Probing particle acceleration and transport through behind-the-limb gamma-ray Solar flare observations

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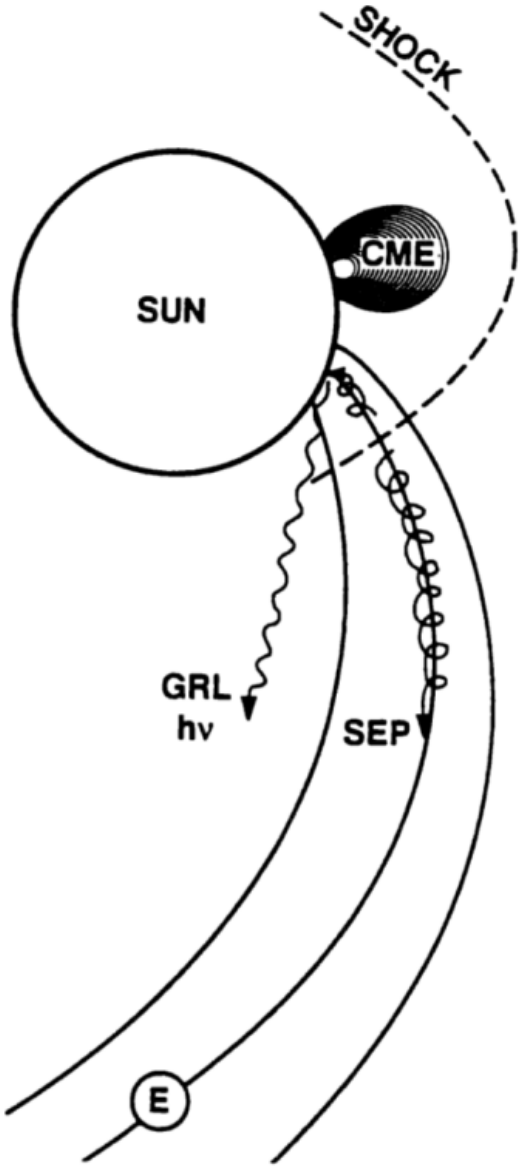
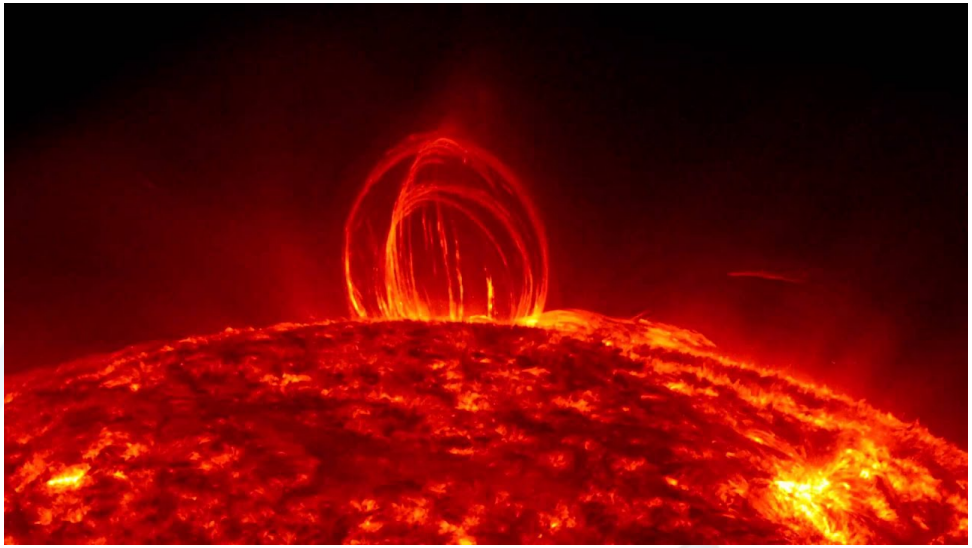
on behalf of the *Fermi*-LAT collaboration

ESPM-17

Behind-the-limb gamma-ray flares



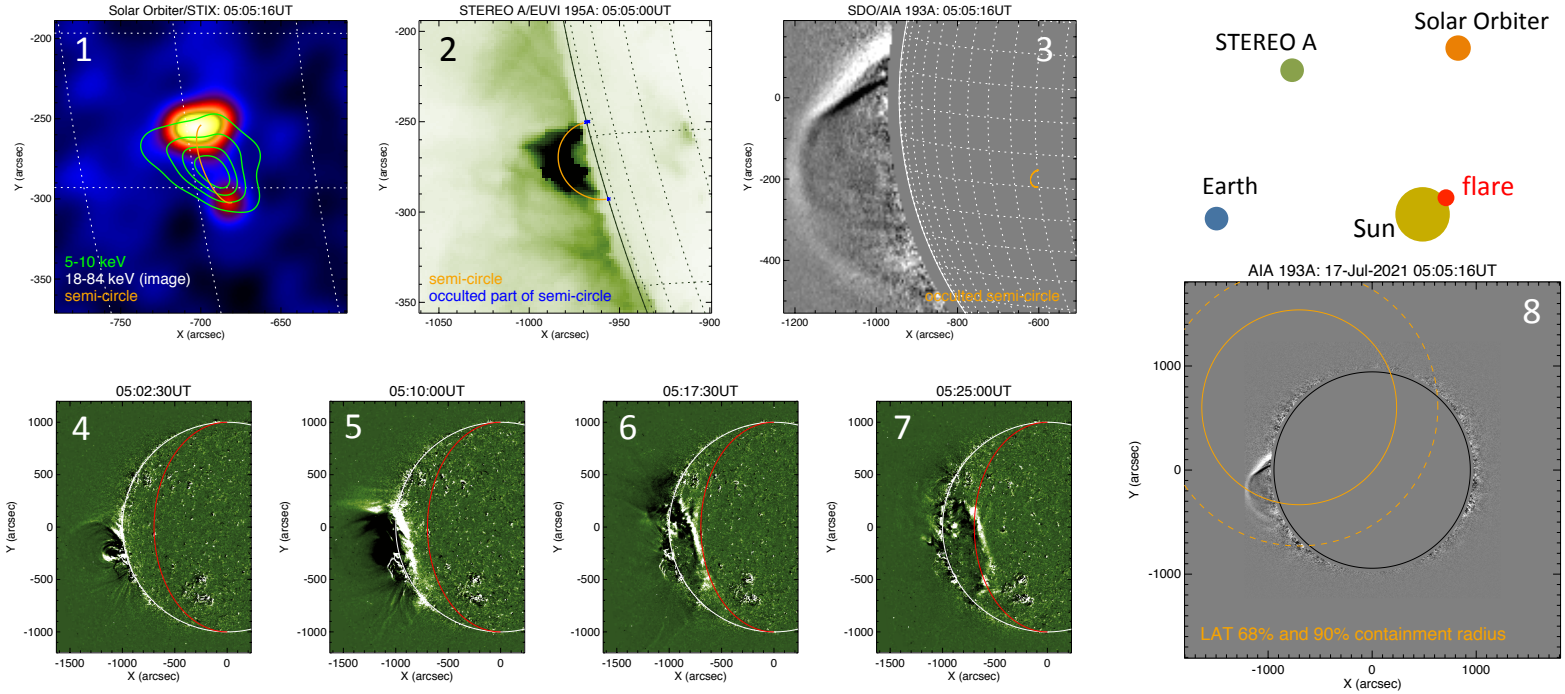
Cliver et al. 1993



- Gamma-ray BTL flares pose interesting questions regarding the acceleration mechanisms at work and the transport of the accelerated particles
- Two main scenarios have been proposed:
  - CME-driven shock (with back precipitation)
  - Trapping of flare-accelerated ions in extended coronal loops
- Observational evidence supporting both scenarios

