Radio and X-Ray Quasi-Periodic Pulsations during the Impulsive Phase of a Confined Solar Flare

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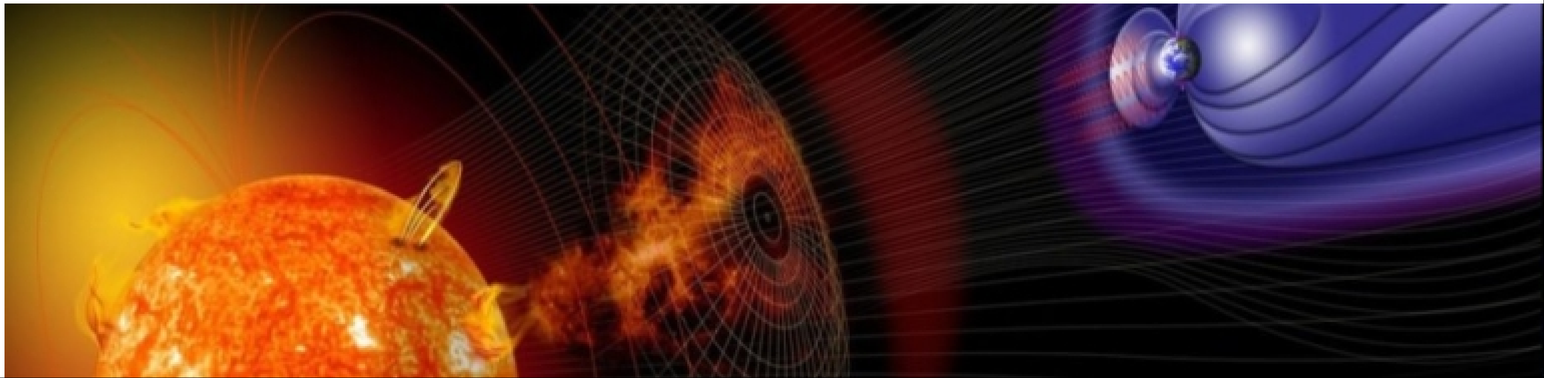
RHESSI-20 Workshop

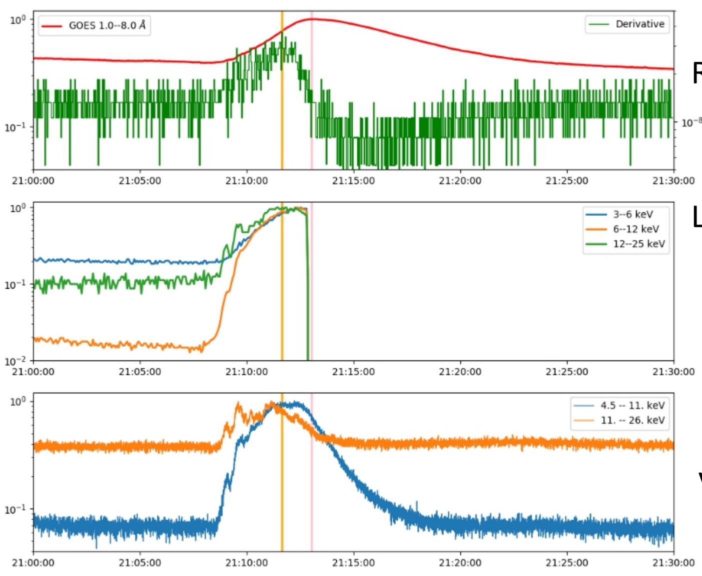
NJIT
New Jersey Institute of Technology



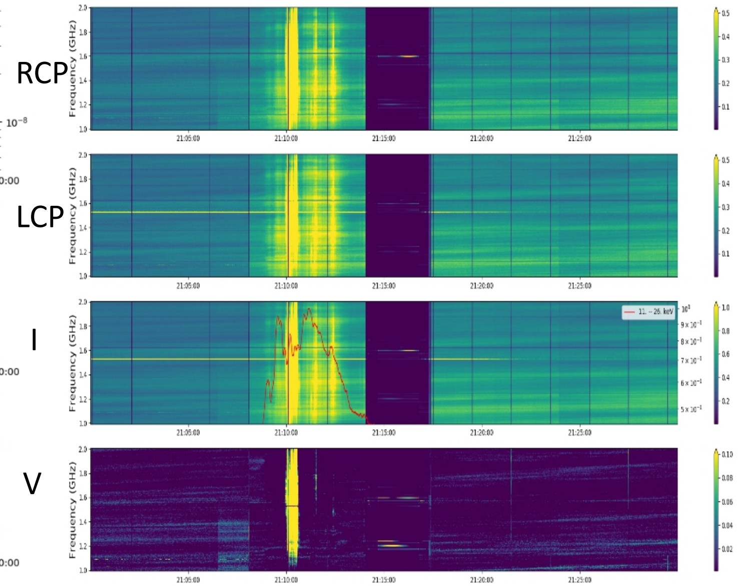
Radio and X-Ray Quasi-Periodic Pulsations during the Impulsive Phase of a Confined Solar Flare

Observations: Combined radio and X-rays QPPs.

X-Ray: Goes; RHESSI; Fermi/GBM



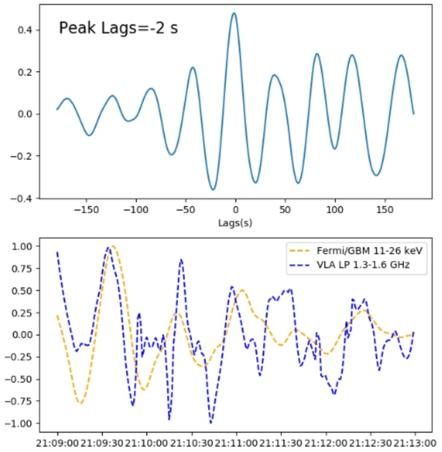
Radio: VLA



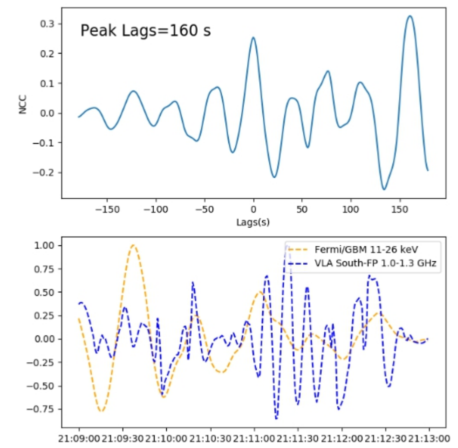
	Peak Intensity	Polarization	Period	Bandwidth	Duration
Strong QPP (I)	Can reach 20 MK	Mostly RCP, typically DOP 40 - 50%, up to 80%	~ 6s	Nearly full bands	~ 20 seconds after the looptop sources, lasts ~ 50 seconds, some weak following pulsations are also detected.
Northern Footpoint (II)	~ 4 MK	RCP	~ 29 - 43 s	1.2 – 1.8 GHz	Similar to the looptop source (IV).
Southern Footpoint (III)	~ 2 MK	LCP	~ 27 - 46 s	< 1.5 GHz	Similar to the looptop source (IV).
Looptop (IV)	~ 3 MK	Weakly Polarized	~ 25 ~ 45 s	1.1 – 1.6 GHz	First detected, lasts over 3 minutes

Cross-Correlation between Radio and X-Ray QPPs: The X-ray QPPs are better correlated with the looptop radio emissions.

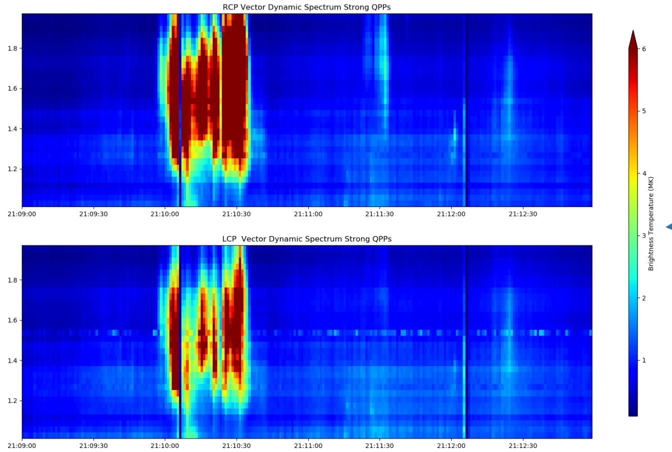
(NCC ~0.48)

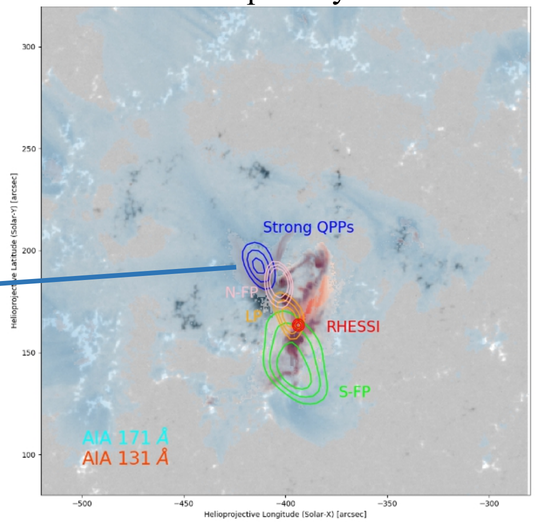


(NCC ~0.32)



VLA Imaging Spectroscopy: The radio QPPs consist of four spatially distinct radio sources with different periodicities.





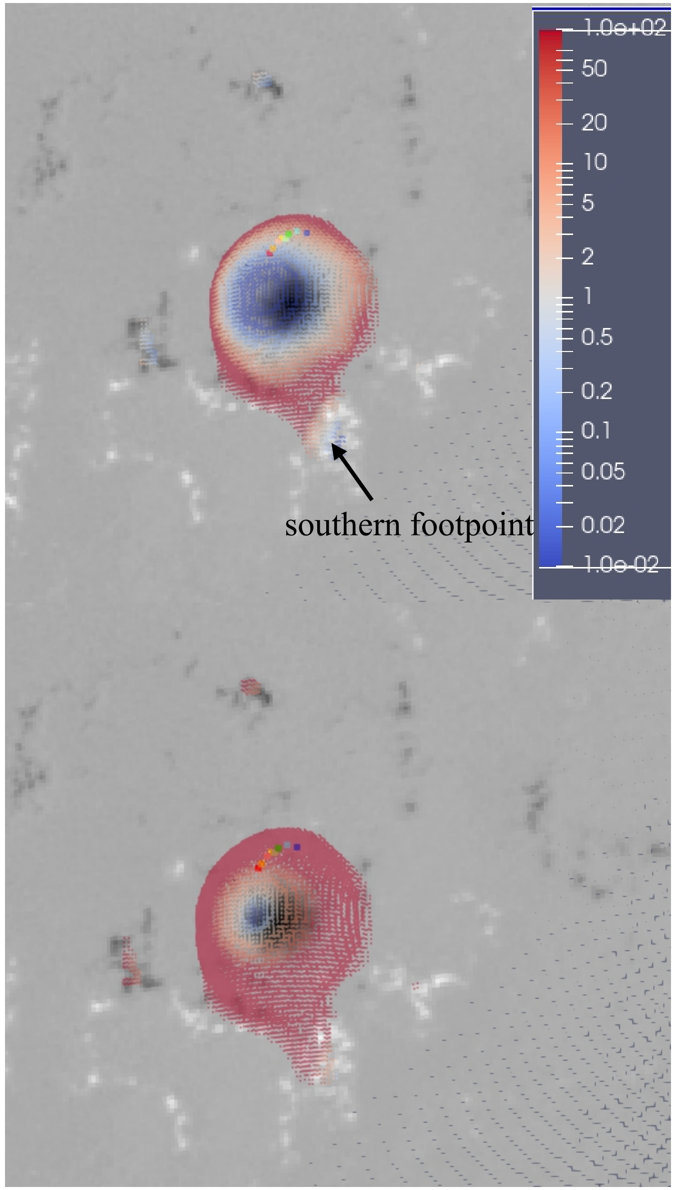
Overview Page

Emission Mechanisms of QPPs: We suggest second harmonic ECME as a probable mechanism for producing strong QPPs and its conjugate footpoint sources.

O-mode (corresponding to RCP at strong QPP), along the LOS

The O-mode (RCP) is easier to escape through the 'hole' compared to the X-mode (LCP) at strong QPPs.

X-mode (corresponding to LCP at strong QPP)



O-mode (corresponding to LCP at southern footpoint).

