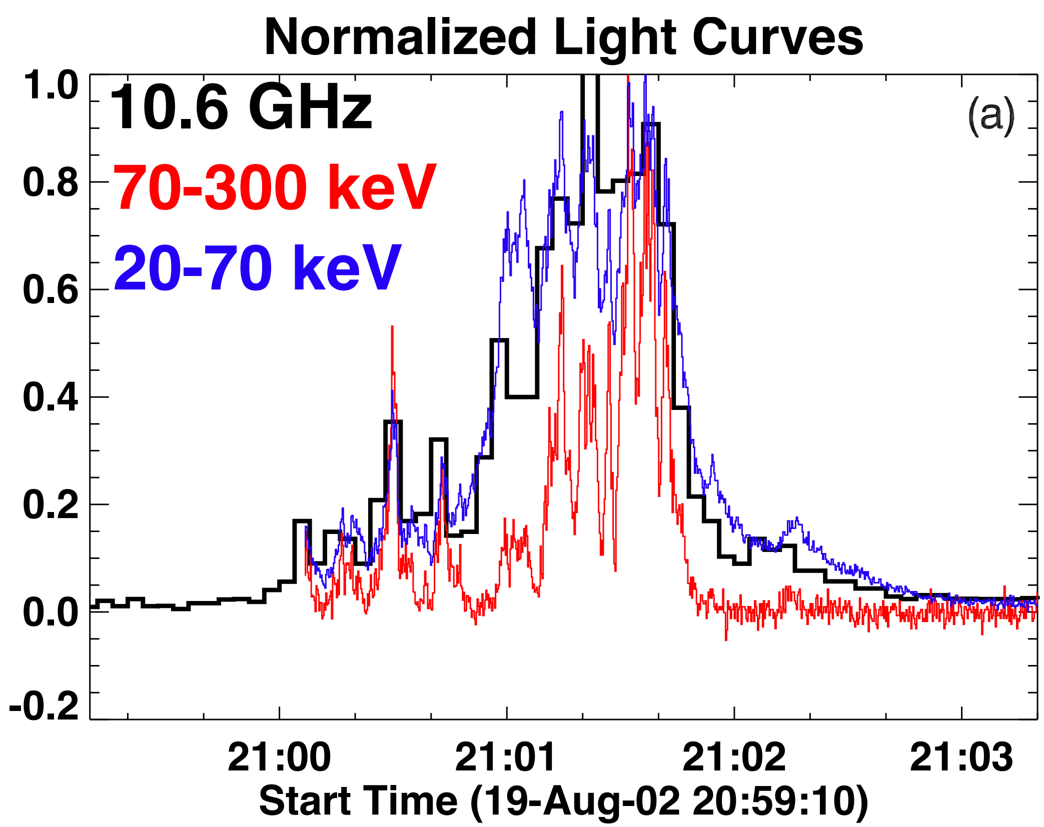
See PPT
for movie!

- TRACE: EUV imager that operated 1998-2010
- On 2002 August 19 TRACE observed a coronal jet from a GOES M3.1 flare.