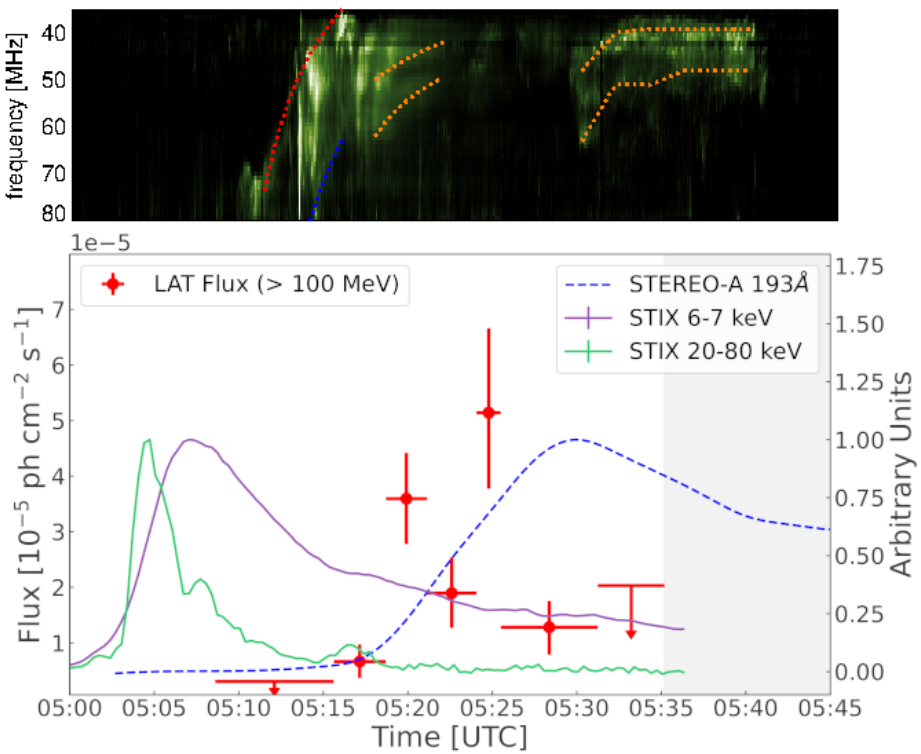
The BTL flare of July 17, 2021

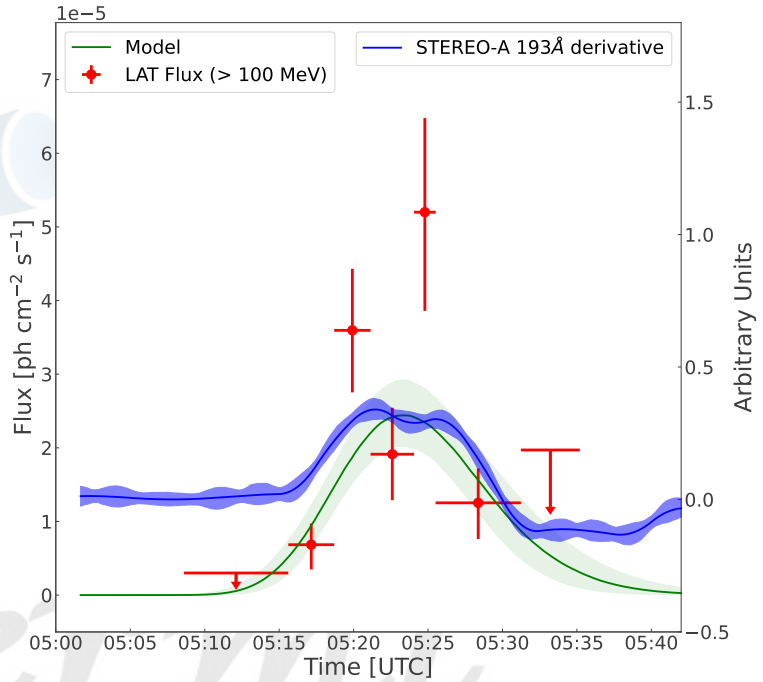
Pesce-Rollins et al. 2022 ApJ 929 172



- Thanks to STIX we were able to localize position of the active region to be 50° behind the visible limb
- Flare detected Fermi-LAT with a significance $>15\sigma$
  - The most distant behind-the-limb flare ever observed in gamma-rays!
- Combined observations with STEREO and SDO indicate that the onset of coronal wave coincides with LAT onset on visible limb

Relation between Coronal wave and LAT flux





Pesce-Rollins et al. 2022 ApJ 929 172

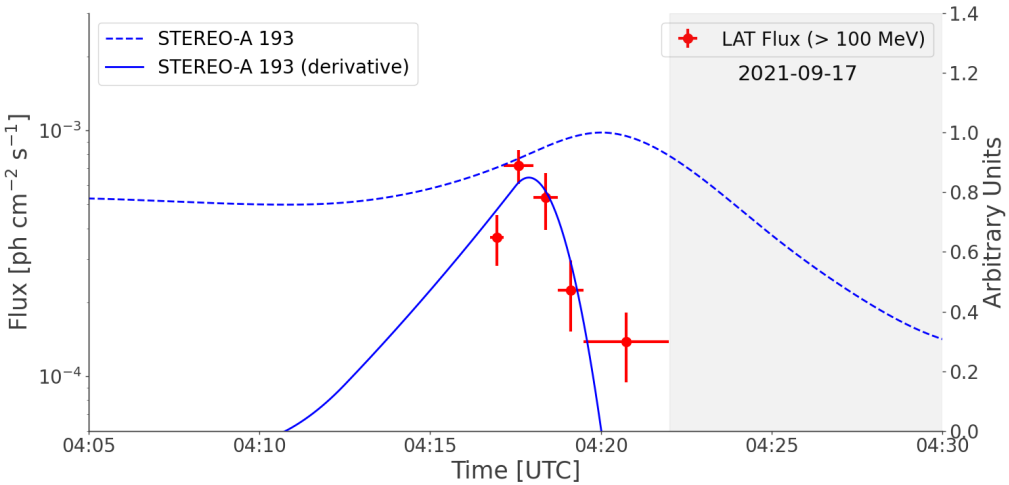
- Radio spectrum from the Gauribidanur Low-Frequency Solar Spectrograph showing Type II radio burst
- The time derivative of the coronal wave light curve peaks at the same time as the LAT flux
  - Probing the rate of particles precipitating to the visible disk
  - Accelerated protons are coupled with the coronal wave