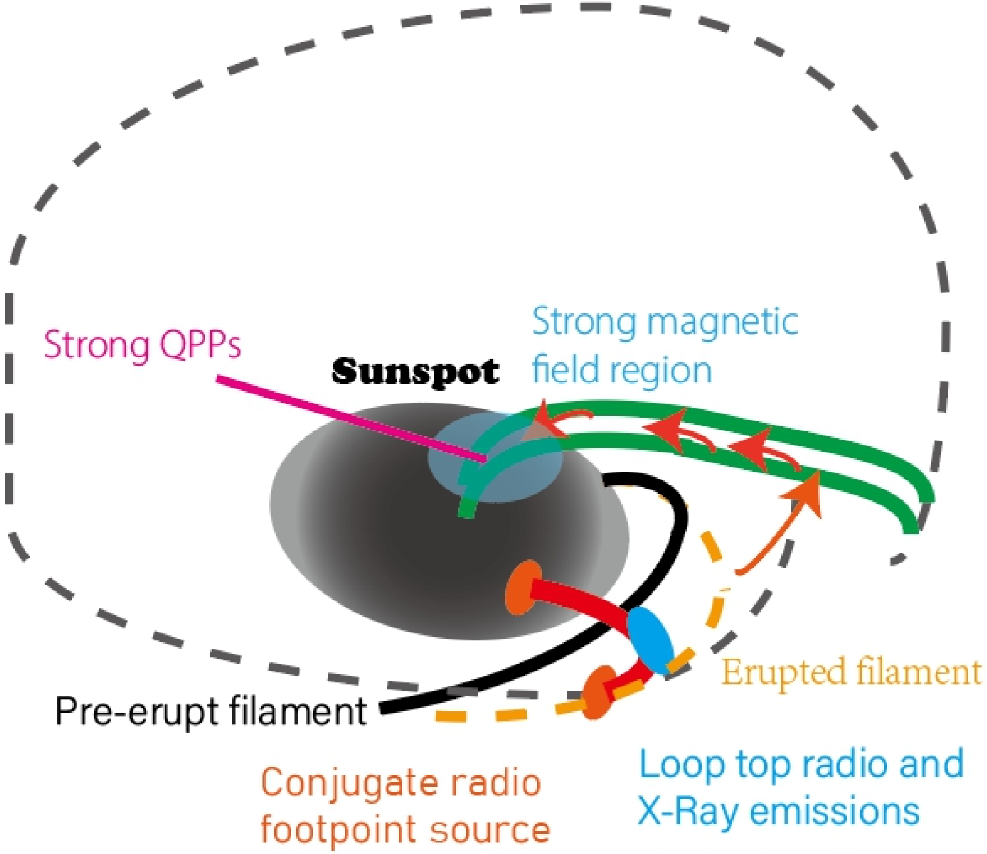
The O-mode (LCP) is easier to escape through the 'hole' compared to the X-mode (LCP) at southern footpoint.

X-mode (corresponding to RCP at southern footpoint).

Optical depth at third harmonic gyroresonance layer

Future Work:

- Other probable mechanisms: Plasma radiation, inhomogeneous gyrosynchrotron emissions, etc.
- The modulation mechanism of QPPs: Periodic reconnection, MHD oscillations.
- The energy transport processes connecting the different sources.



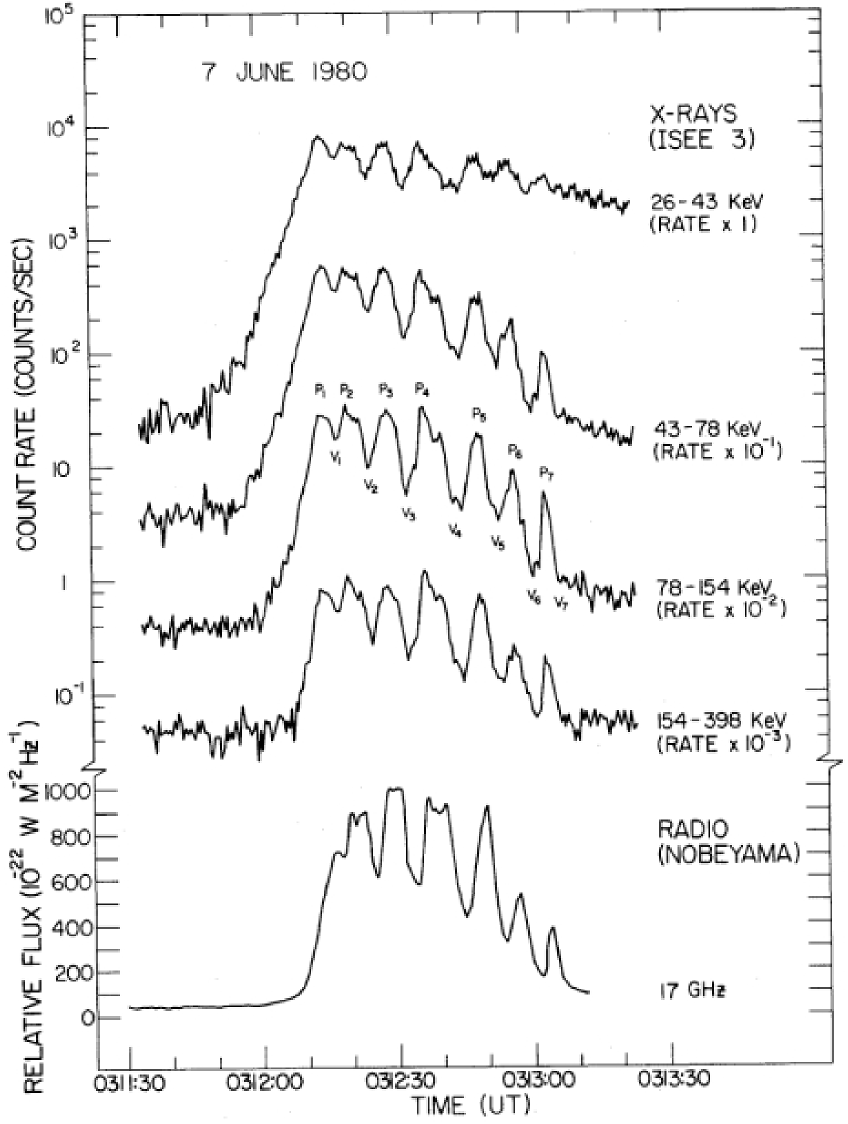
Quasi-Periodic Pulsations (QPPs)

Periodic variations in flux, ubiquitous during solar flares

Flare-associated QPPs:

- Observed in nearly all wavelengths, from radio to γ-ray.
- Periods range from sub-seconds to several minutes.
- Can occur in nearly all phases during the flares.

Significance:
Contributes to understanding modulations of the flare energy release, loop oscillations, or emission processes.



Kane et al. (1983)

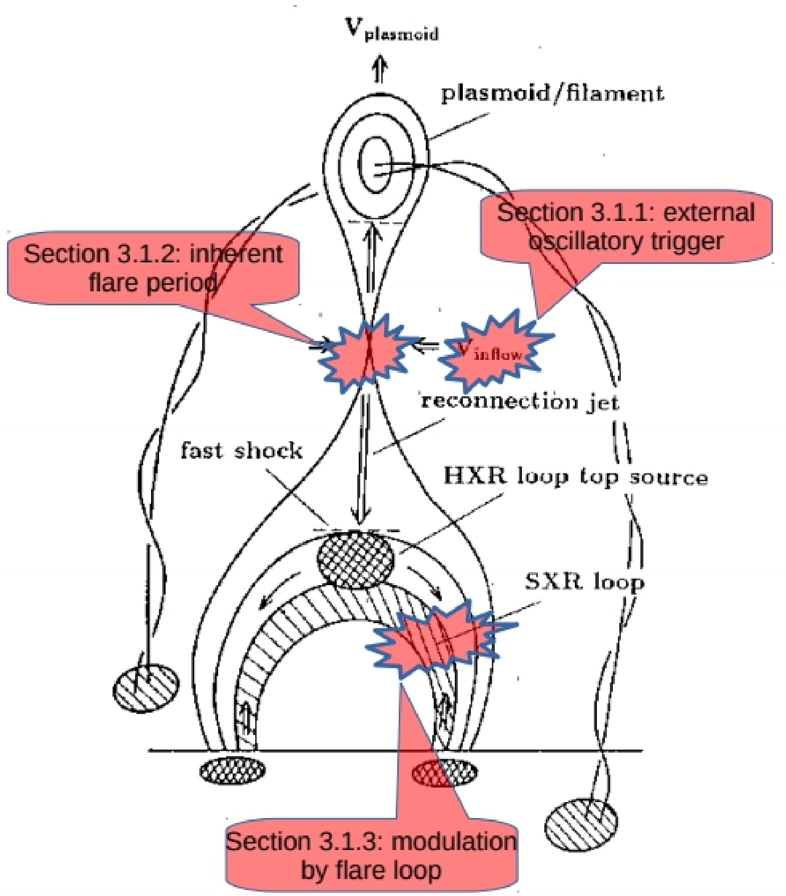
Quasi-Periodic Pulsations (QPPs)

Possible Scenarios:

- External oscillatory trigger.
- Periods related to the flare itself.
- MHD oscillations in flare loop system.

Combined radio and X-ray observations have been proved to be a good diagnose methods for QPP (Asai et al. 2001; Grechnev et al. 2003; Inglis et. al 2009; Huang et al. 2014;).

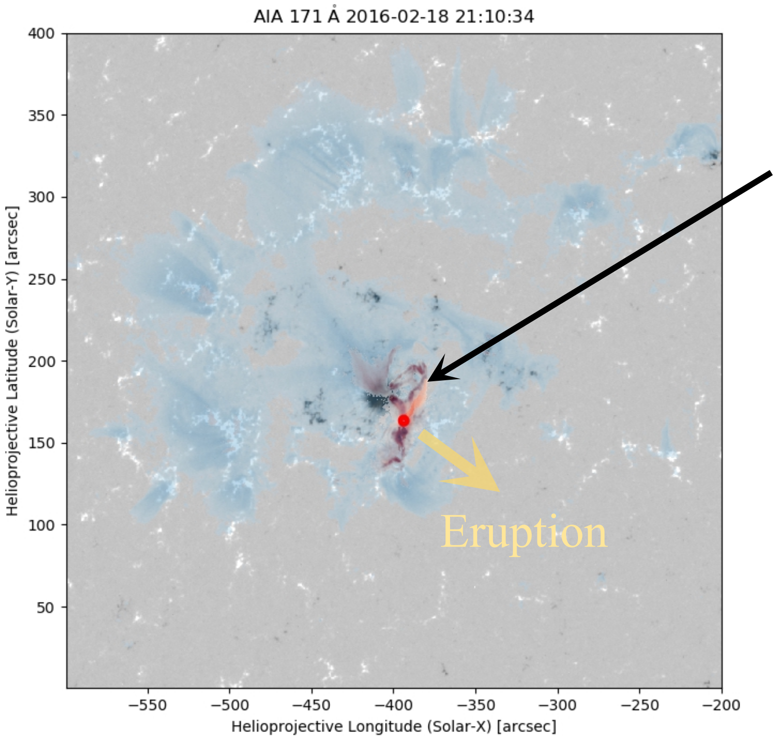
Here we report radio and X-Ray QPPs during the impulsive phase of a C-1.8 flare with the high-resolution spatial and temporal information.



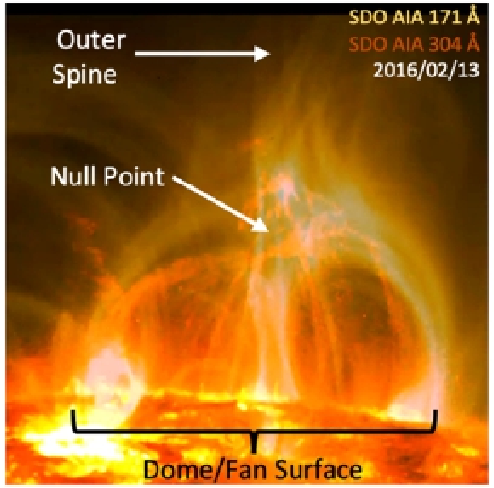
Van Doorsselaere et al. 2016, flare model cartoon takes from Shibata et al. (1995)

Event Overview

QPPs occur during the impulsive phase of a short duration C1.8 flare. RHESSI partly covers the impulsive phase.