Hard X-ray and microwave data

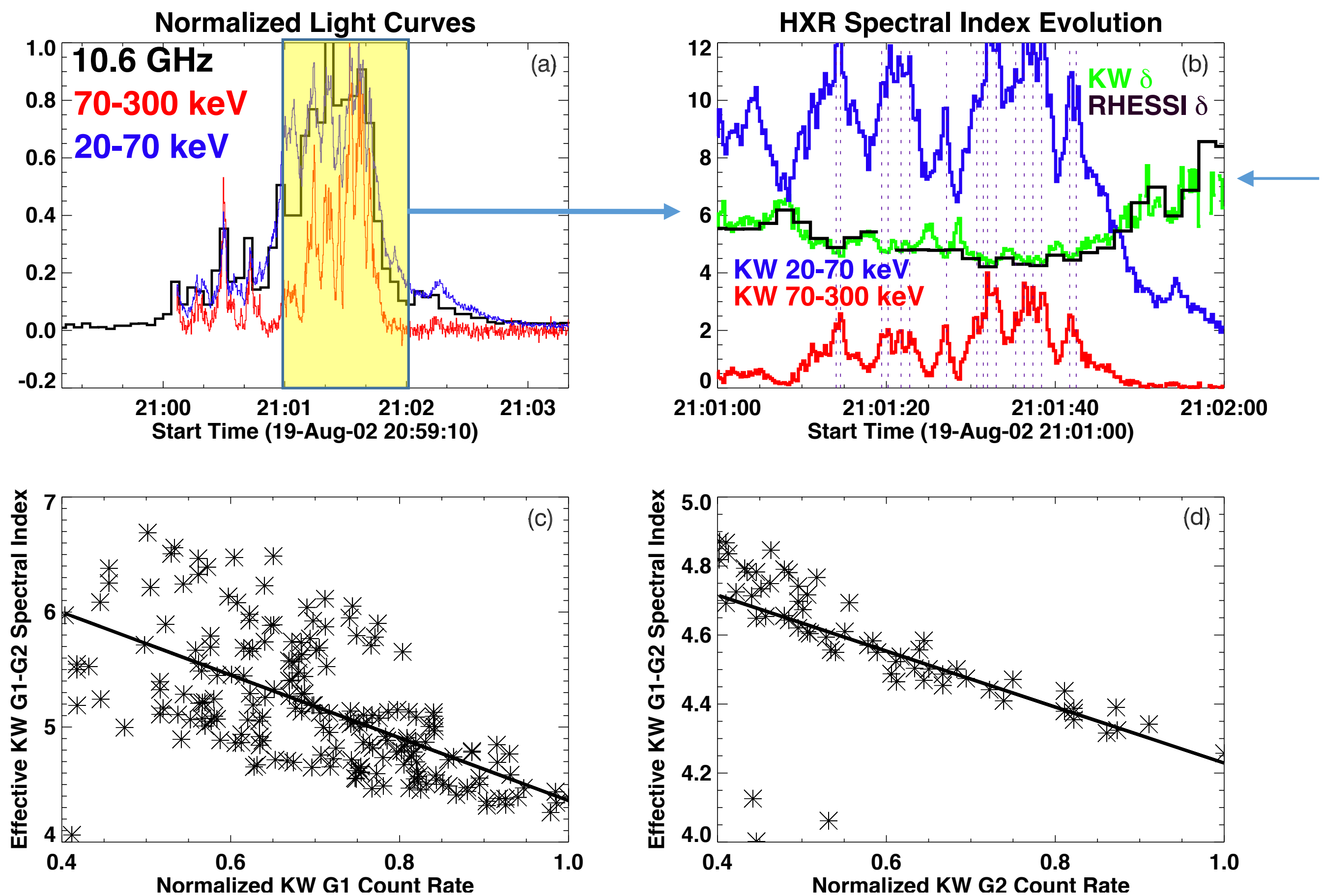
- Hard X-ray data:
  - RHESSI images & spectra
  - Konus-Wind spectra
    - NaI(Tl) scintillator
    - 10 keV – 1 MeV
    - High time resolution

- Microwave data from the Owens Valley Solar Array (OVSA)



Konus-Wind database: See talk by Alexandra Lysenko

Hard X-ray temporal dynamics

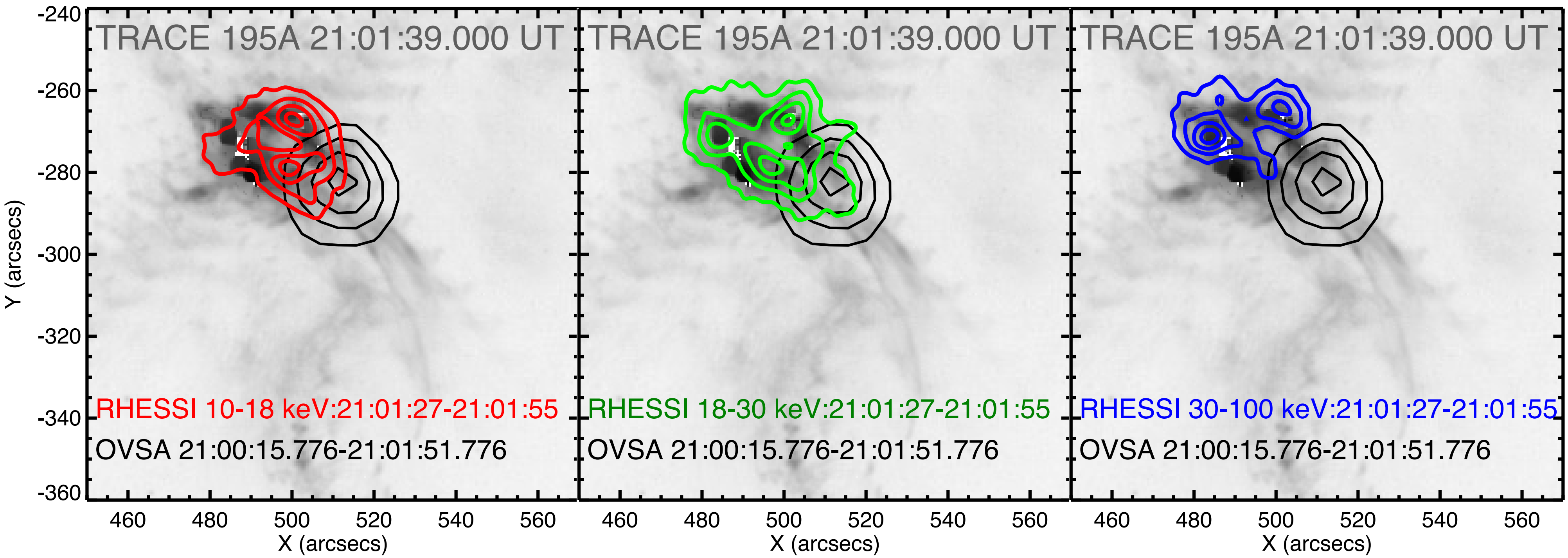


Electron spectral index δ

- Fast time variations in HXR lightcurves!
- Each HXR peak is associated with a spectral hardening (SHS behavior) → isolated bursts of particle acceleration?