Correlation also in other BTL flares

Gamma-ray behind-the-limb flares

Flare	LAT peak flux time (UT)	EUV peak time (UT)
FLSF 2013-10-11	07:19 ± 1 minute	07:16
FLSF 2014-09-01	11:11 ± 1 minute	11:14
FLSF 2021-07-17	05:23 ± 1 minute	05:21
FLSF 2021-09-17	04:17 ±0.5 minute	04:17

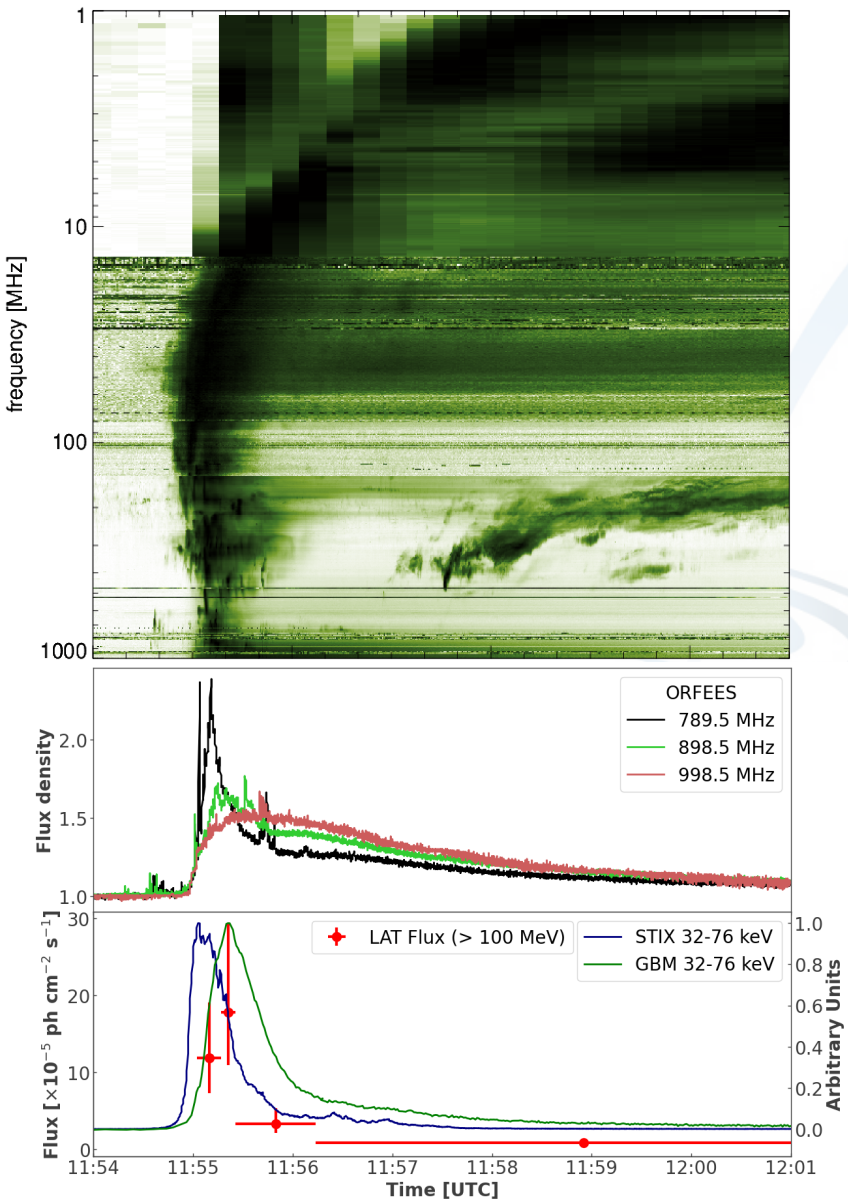
Pesce-Rollins et al. 2022 ApJ 929 172



- At the time of the study, a total of 5 BTL flares had been detected by the LAT
- Analyzed EUV coronal wave data for these flares and found same correlation to be present in four of the flares
  - Flare of 2014-01-06 was lacking gamma-ray statistics to perform the study

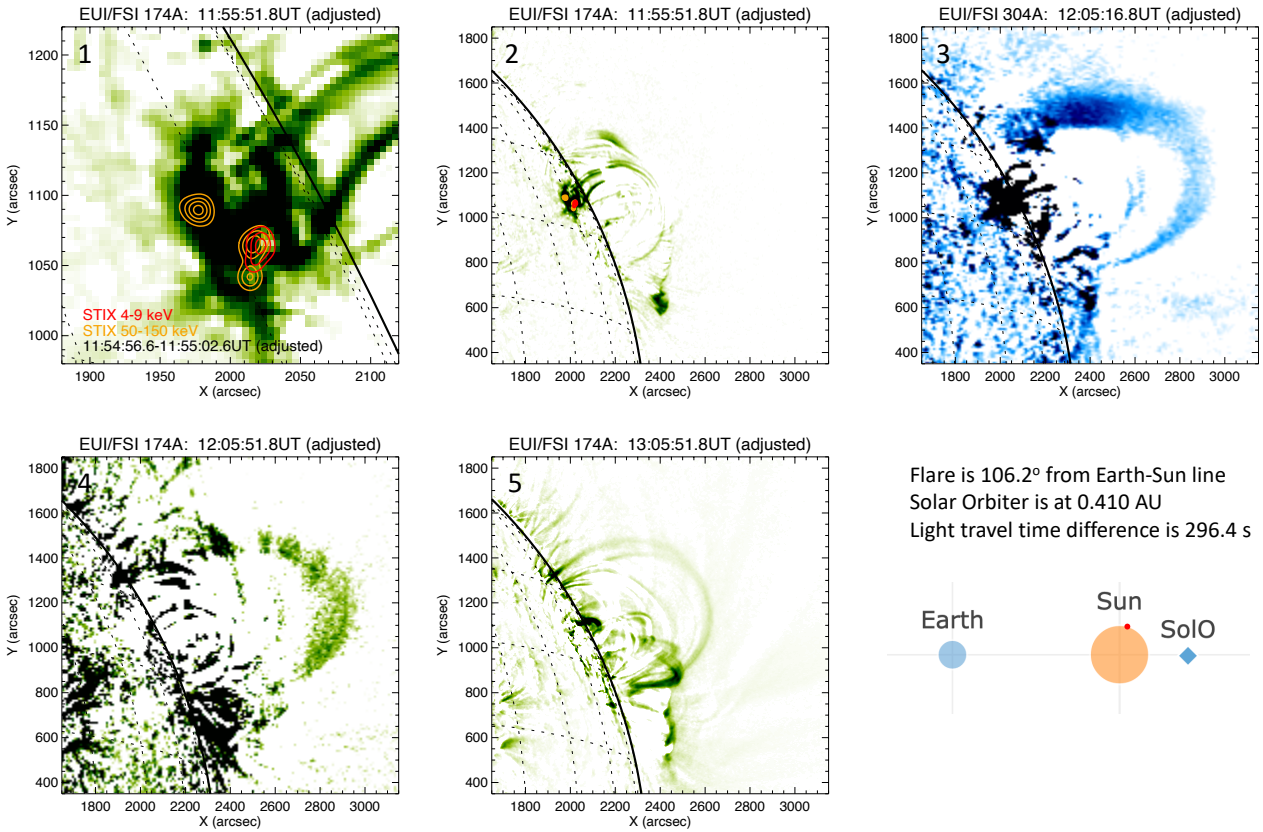
- CME-shock acceleration is most likely the driving mechanism for the γ-rays observed in these four behind-the-limb flares observed by the LAT