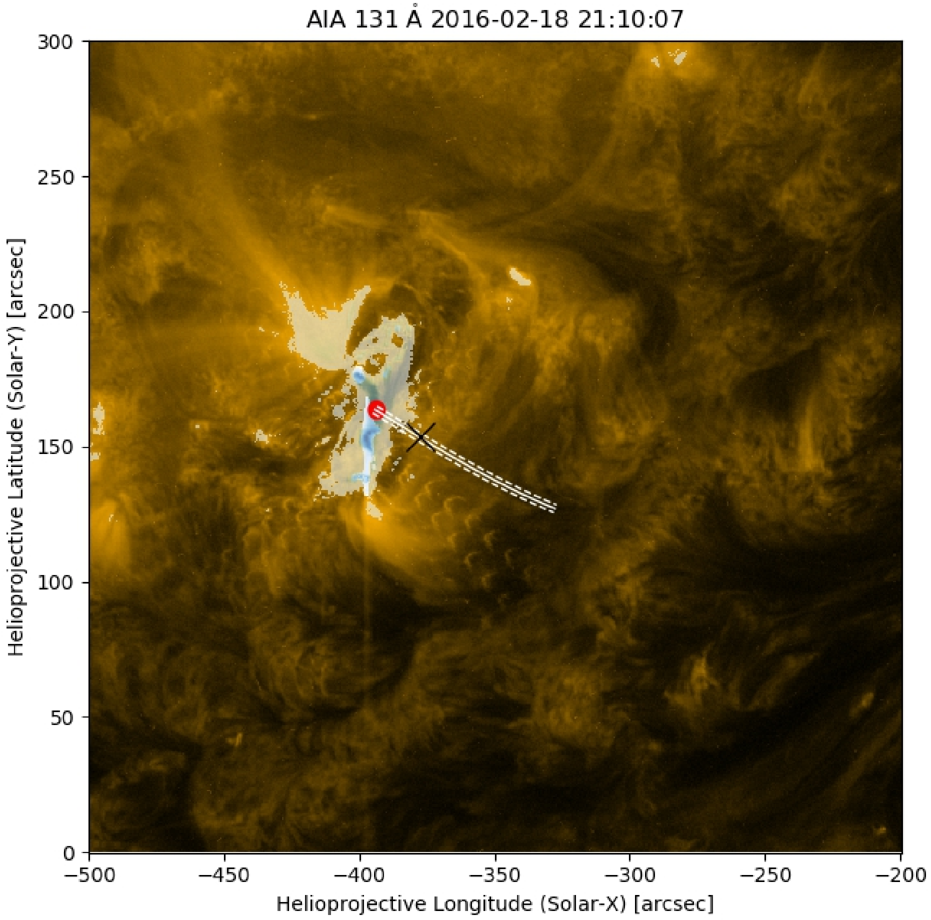


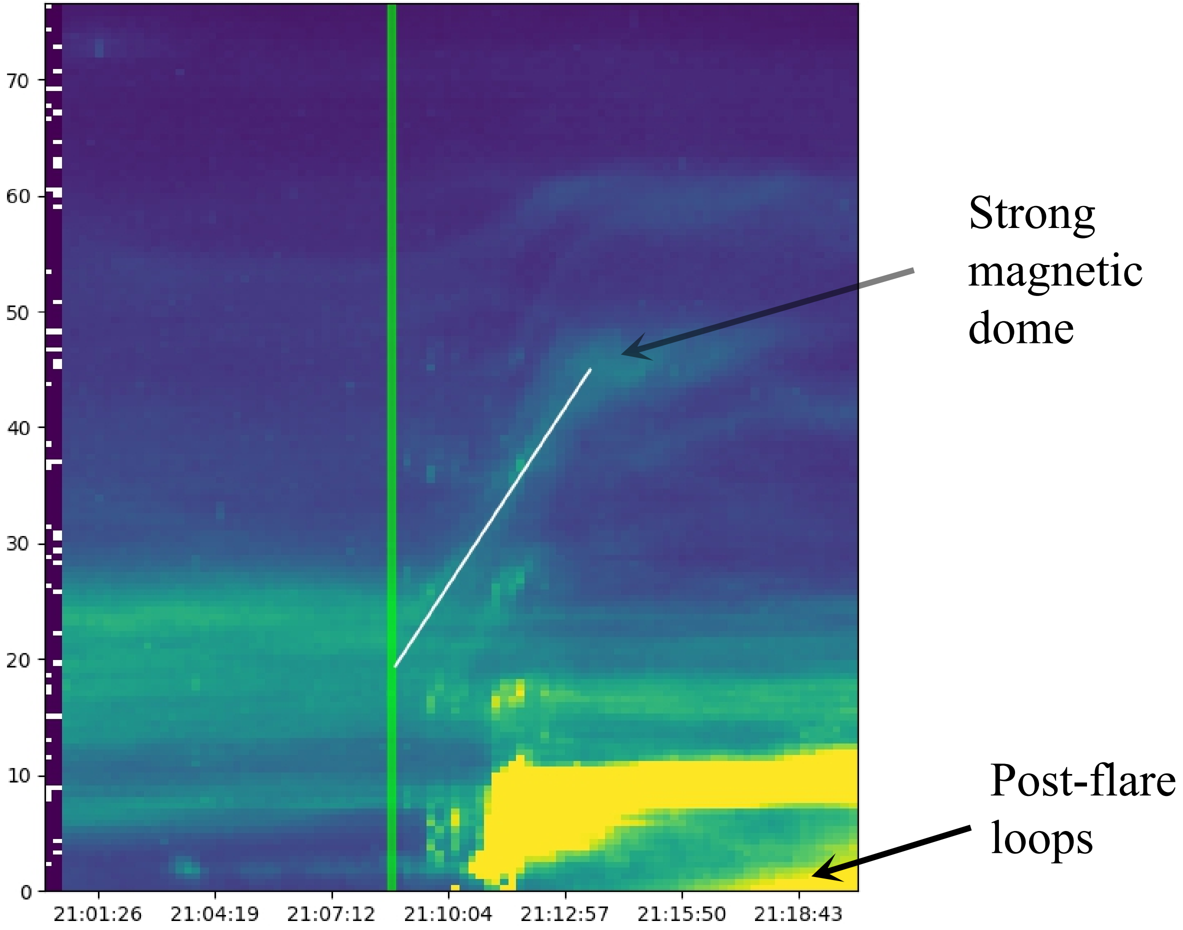
Reconnected flare arcades and x-ray looptop source.



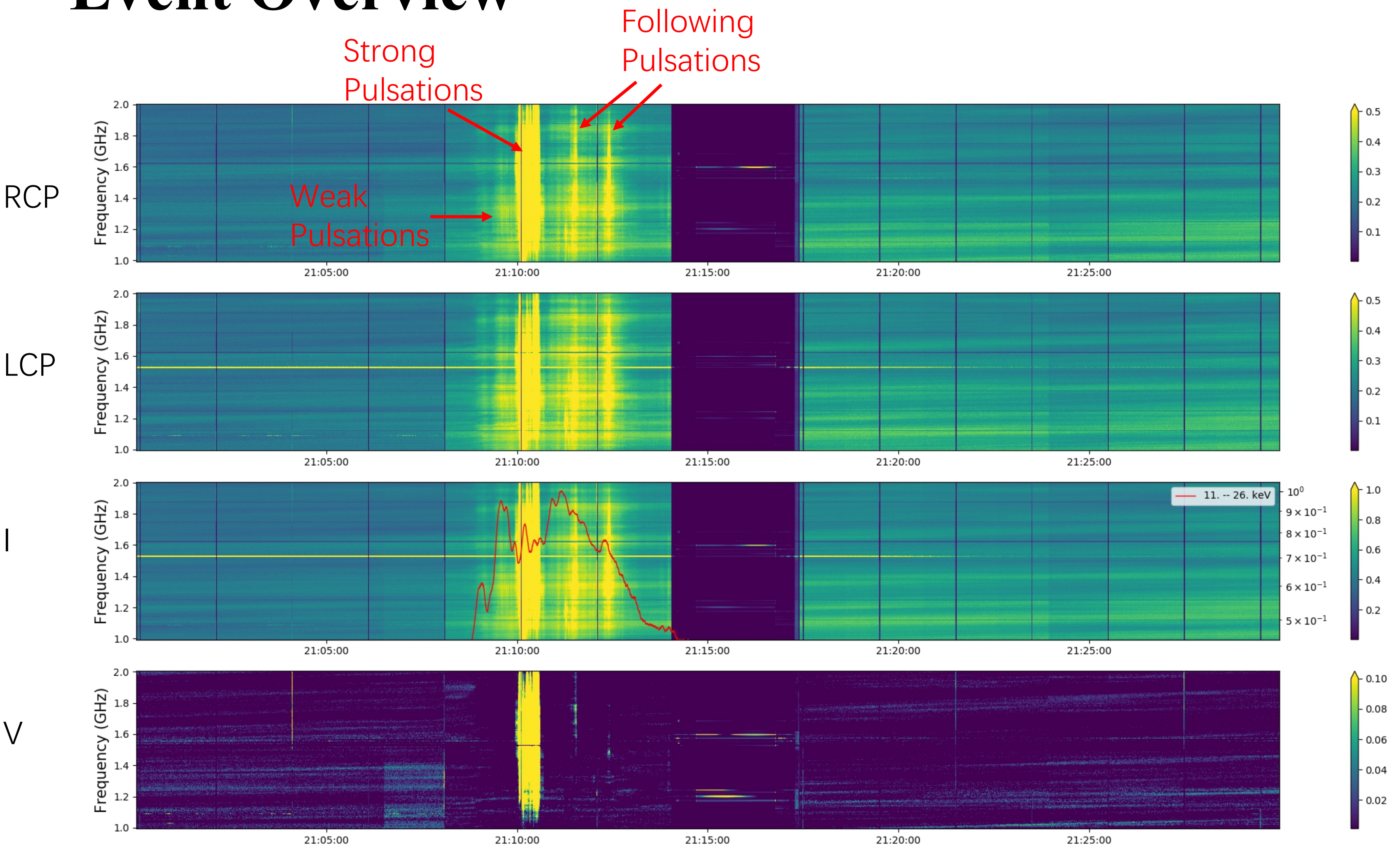
From Mason et. al 2019, 2021, the active region seems to maintain a fan-spine geometry during its course of rotation from the east limb to the solar disk.

Event Overview: Failed Eruption

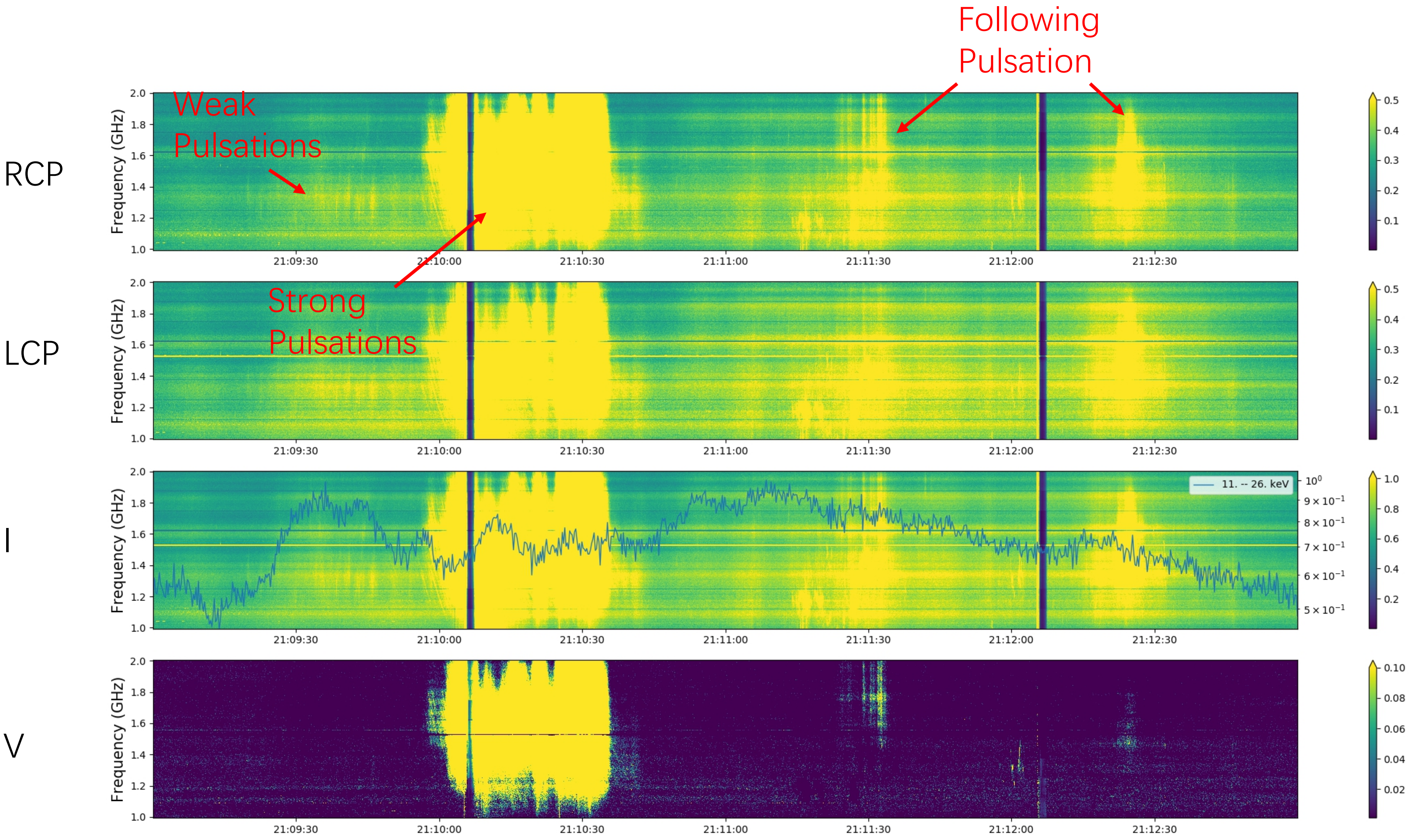




Event Overview



Event Overview



Zoomed View

Complex QPPs are observed.