Locations of hard X-ray emission

RHESSI CLEAN images (colors) on TRACE:



10-18 keV:
Thermal loops?

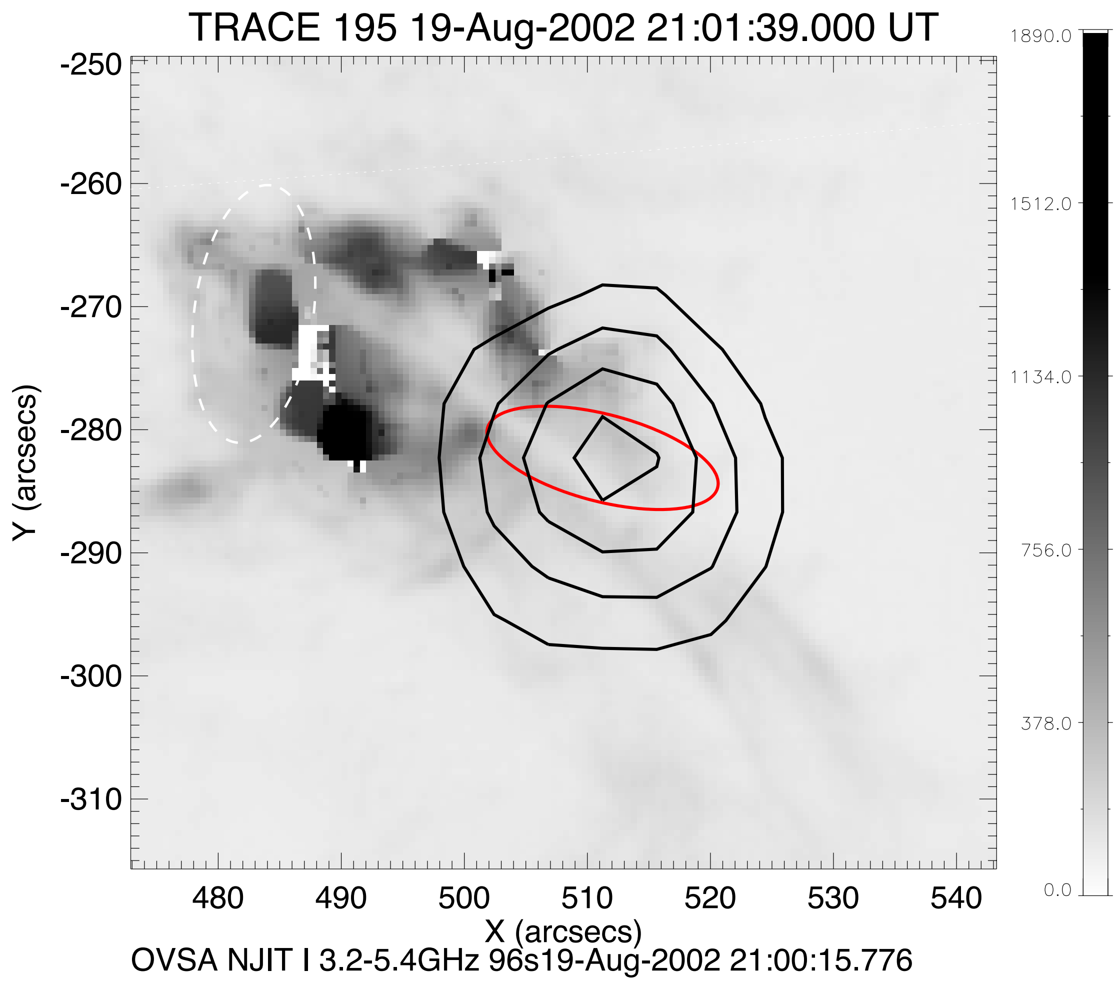
18-30 keV:
Extension along the jet

30-100 keV:
Nonthermal footpoints

Contour levels are 30, 50, 70, 90% of max.