Time profiles of the September 29, 2022 flare



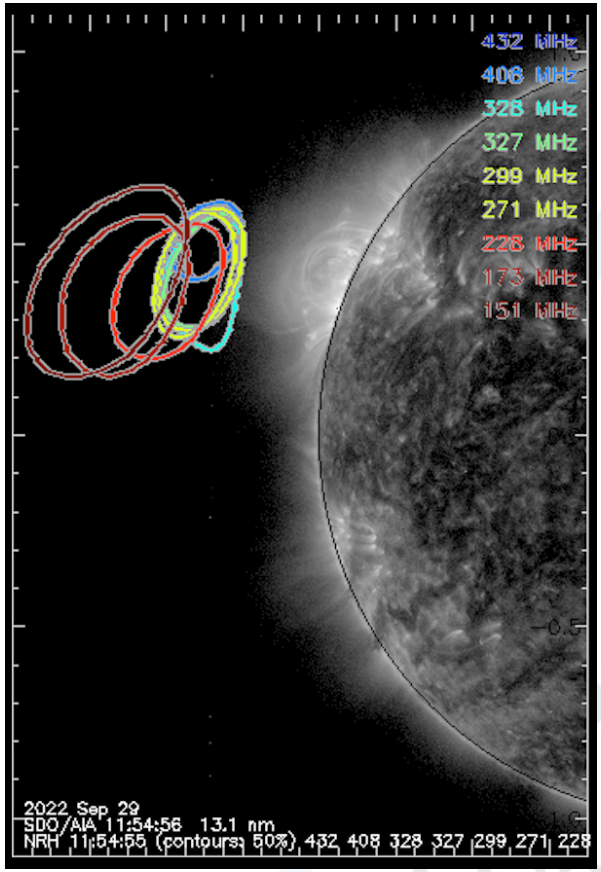
- From top to bottom:
  - Combined dynamic radio spectrum
  - ORFEES normalized flux density in three frequencies
  - >100 MeV flux points, normalized STIX and GBM time profiles in 32-76 keV
- There is a type II burst during the decay phase of the LAT emission, not the source of the ion acceleration
- from 11:55 a complex group of fast-drifting bursts are also visible, with type III bursts
- LAT time profile peaks together with GBM and is impulsive-like
  - Unlike the other BTL flares observed by LAT

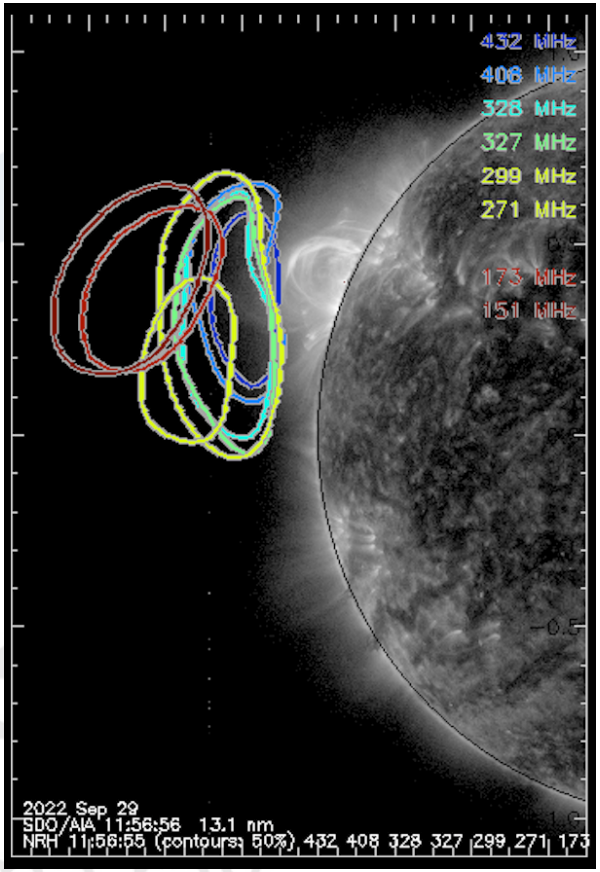
Imaging from STIX and EUI/FSI



- STIX thermal (red) and nonthermal (orange) sources overlaid on the 174 Å EUI/FSI image at 11:55:51 UT
- Insert gives the position of Solar Orbiter and Earth relative to the flare site. Active region 16° behind the eastern visible limb
- Large loops still present even at 13:05 UT

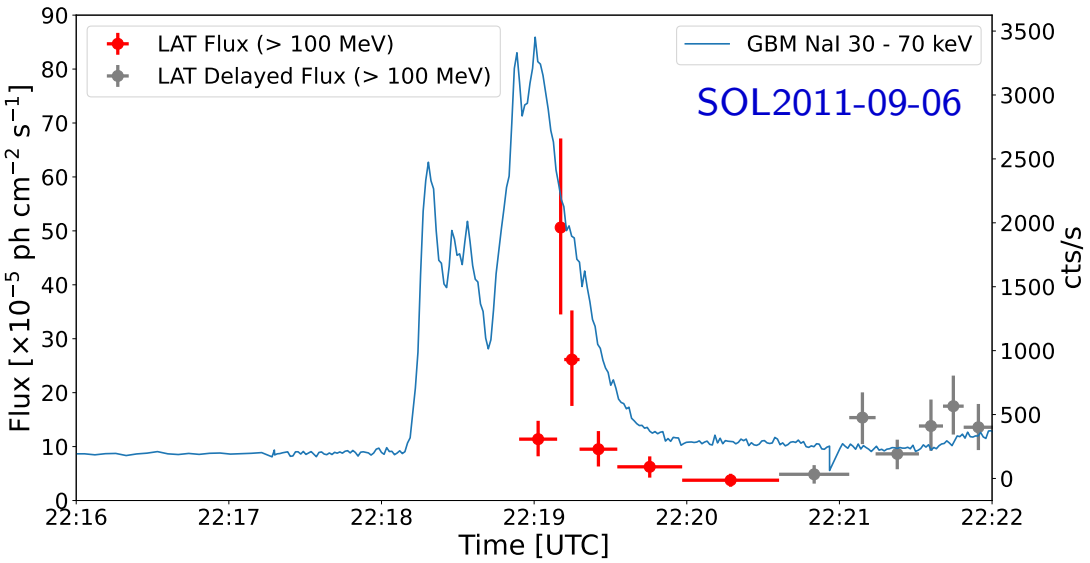
EUV and Radio imaging during the flare





- SDO AIA 131 Å images of the Sun during the flaring activity
- Loops seen up to 120 Mm above the solar limb
- Radio geometry is consistent with a loop structure that connects the parent active region behind the limb to the disk