Radio QPPs: VLA

* 50ms of time resolution, 2MHz of frequency resolution, 1 – 2 GHz (L band)

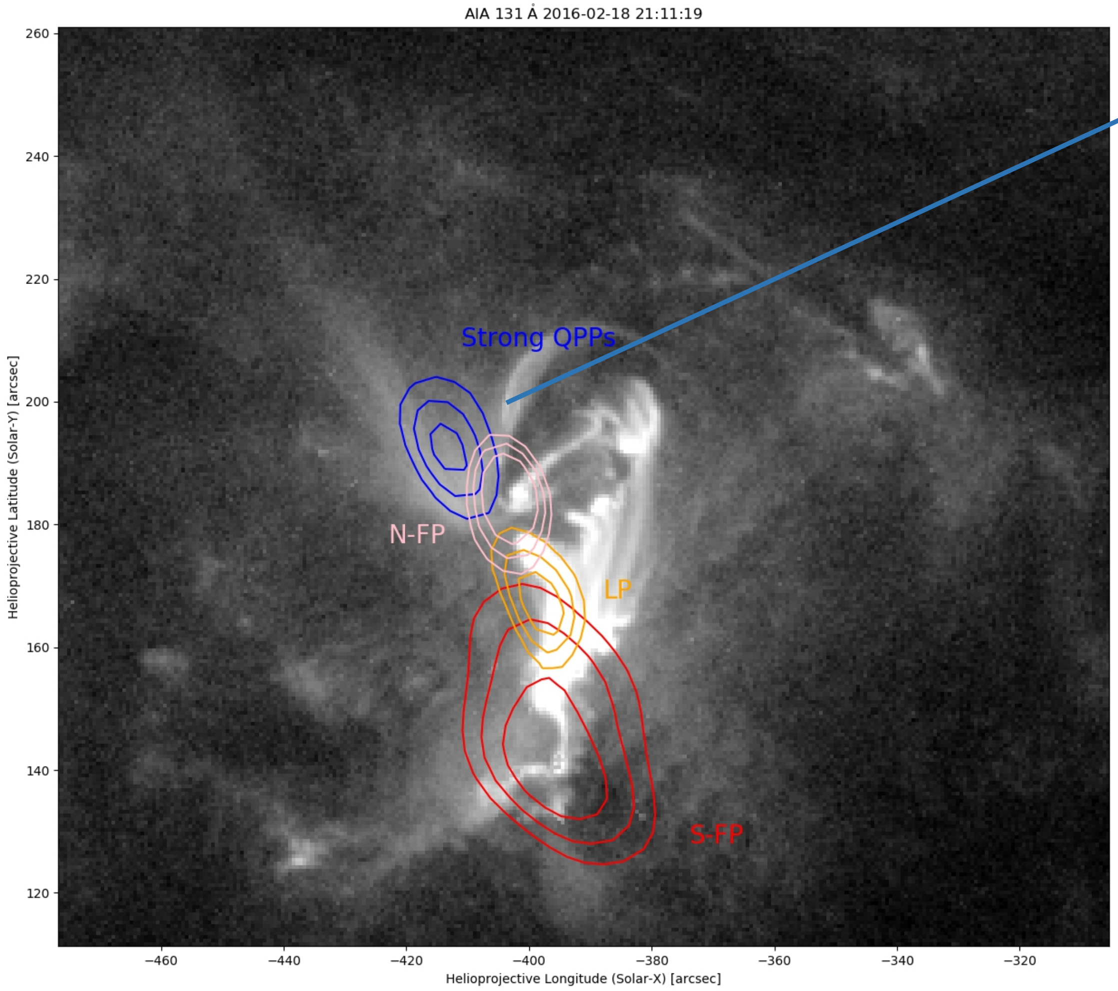
* Enable solar observations with **broadband dynamic spectroscopic imaging**

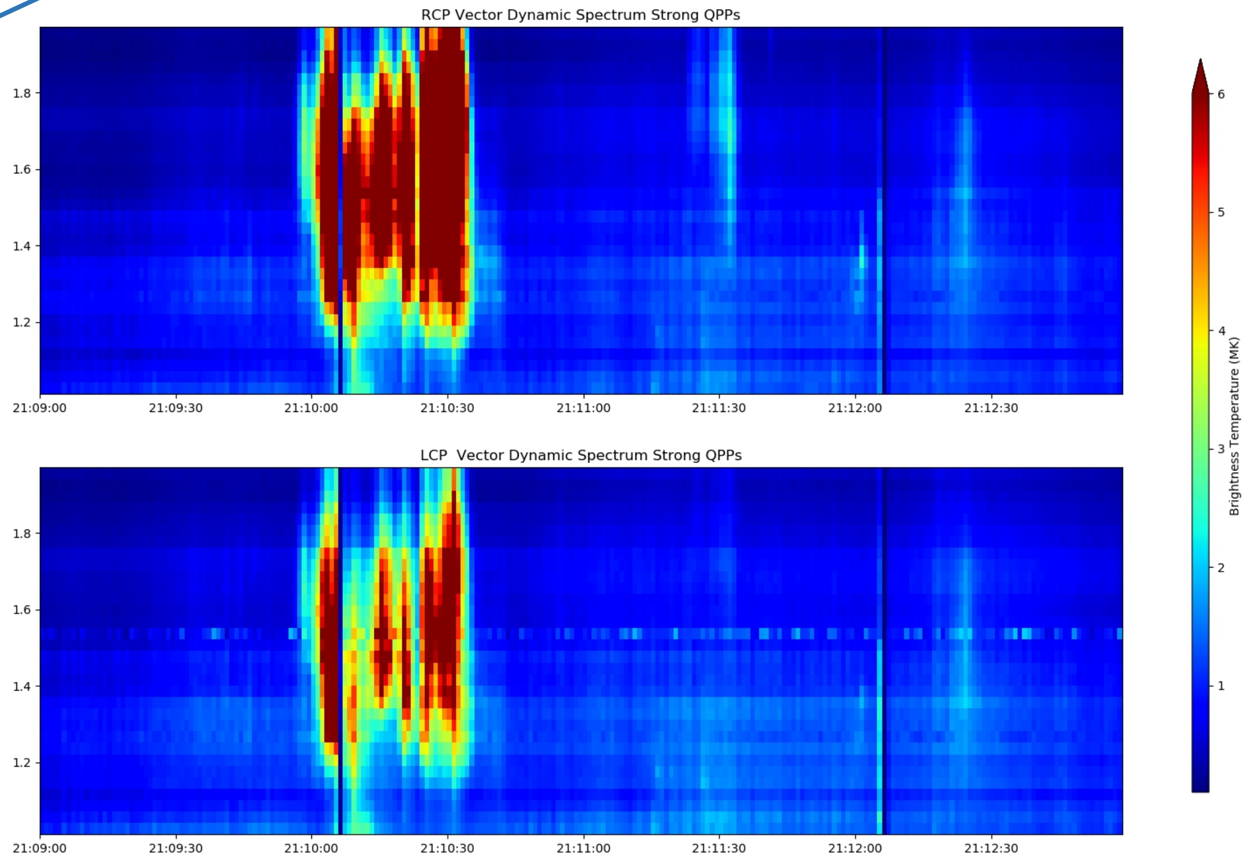
4.5D image cubes: two in space, one in frequency, one in time and 0.5 represents the two different polarizations. → **Spatially and temporally-resolved radio spectrum (Vector Dynamic Spectrum)**

Radio QPPs: Vector Dynamic Spectrum

Radio QPPs consist of 4 spatial distinct radio sources.

(I) Strong QPP





Radio QPPs: Vector Dynamic Spectrum

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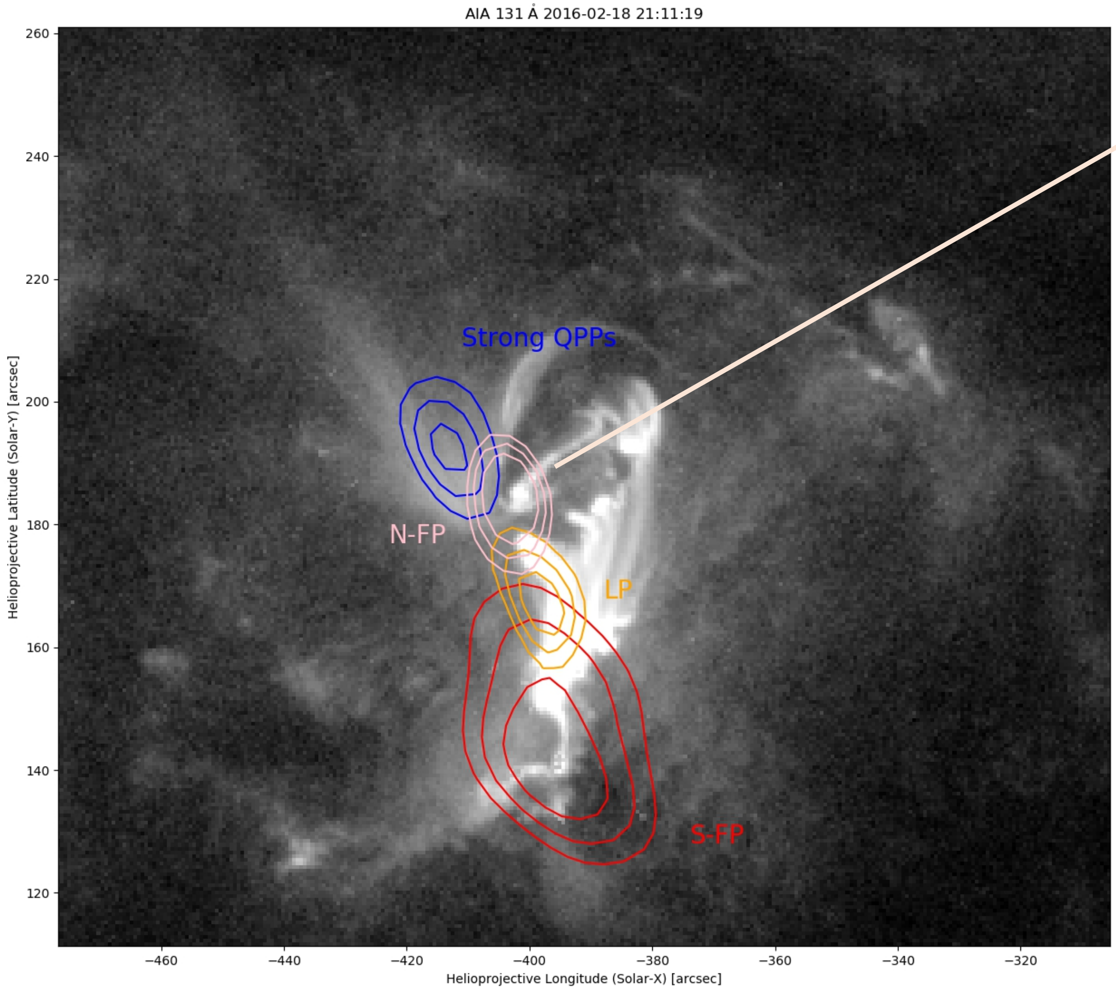
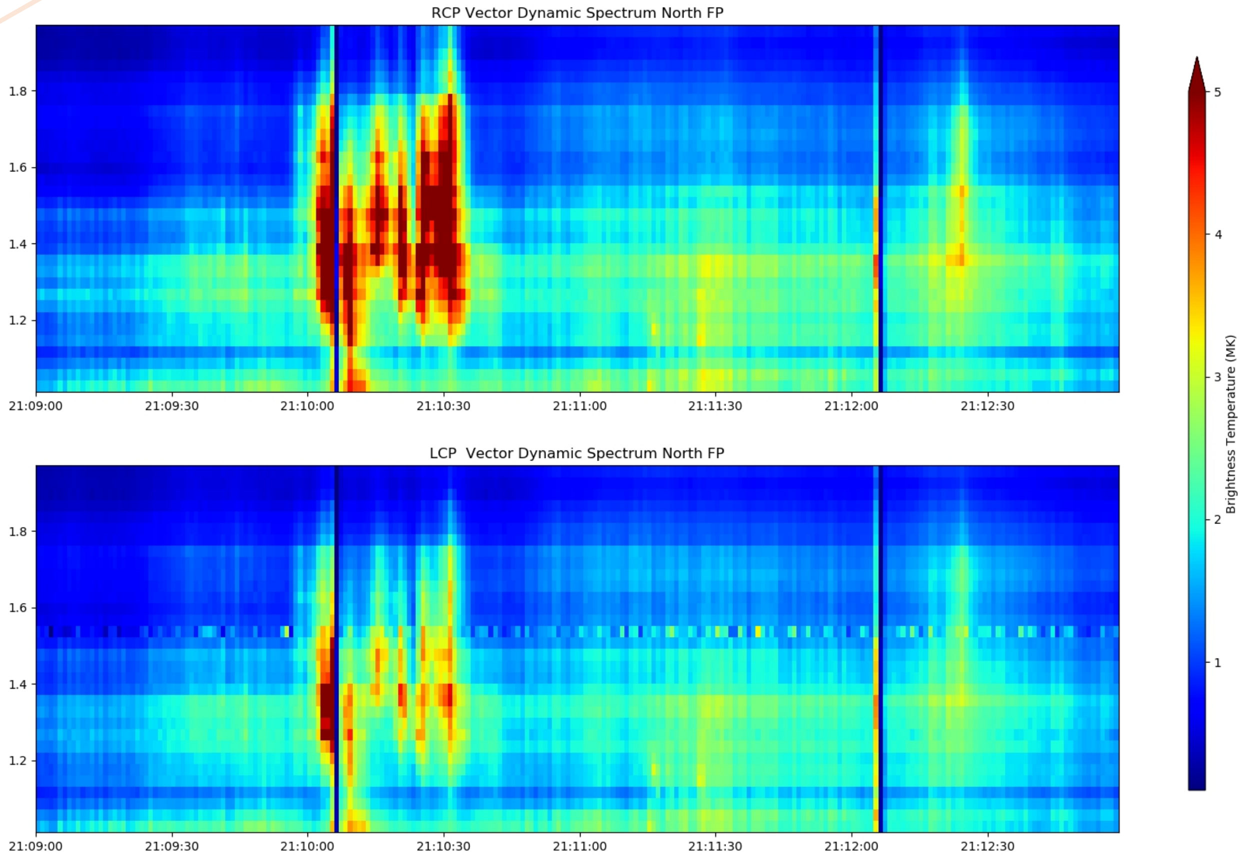