Owens Valley Solar Array (OVSA) jet data

- Background: TRACE 195
- Black: OVSA image
  - Integrated 96 seconds
  - 3.2-5.4 GHz
  - CLEAN+SELFCAL method
- White dashed: Asymmetric beam
- Red Contour: Deconvolved OVSA image
- Result: OVSA emission is both cospatial with the jet and is elongated along it.



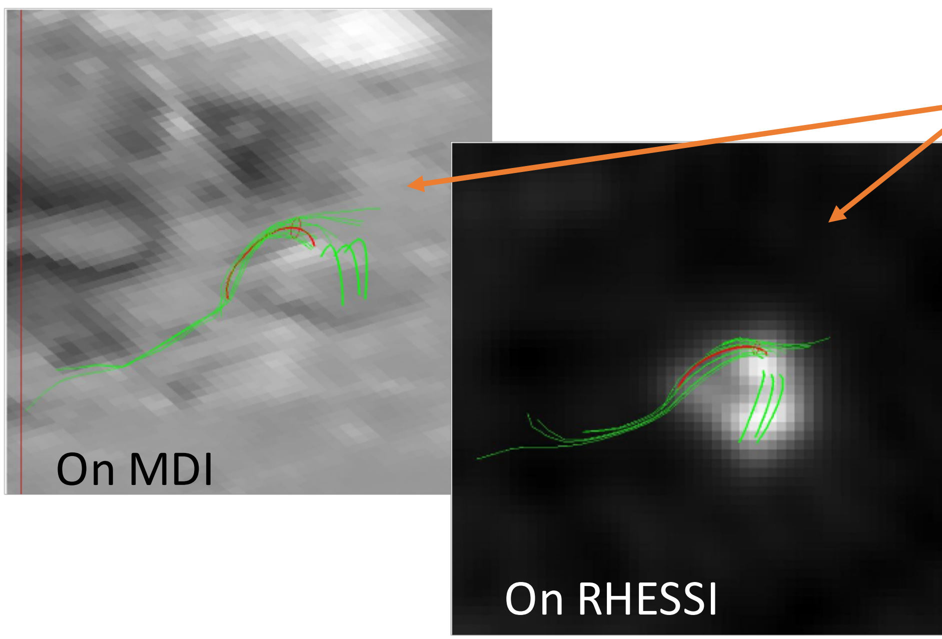
GX Simulator

Gyrosynchrotron/X-ray Simulator modeling framework:

1. Build coronal magnetic field from photospheric B maps
2. Insert electron distributions
3. Compute hard X-ray and gyrosynchrotron emission that can be compared with observations.

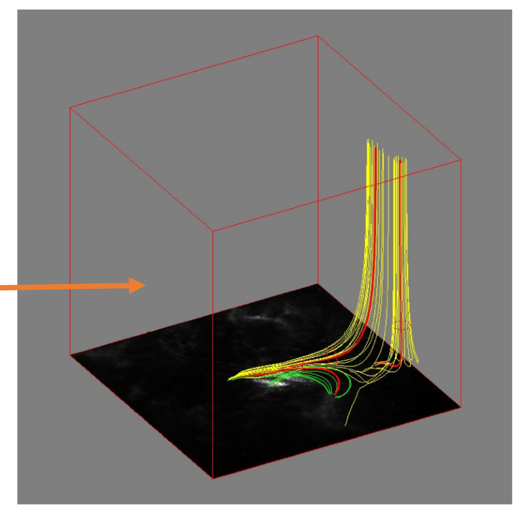
For 2002 August 19:

- Use MDI data as the constraint and perform linear force free field (LFFF) extrapolations.
- Model the **closed loops** and **open field separately**, with different values for the force-free parameter.



High-twist closed loops

Low-twist including open field



Electron distributions

We varied the spatial distribution of the nonthermal electrons in the jet, their number density, and spectral shape until we obtained a reasonable agreement with the imaging data and spectral data at low frequencies, where the jet contribution dominates the radio.

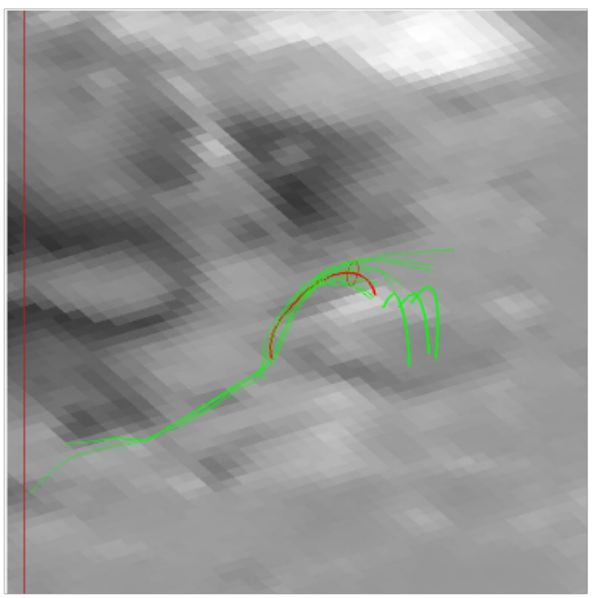
Closed flare loops:

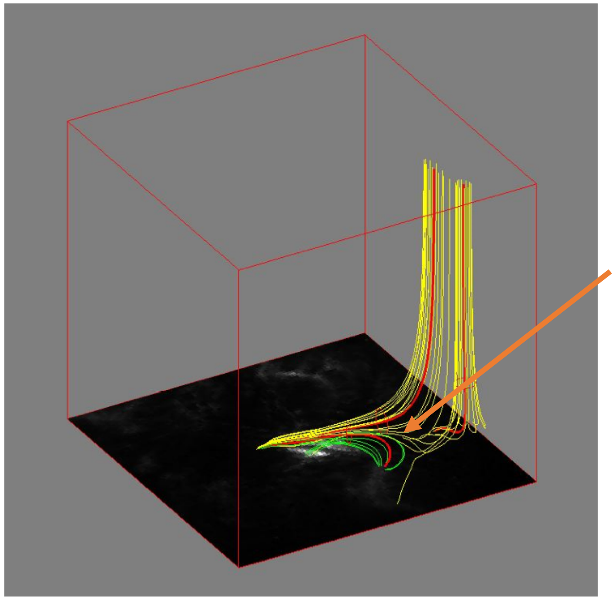
- Thermal parameters:
  - T = 20 MK
  - $n = 10^{11}$ cm^{-3}
- Nonthermal parameters:
  - Looptop density ($>E_{min}$) 2.3×10^{9} cm^{-3}
  - E_{min} = 25 keV
  - $\delta = 5$

Chosen to be consistent with RHESSI fit

Open field (jet):

- Thermal parameters:
  - T = 20 MK
  - $n = 10^{10}$ cm^{-3}
- Nonthermal parameters:
  - Looptop density ($>E_{min}$) 1.5×10^{7} cm^{-3}
  - E_{min} = 25 keV
  - $\delta = 5$