Comparison with other BTL/On-Disk flares



- Compared basic gamma-ray properties of this event with the impulsive on disk flare SOL2011-09-06
- The flare of September 29, 2022 is remarkably similar to the on disk flare
- Data indicates that >100 MeV emission originates from particles accelerated in large loops

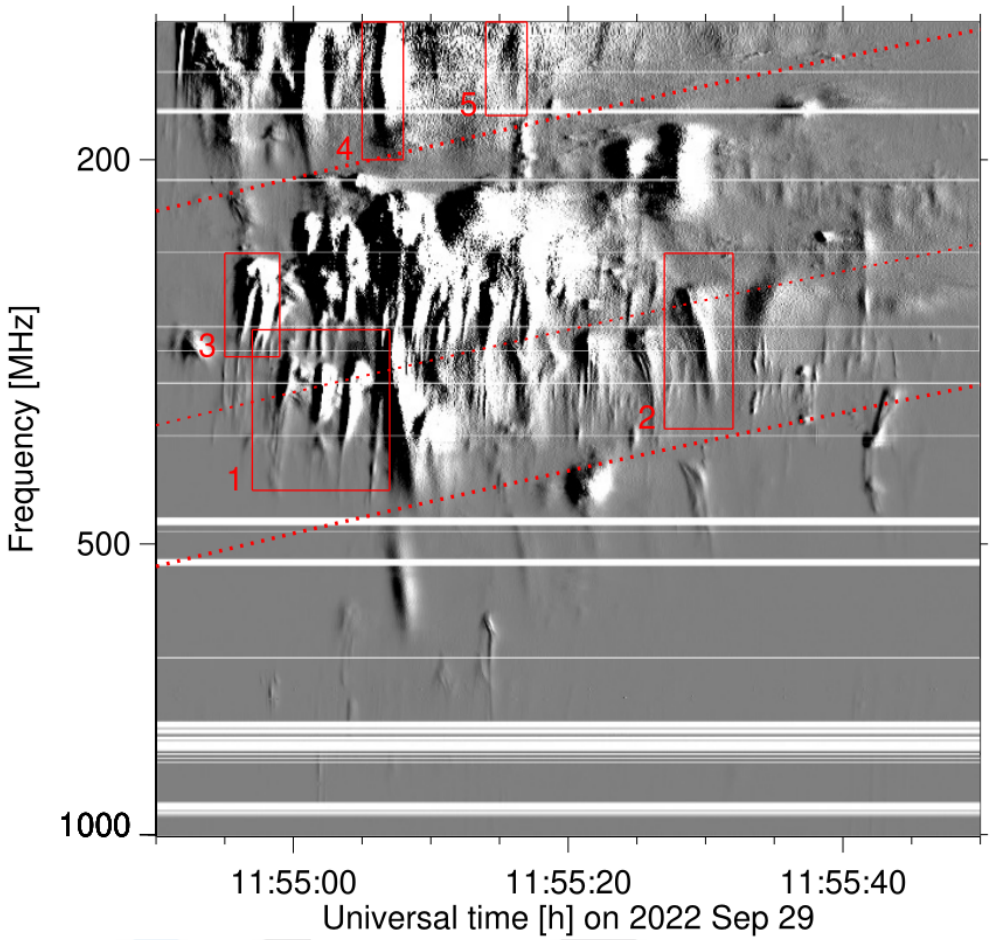
Flare	Rise time (min:sec)	ΔPeak (sec)	Peak Flux (10^{-5} ph cm^{-2} s^{-1})	AR
2013-10-11	9:00 ±1:00	600 ± 60	49±2	N21E103
2014-09-01	9:00 ±1:00	240 ± 60	565±21	N14E126
2021-07-17	8:00 ±1:00	-	4±1	S20E140
2021-09-17	1:09 ±0:07	180 ± 60	67±20	S30E100
2022-09-29	0:18 ± 0:04	5 ± 4	44±14	N26E106
2011-09-06	0:16 ± 0:01	10 ± 1	50±16	N14W18

Summary

- The coupling between the coronal waves and the ion acceleration in four behind-the-limb gamma-ray solar flares provides supporting evidence for the shock wave scenario
- The flare of September 29, 2022 is the first case where there is observational evidence for ion acceleration in large loops for a gamma-ray behind-the-limb solar flare
- It appears that there are more ways than one to produce the gamma-ray emission in behind-the-limb flares :-)
  - This could be the case also for the long duration gamma-ray flares