(II) Northern Footpoint



Radio QPPs: Vector Dynamic Spectrum

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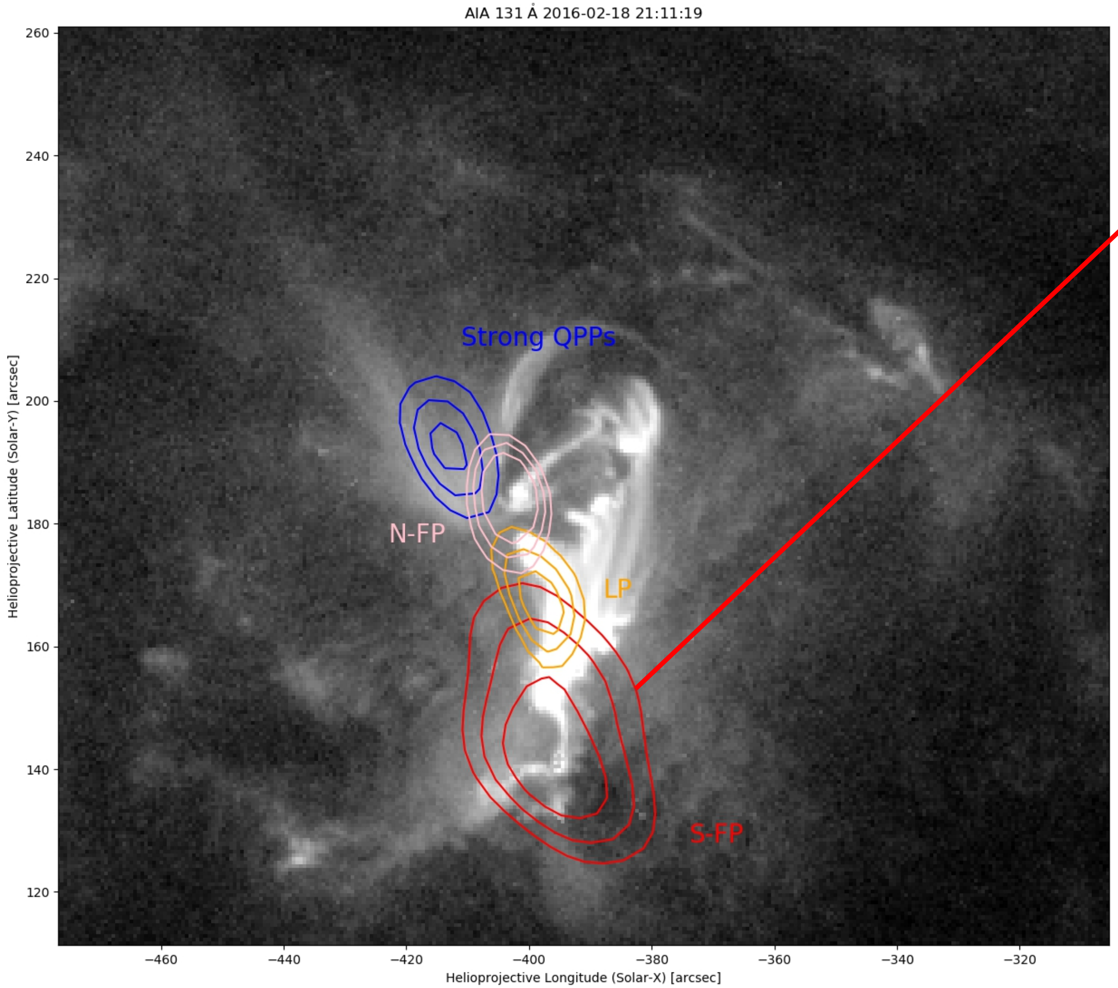
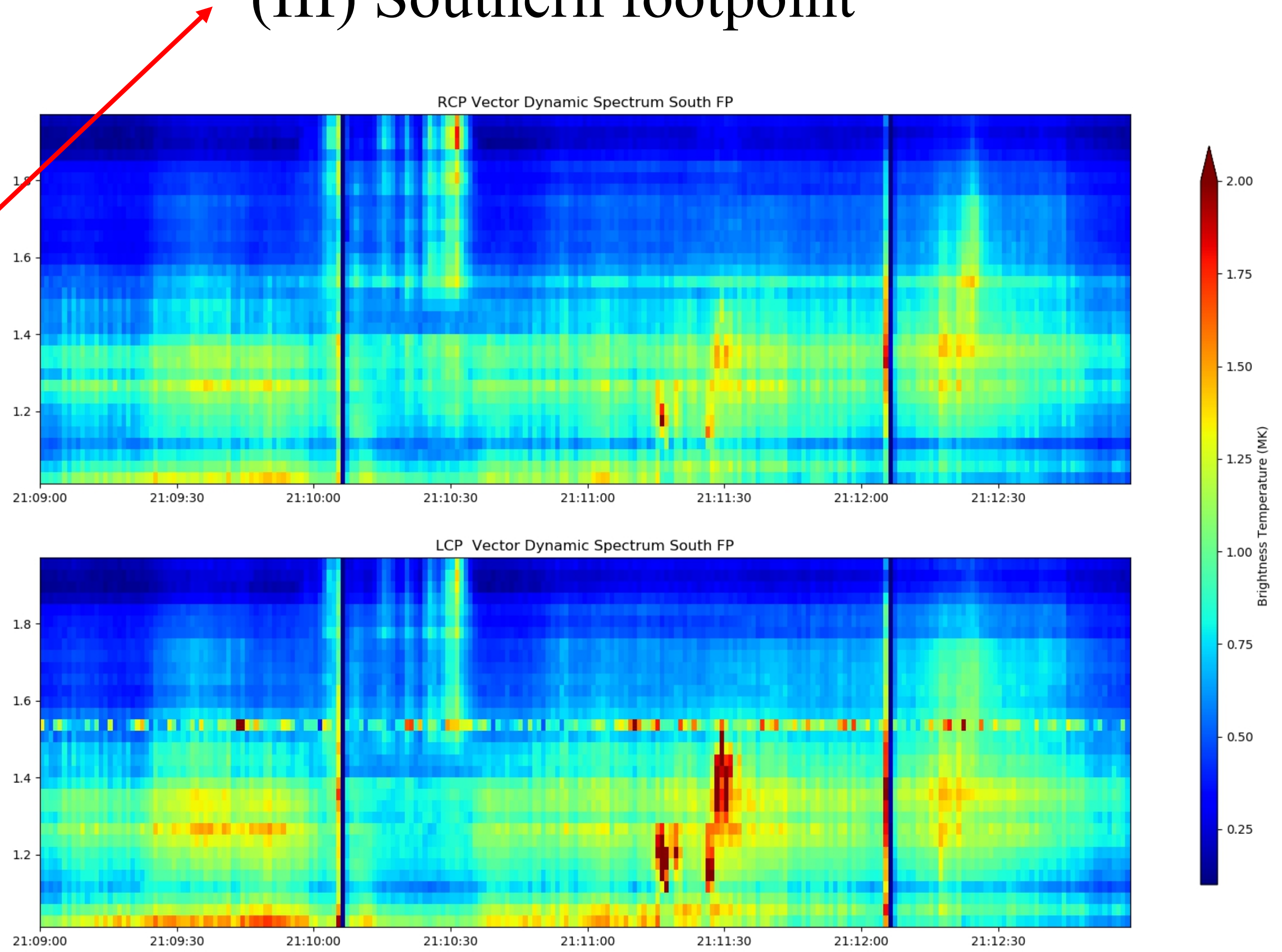


(III) Southern footpoint



Radio QPPs: Vector Dynamic Spectrum

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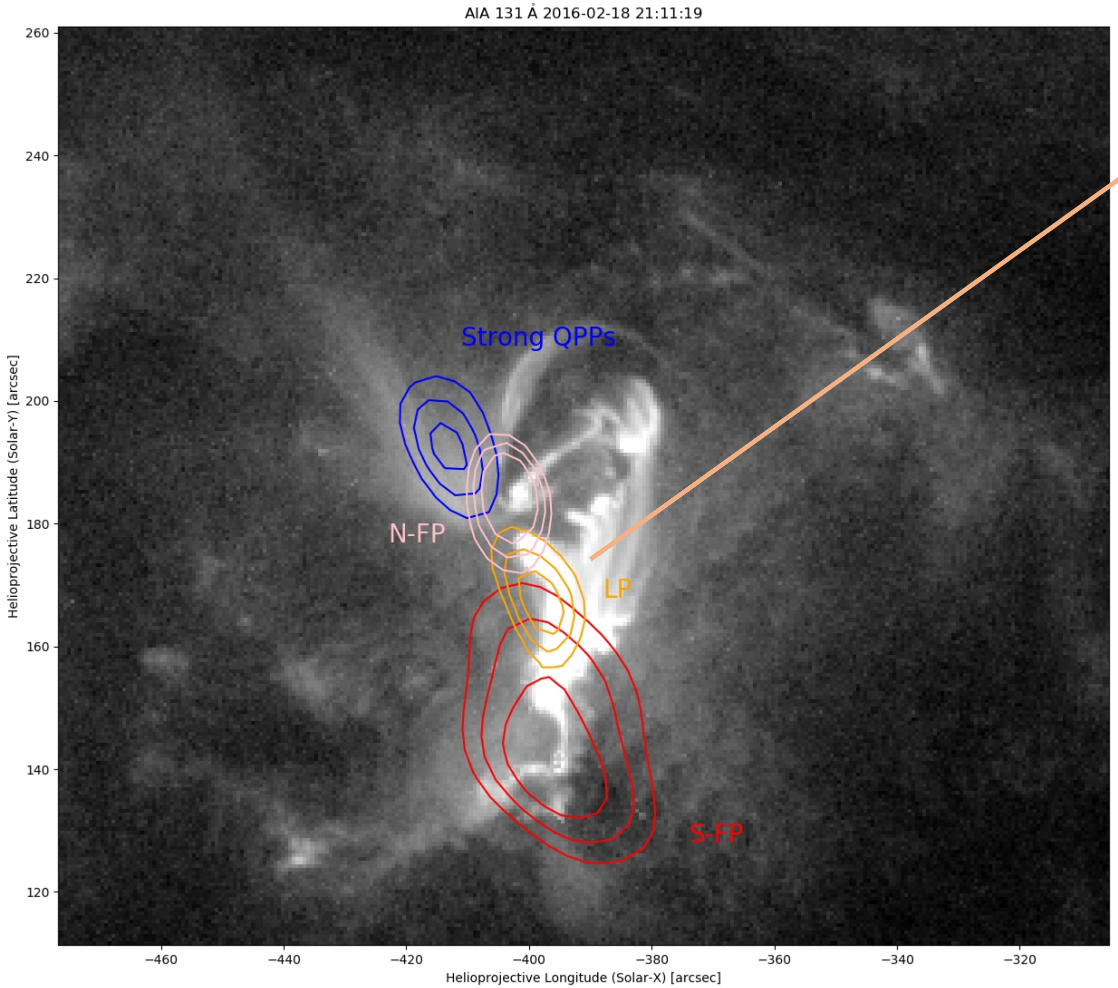
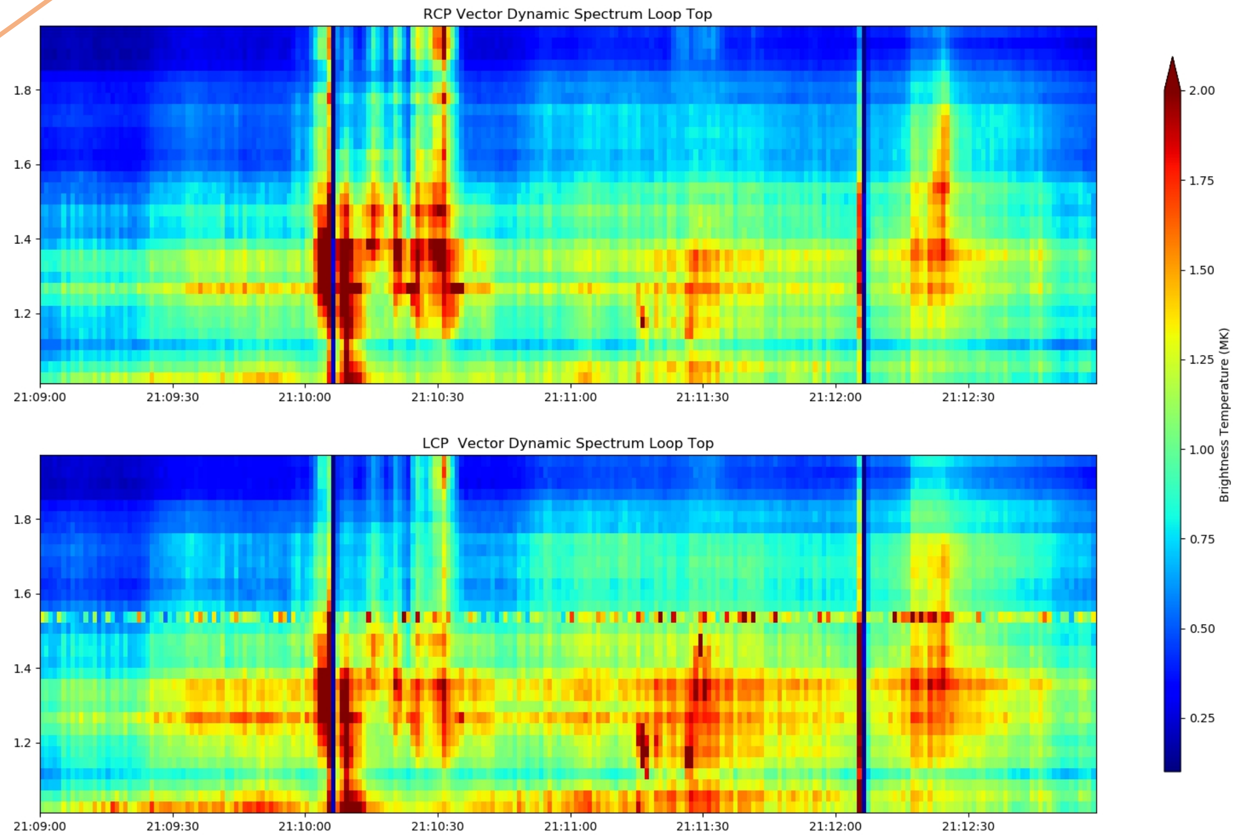