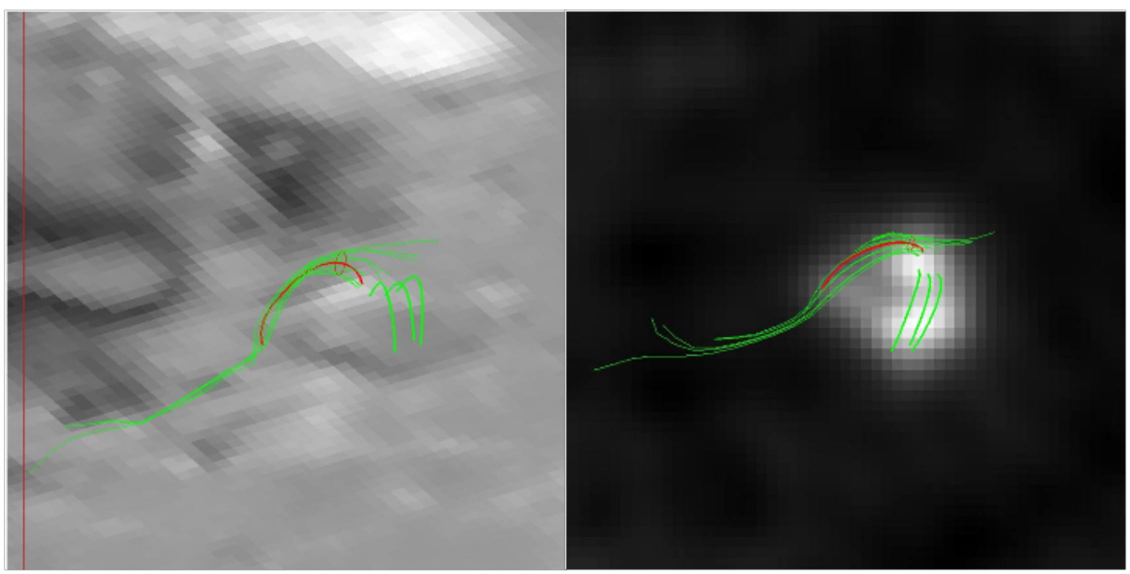


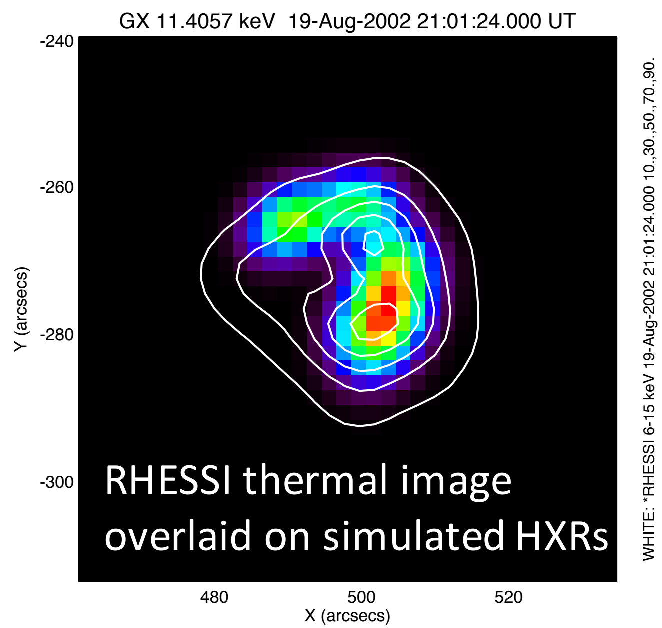


In addition, a small number of accelerated electrons are inserted in this closed loop, to match high-frequency OVSA spectrum

How do data constrain the GX Simulator electron distributions?

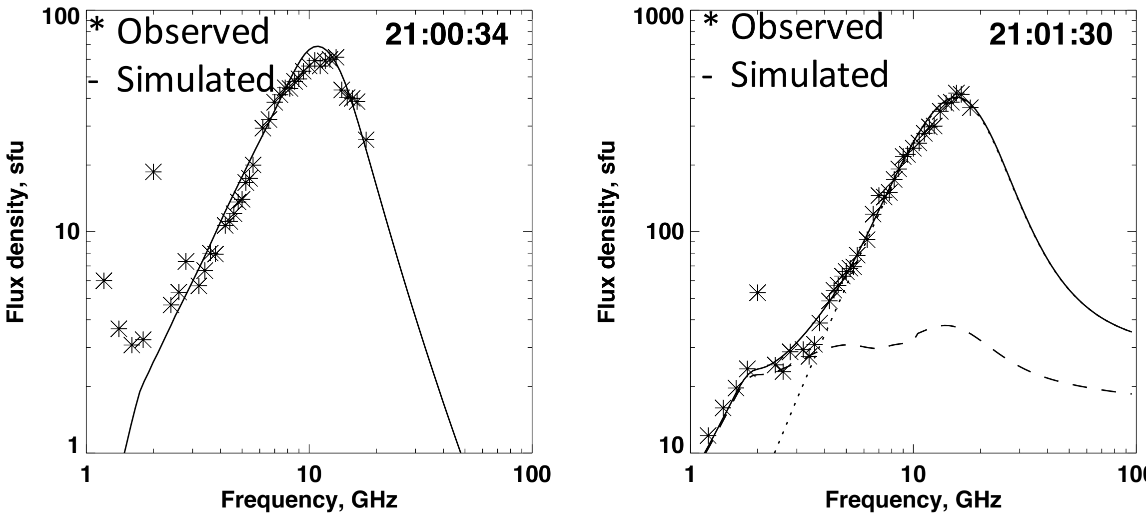
- MDI images are magnetic constraints at photospheric (LFFF extrapolation).
- For closed, twisted field, thermal and nonthermal HXR data give locations and spectra. Field and electron distributions are adjusted to match.
- **For the jet, OVSA emission must be matched in location and spectral shape, and simulated HXR emission must lie below the observed RHESSI emission.**