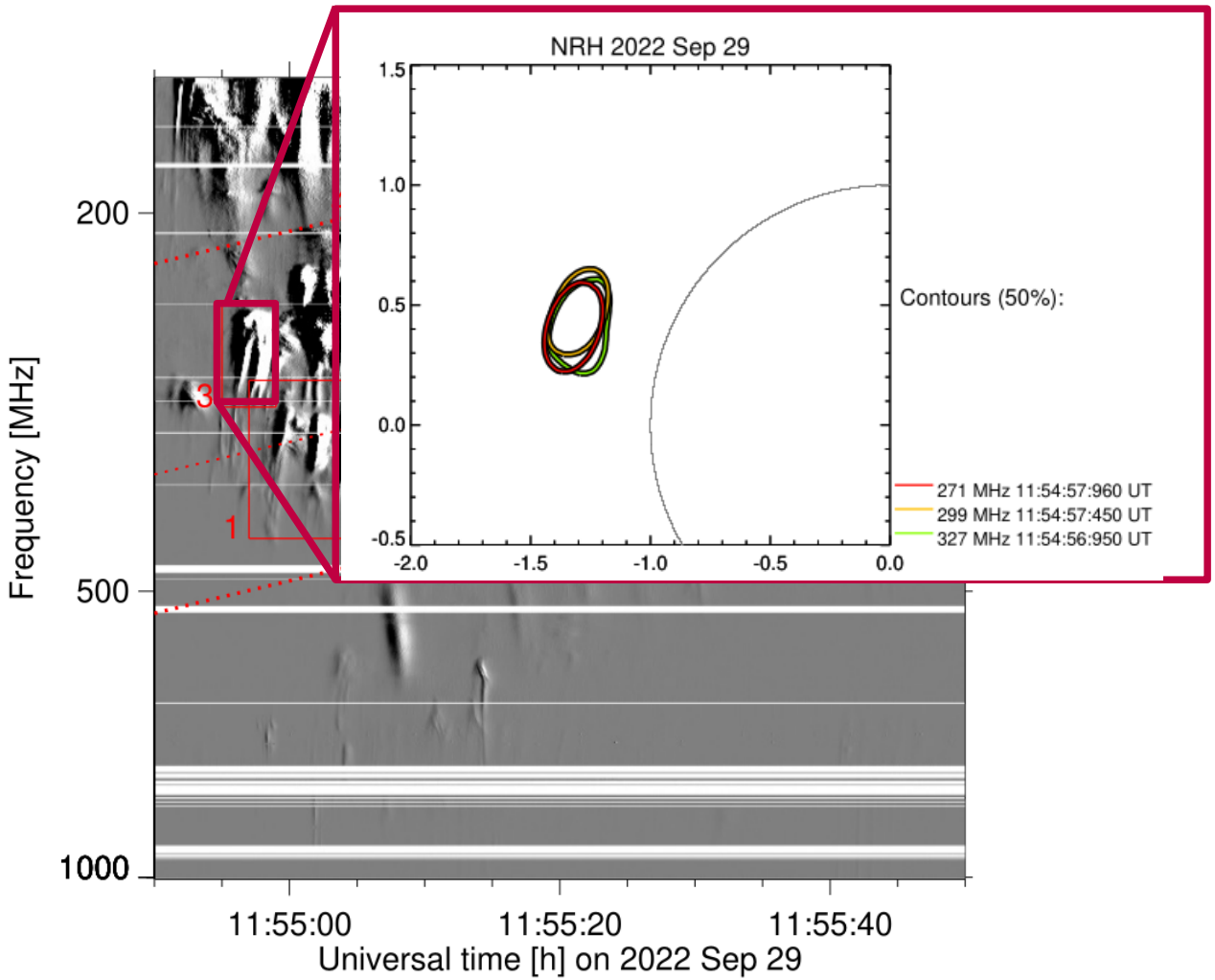
Spare slides

Radio spectral imaging



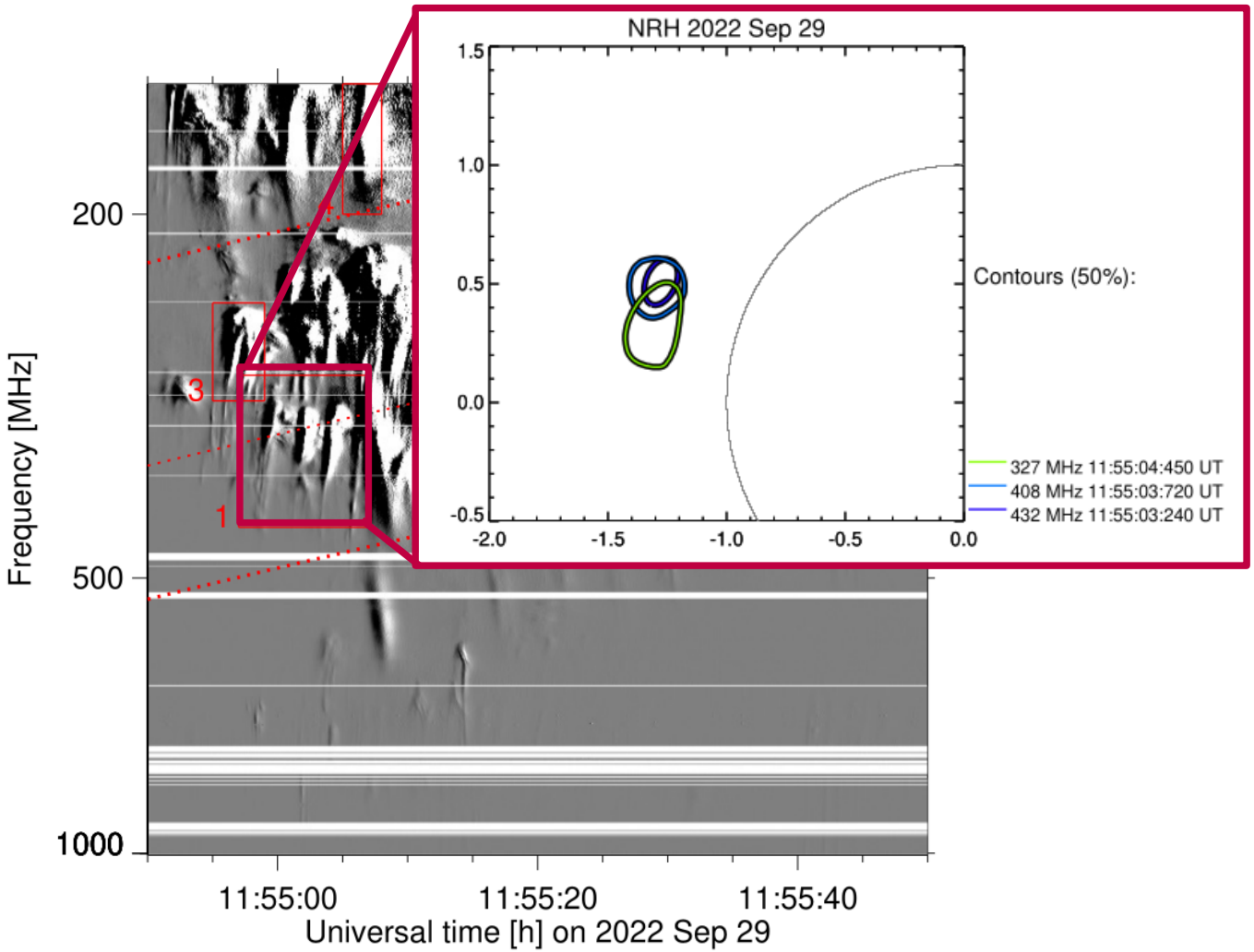
- Time-differenced ORFEES dynamic spectrum
- Strong bursts accompany the microwave emission and the HXR burst observed by GBM
- Overall the bursts cluster in four slowly-drifting chains