(IV) Looptop



Radio QPPs: Characteristics of Different Sources

	Peak Intensity	Polarization	Period	Bandwidth	Duration
Strong QPP (I)	Can reach 20 MK	Mostly RCP, typically DOP 40 - 50%, up to 80%	~ 6s	Nearly full bands	~ 20 seconds after the looptop sources, lasts ~ 50 seconds, some weak following pulsations are also detected.
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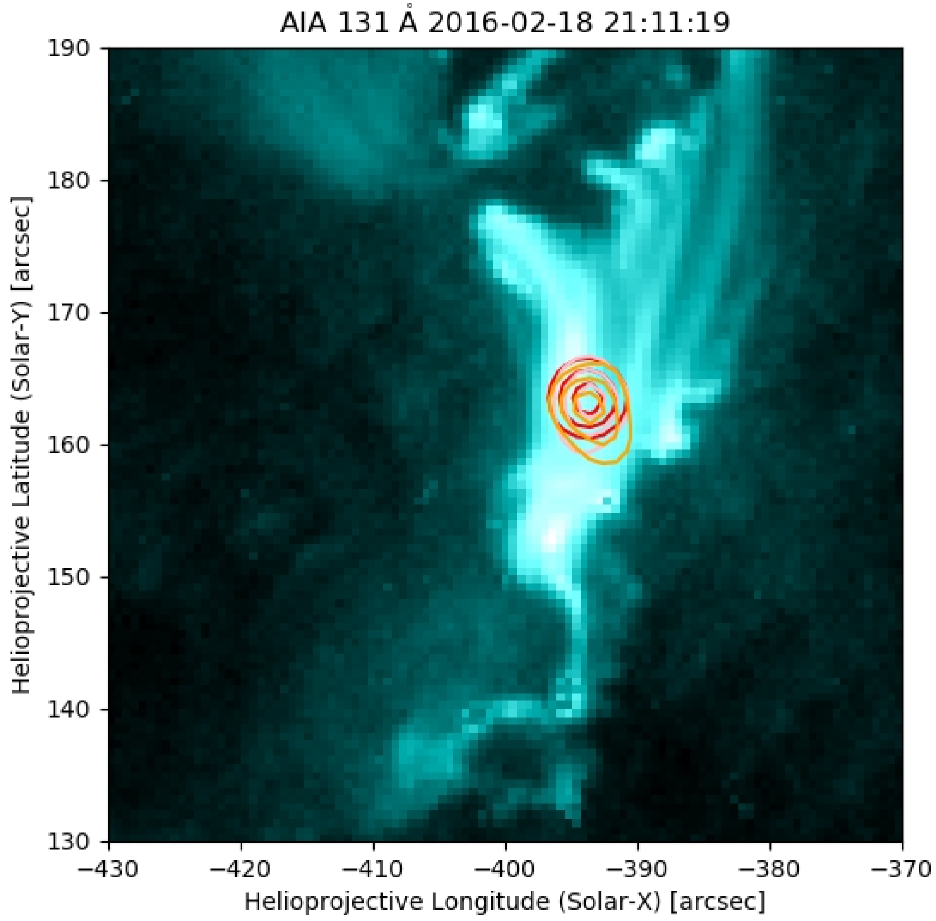
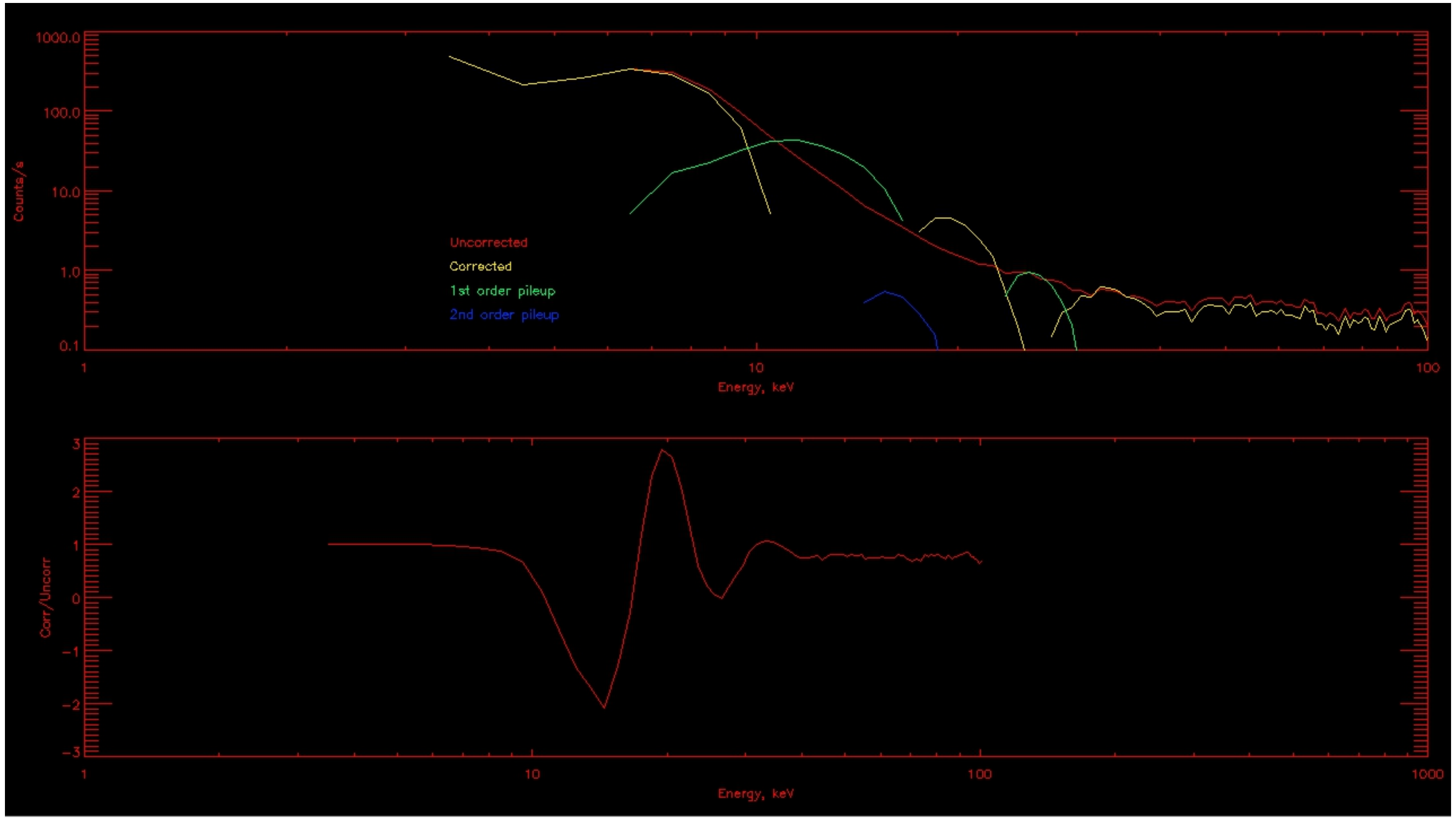
X-Ray QPPs: RHESSI

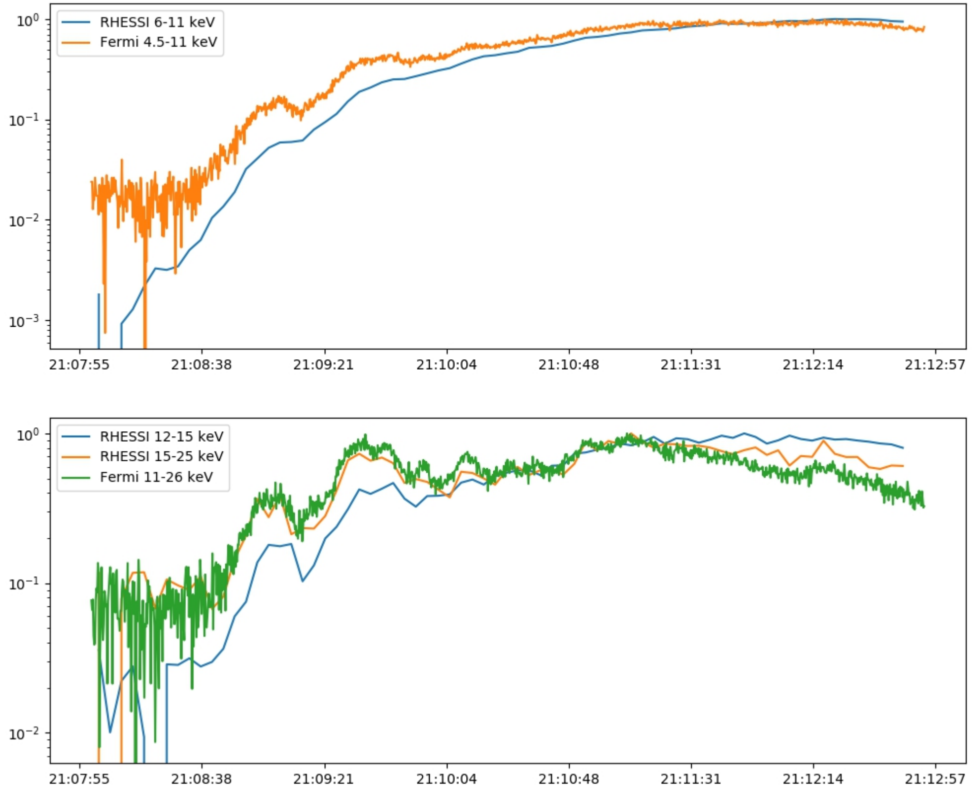
- RHESSI: Partly cover the impulsive phase, however, from the pileup-check, the signal above 11 keV may be affected by pileup --- overestimation here, suggestions are welcome.



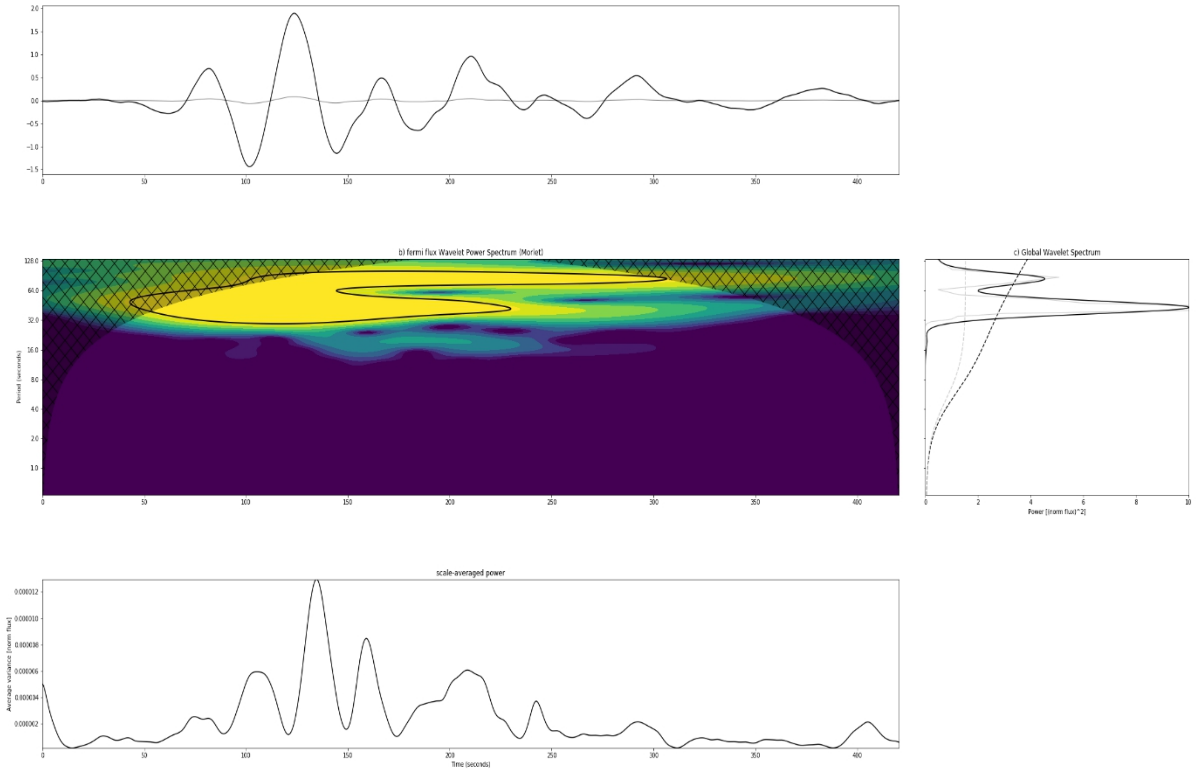


X-Ray QPPs: Fermi/GBM

- Fermi/GBM: Temporal profiles show QPPs below 30 keV



Fermi/GBM light curves are consistent with RHESSI's, indicating the X-ray QPPs are possibly coming from the looptop region.