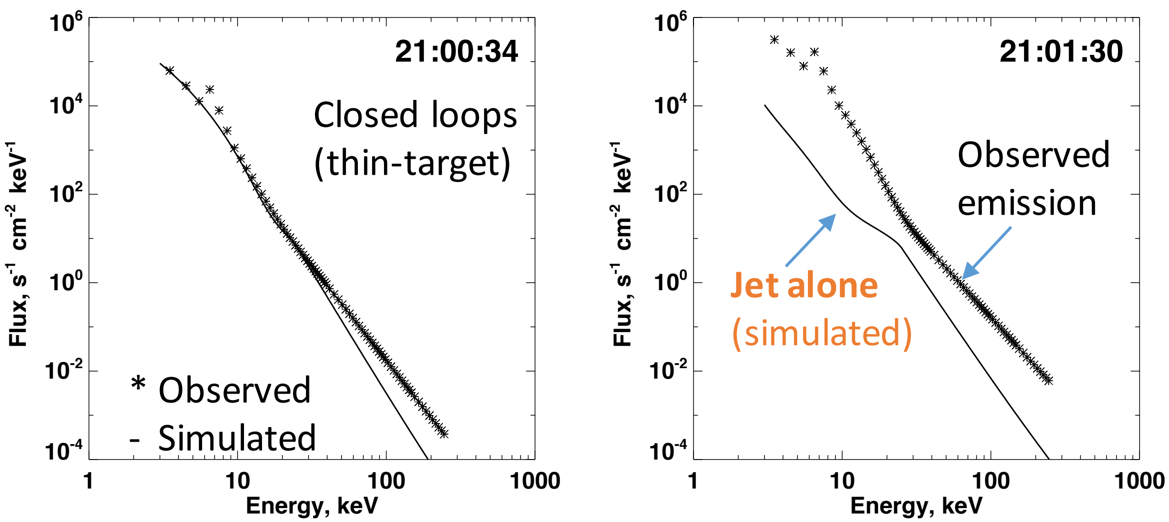


Simulated HXR and microwave emission

Simulated and observed microwave power spectra



Simulated and observed X-ray spectra



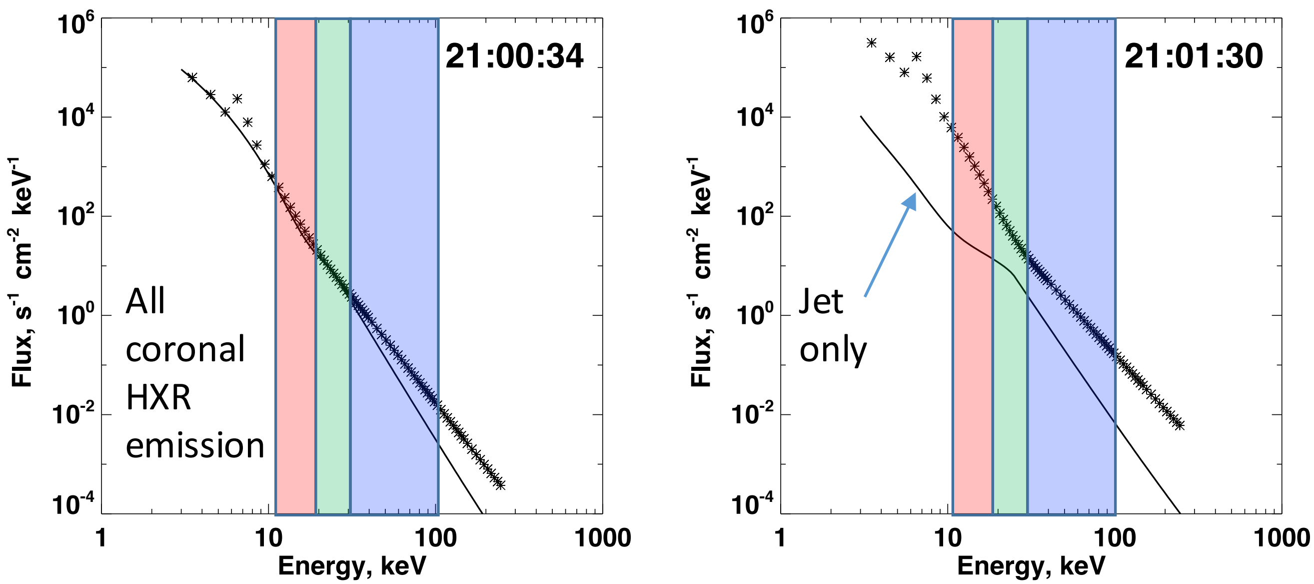
Microwaves

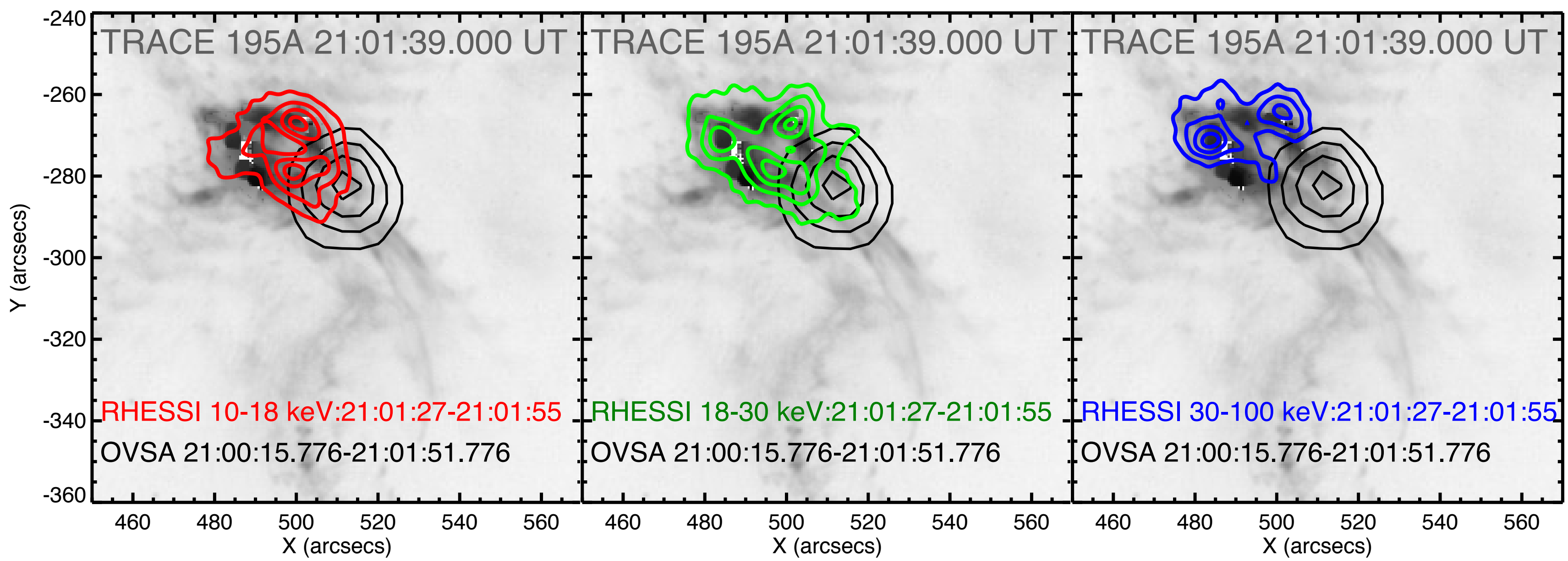
- Jet dominates at low frequencies due to weaker magnetic field (dashed line).