Radio spectral imaging



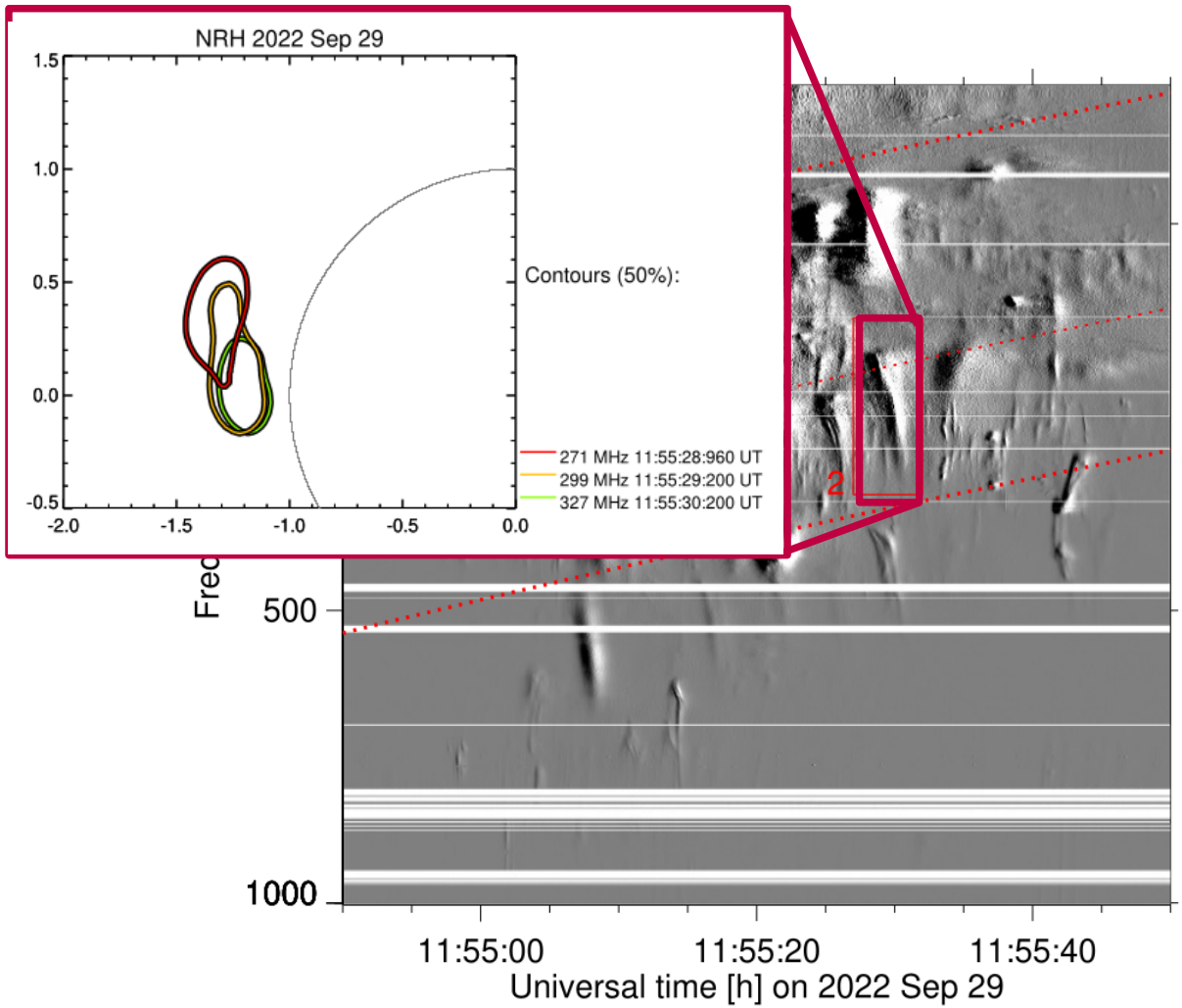
- At 11:54:57 UT: the sources at different frequencies appear superposed
- Magnetic field lines that guide the electron beams are parallel to the line of sight

Radio spectral imaging



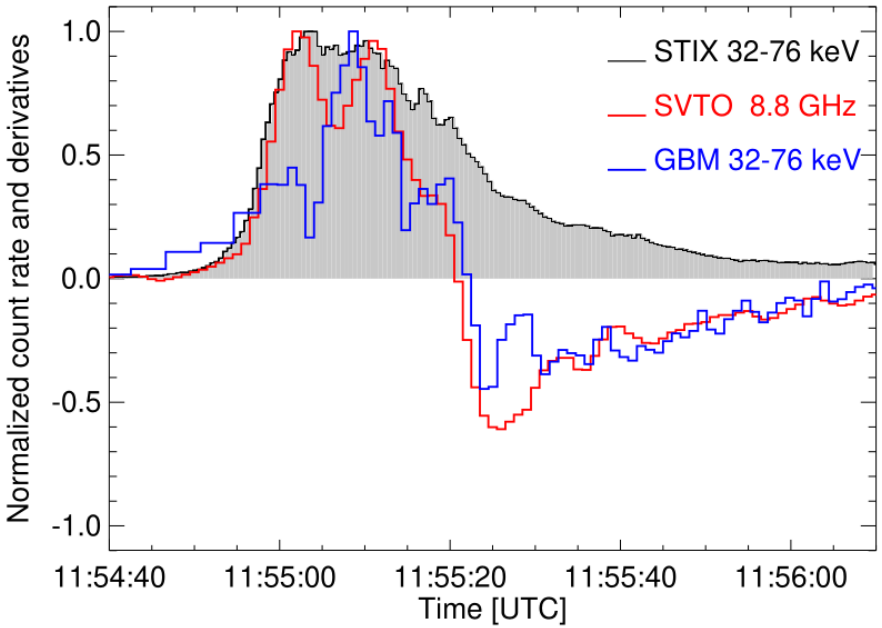
- At 11:55:04 UT: the southward location of the lower frequency source is a projection effect
- Parent magnetic structure connecting the AR to the visible disk

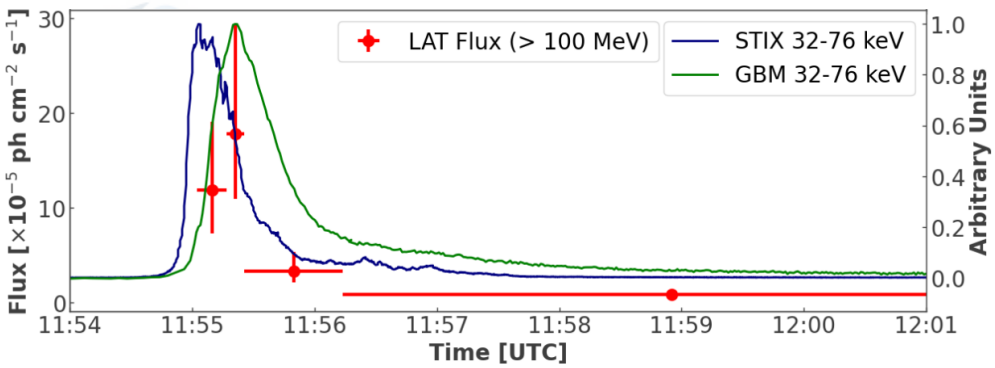
Radio spectral imaging



- At 11:56:28 UT: high-frequency source is now south-westward of the low-frequency sources
- Positively-drifting burst is observed in the Earth-ward leg of the structure