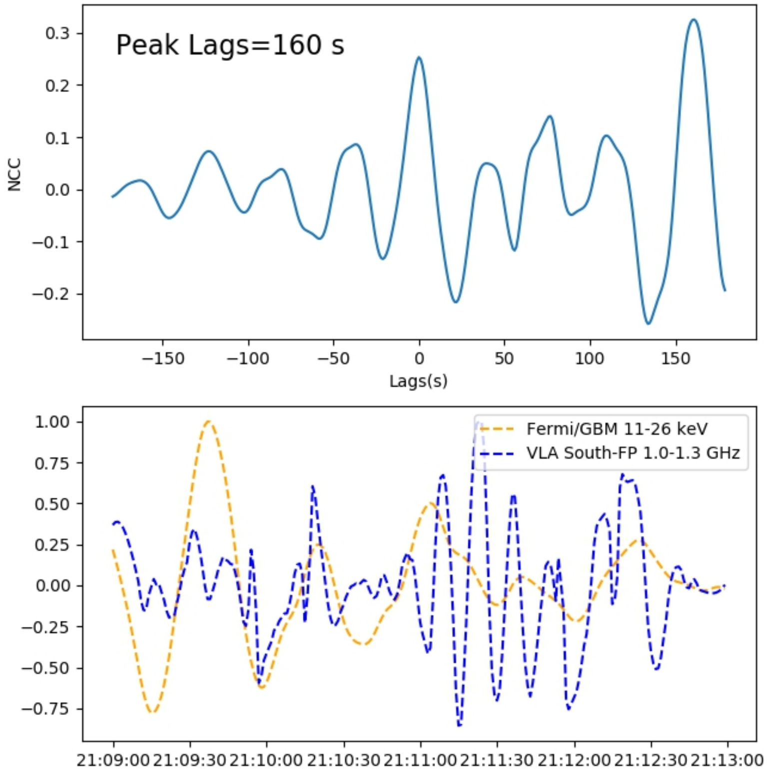


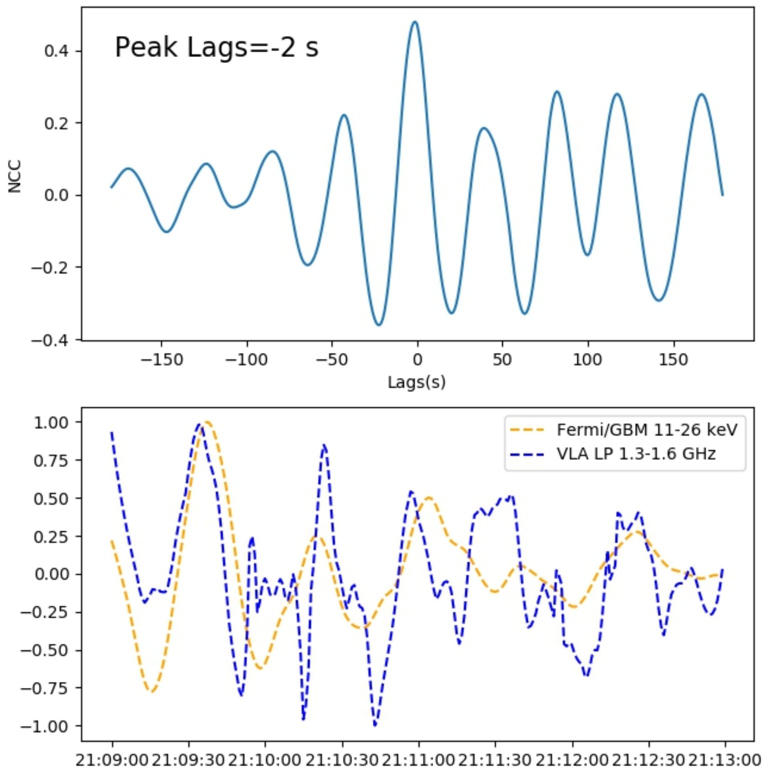
Wavelet analysis of Fermi/GBM 11-26 keV light curve shows a QPP with a period ~ 43 seconds

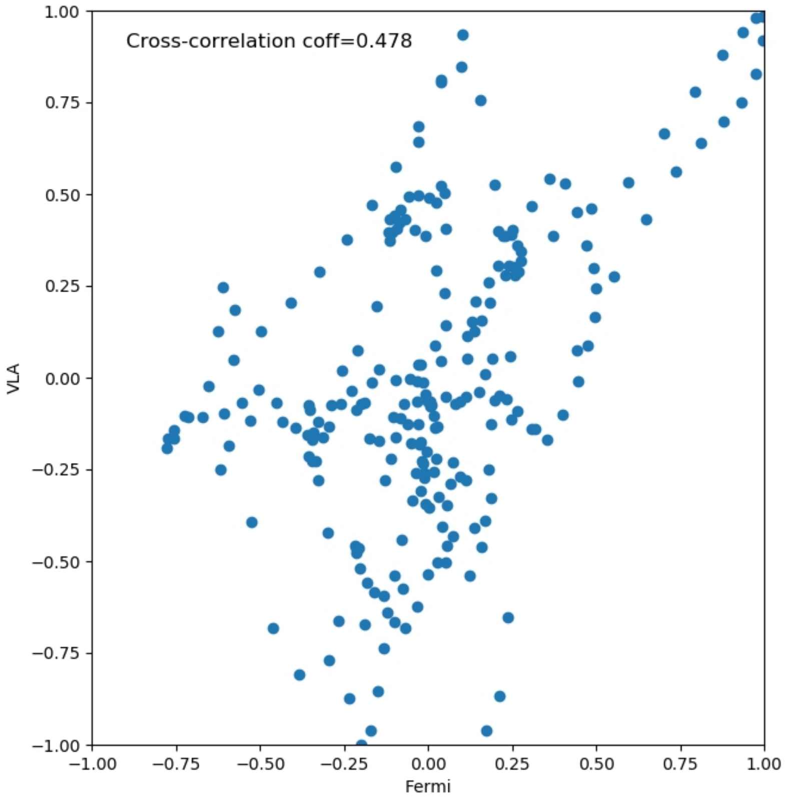
X-Ray QPPs: Cross-Correlation with Radio Emissions

Cross-Correlation between southern footpoint radio source and Fermi/GBM 11-26 keV: weakly correlated (NCC ~0.32).

Cross-Correlation between looptop radio source and Fermi/GBM 11-26 keV: moderately correlated (NCC ~0.48).



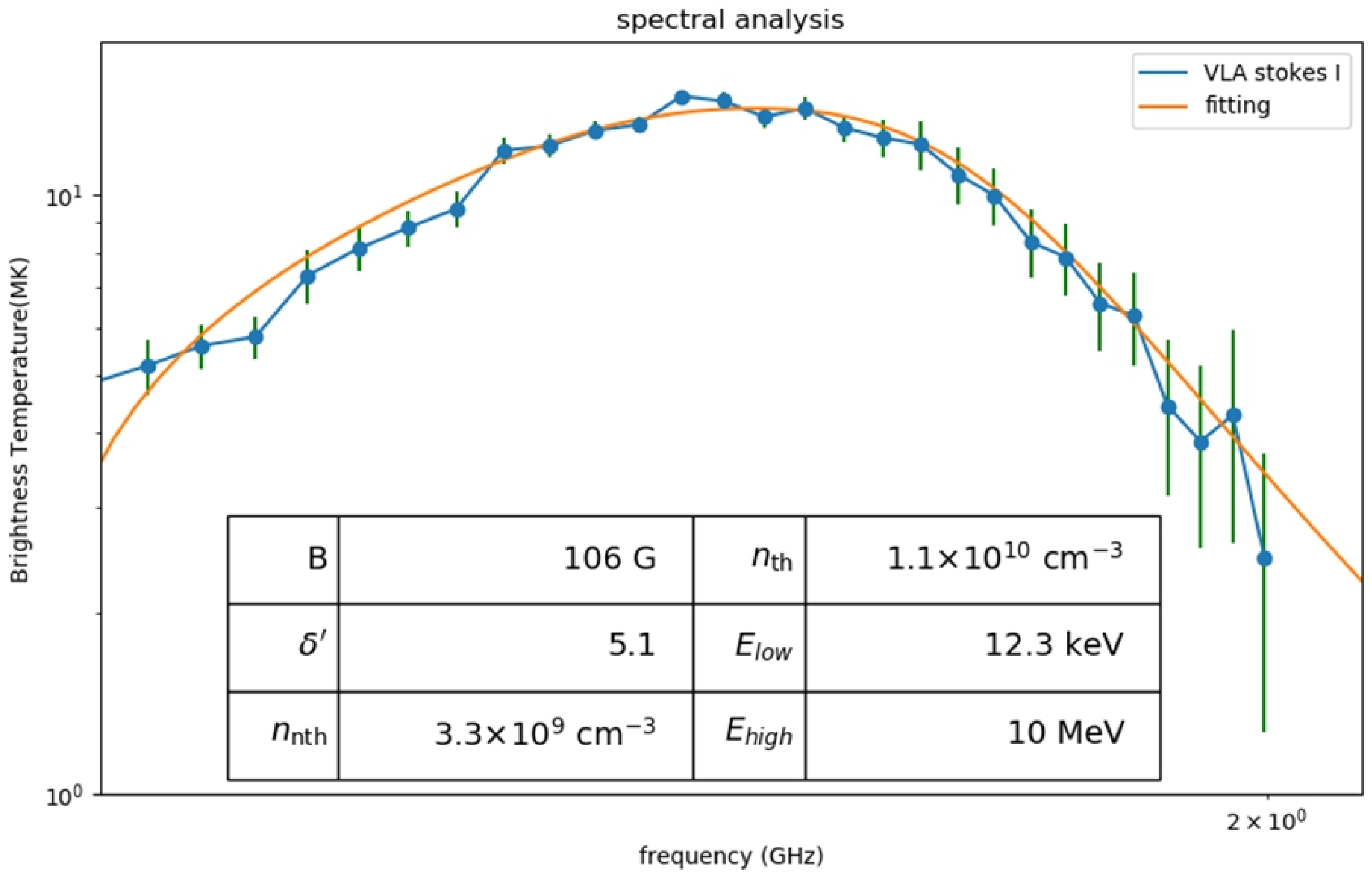




The X-ray QPPs are better correlated with the looptop radio emissions. Combining with their consistent spatial location, it is highly possible both emissions are coming from the same accelerated particles.

Emission Mechanisms of QPPs: Strong QPP

Incoherent Gyrosynchrotron Emission:

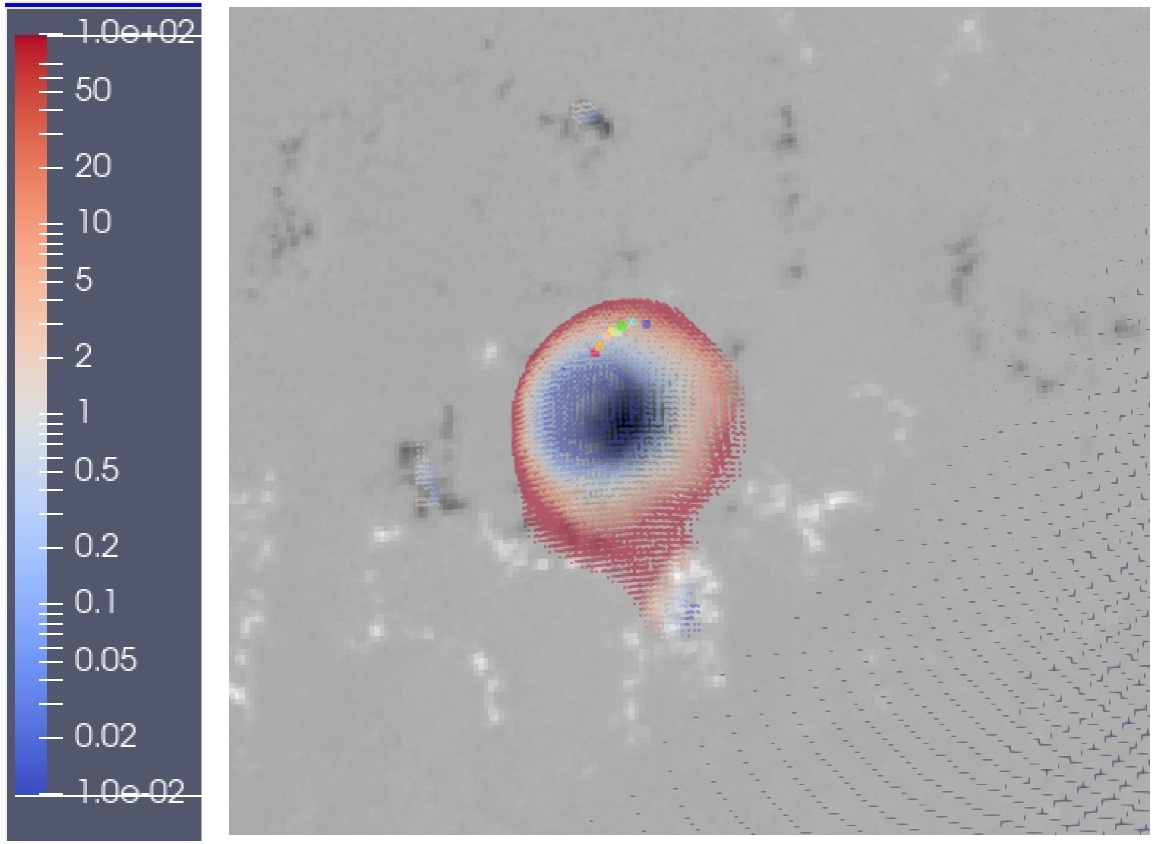


An example gyrosynchrotron fit of stokes I spectrum is shown on the left. However, we cannot use a simple homogenous model to fit the polarized spectrum. Also, the high DOP (up to 80%) is not consistent the gyrosynchrotron emission.