Hard X-rays

- Thin-target emission from closed loops matches observed HXRs for most energies.
  - Exception: Simulated emission does not include footpoints, so high energies are underestimated.
- Jet emission lies below the total observed HXR spectrum, as it must be.

Another look at the RHESSI images.

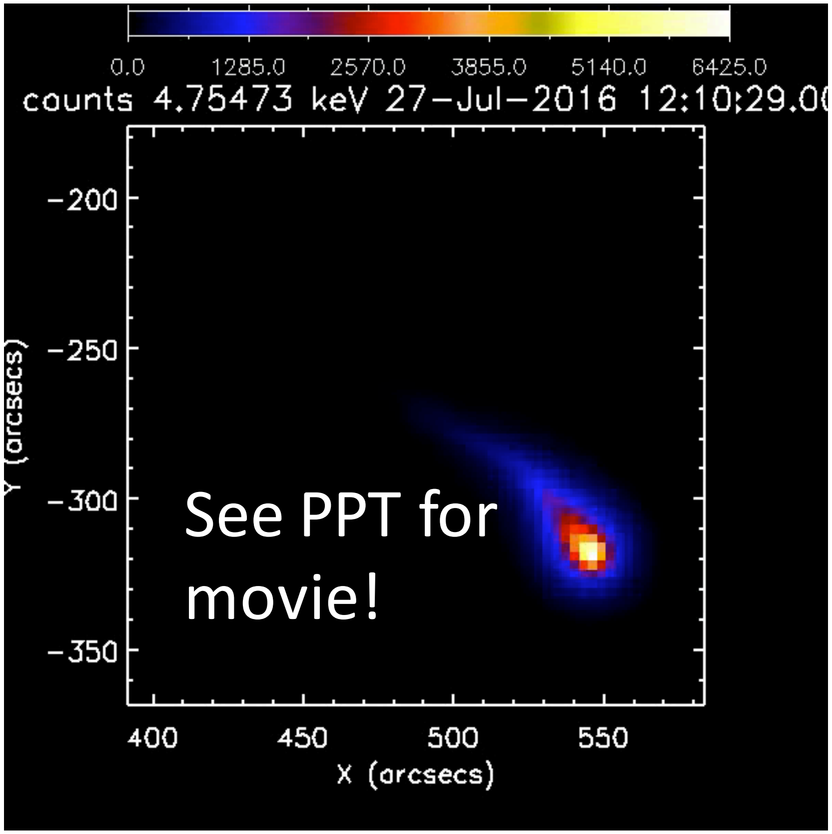




Wouldn't it be nice to have detailed HXR imaging spectroscopy of a jet like this?

- Simulated FOXSI emission using the electron population (thermal + nonthermal) from GX Simulator.

Side note: we can do this for any of your favorite X-ray sources, if you have an input (e.g. HXR image and/or spectrum)



Simulated FOXSI-SMEX observation over 30 seconds

Concluding thoughts

- The 2002 August 19 jet is a highly time-variable flare that displays evidence of energetic electrons on the open field. To our knowledge, this is the first observation of gyrosynchrotron emission from a jet.

- Best-yet *estimates* of energetic electron distribution in a jet by using constraints from HXRs and microwaves.

- The event demonstrates the complementary nature of HXR and radio data, and the usefulness of combining these data with modeling to constrain electron distributions.

- Expect more events like this with future HXRs and EOVSA!