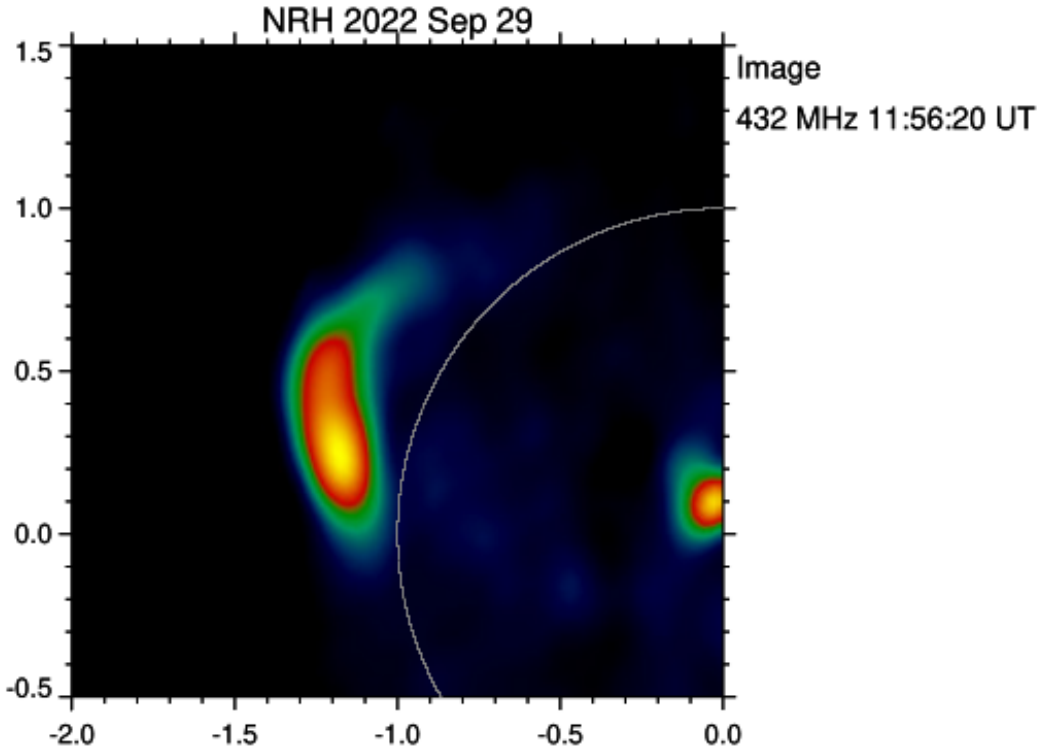
Connection between BTL and on-disk HXR emission





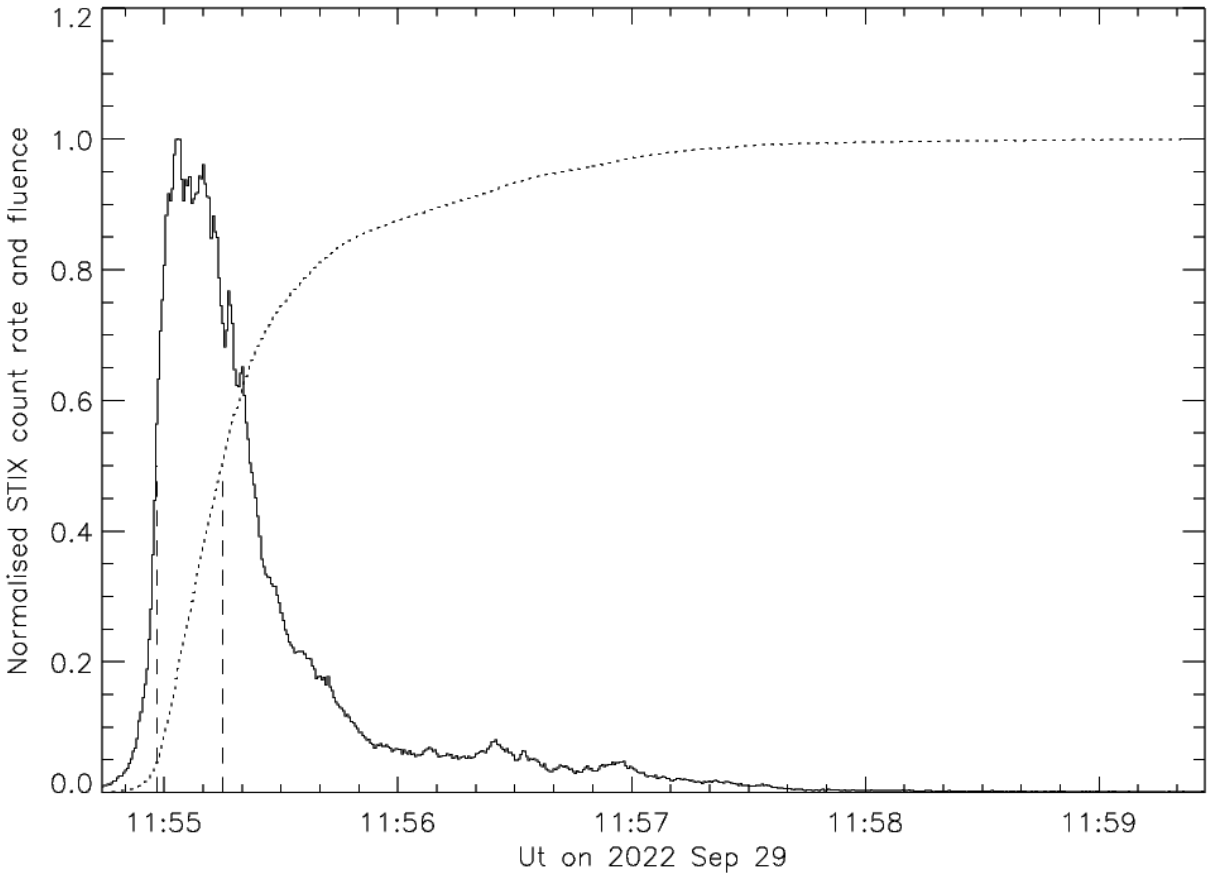
- STIX time profile is bursty whereas GBM is smooth
- Time derivative of the GBM and microwaves to emphasize the changes
- Three distinct components of the STIX profile have counterparts in the derivative curves
- Suggesting emission seen by STIX and from Earth come from same processes of acceleration
  - Electron energy release signatures smeared out by trapping in large loops

NRH maps



- Continuum source at 432 MHz time integrated over 11:56:20 - 11:56:50 UT
- Fluctuations from the residual weak burst and sidelobes of the noise storm near disk center have been filtered out

Time delay and trapping



- Assuming that the STIX time profile represents the injection function
- The integrated count rate (dotted line), taken to be a proxy of the number of electrons in the trap
- The two vertical dashed lines mark the times when the count rate and the integrated count rate reach half their maximum level