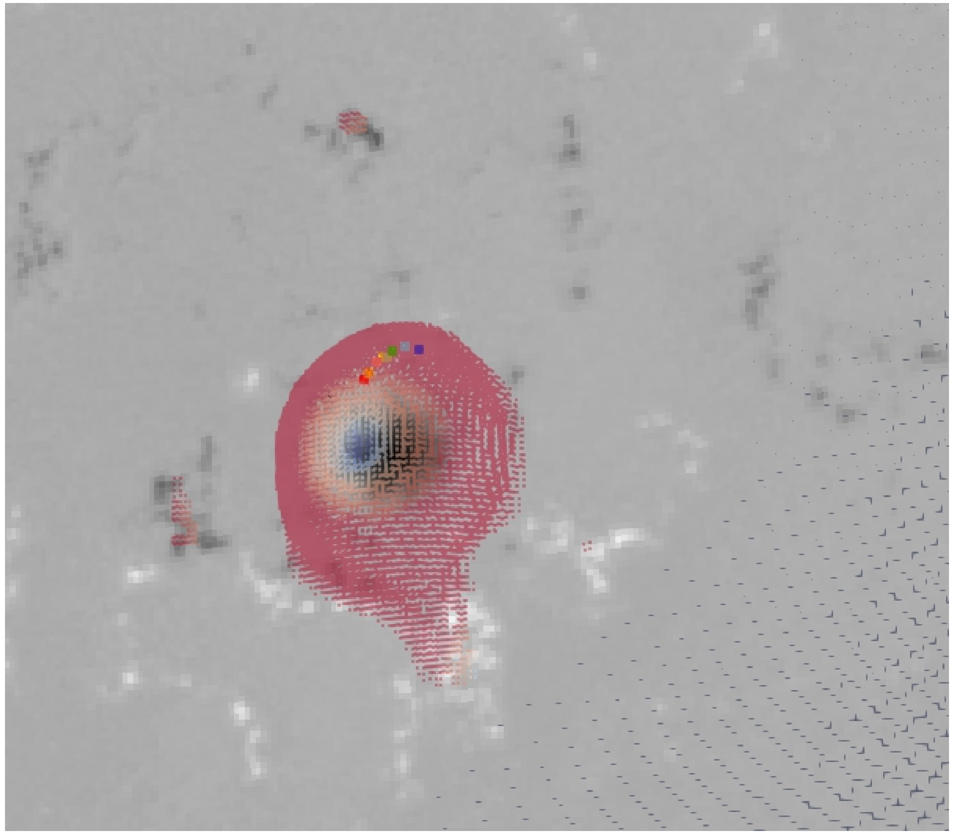
Emission Mechanisms of QPPs: Strong QPP

Coherent ECME: Second harmonic ECME is preferred in this case.

Optical depth at third harmonic gyroresonance layer,
O-mode (corresponding to RCP at strong QPP), along the LOS

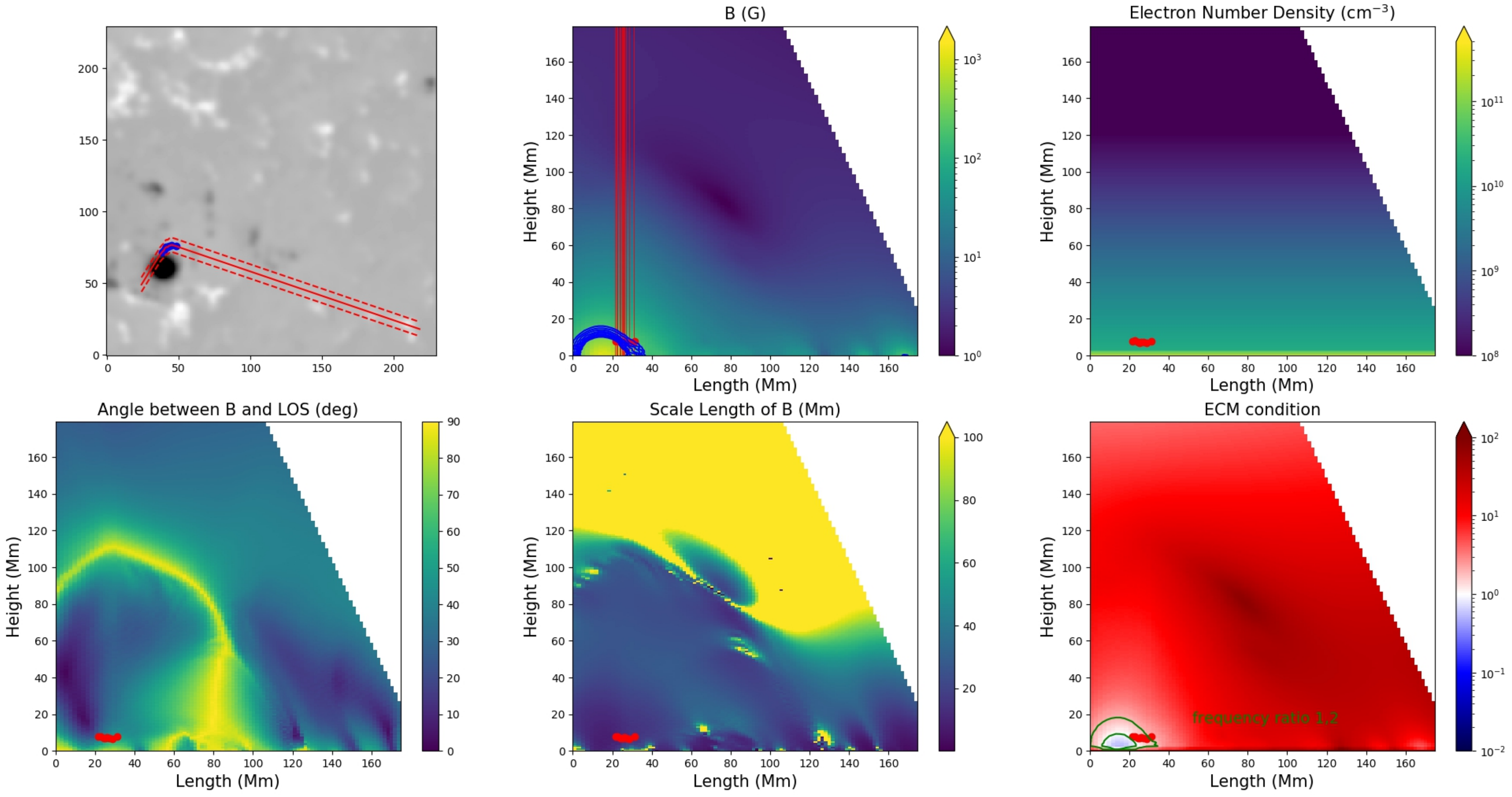


X-mode (corresponding to LCP)

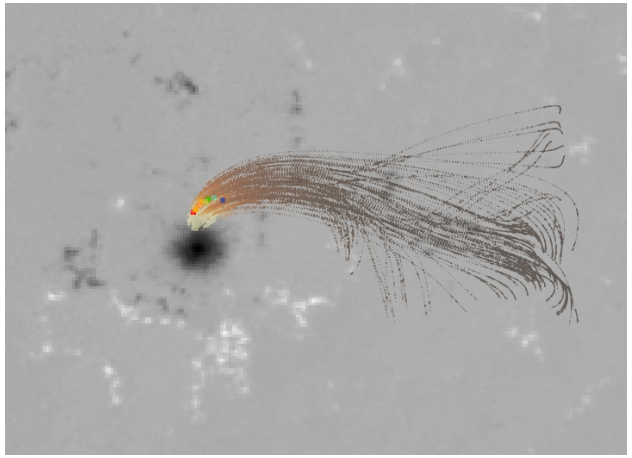


We perform an NLFFF extrapolation and embed the radio sources based on the second harmonic ECME assumption. The O-mode (RCP) is easier to escape through the 'hole' compared to the X-mode (LCP).

Emission Mechanisms of QPPs: Strong QPP



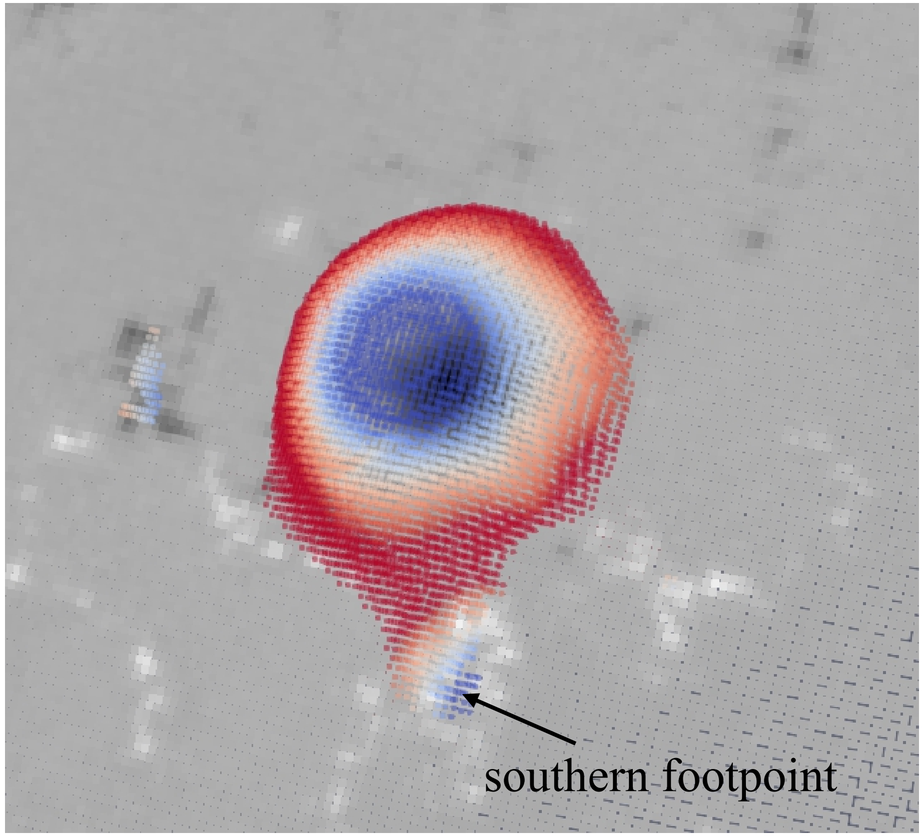
The cut along the centroids of the sources and the LOS. The radio sources are located within the ECM-permitted region.



Emission Mechanisms of QPPs: Conjugate Footpoints

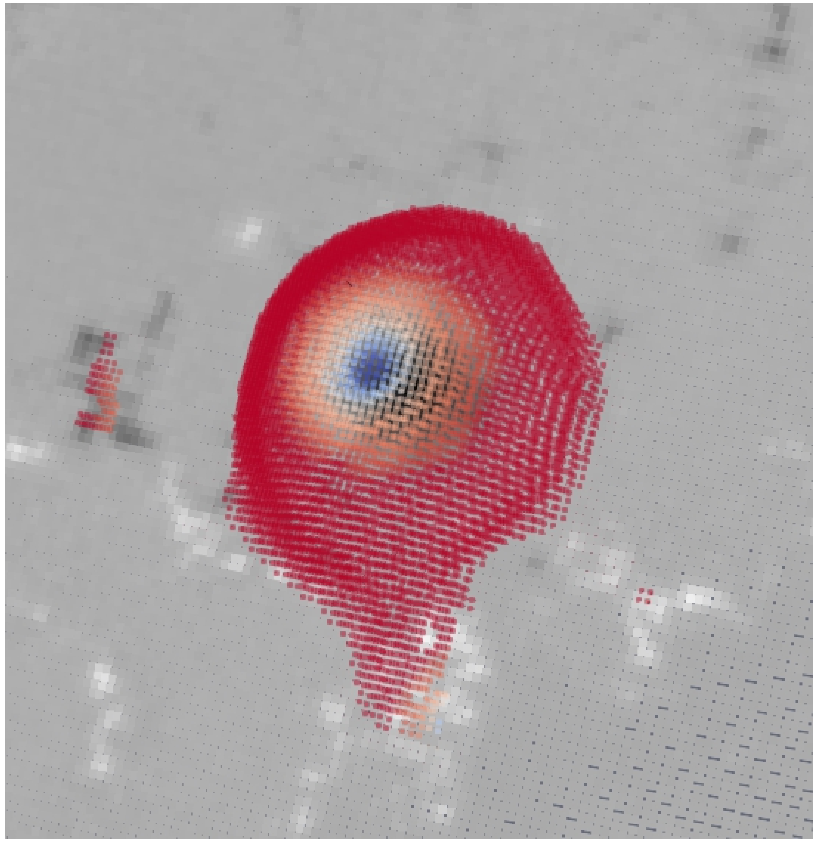
The radio emissions at two conjugate footpoints are in opposite polarizations and have similar temporal properties. They are highly possible to share the same mechanism.

The previous ECME scenario also works here, use southern footpoint as an example.



Optical depth at third harmonic gyroresonance layer,
O-mode (corresponding to LCP at southern footpoint), along the LOS

Only O-mode can escape, consistent with the high DOP at footpoints.



X-mode (corresponding to RCP)

Discussion and Future Work

Utilizing radio imaging spectroscopy data obtained by the VLA, we show the characteristics of spatially distinct radio QPPs. We discussed the mechanisms for each source and suggest ECME as a probable mechanism for producing strong QPPs and its conjugate footpoint sources. Our future work will focus on the following intriguing questions:

- Other probable mechanisms: Plasma radiation, inhomogeneous gyrosynchrotron emissions, etc.
- The modulation mechanism of QPPs: Periodic reconnection, MHD oscillations
    - The periodic reconnection may be responsible for the QPPs near the brightened arcades.
    - MHD oscillations trigger the strong QPP.
- The energy transport processes connecting the different sources.