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Owens Valley Solar Array

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Flare Dynamic Microwave Imaging Spectroscopy

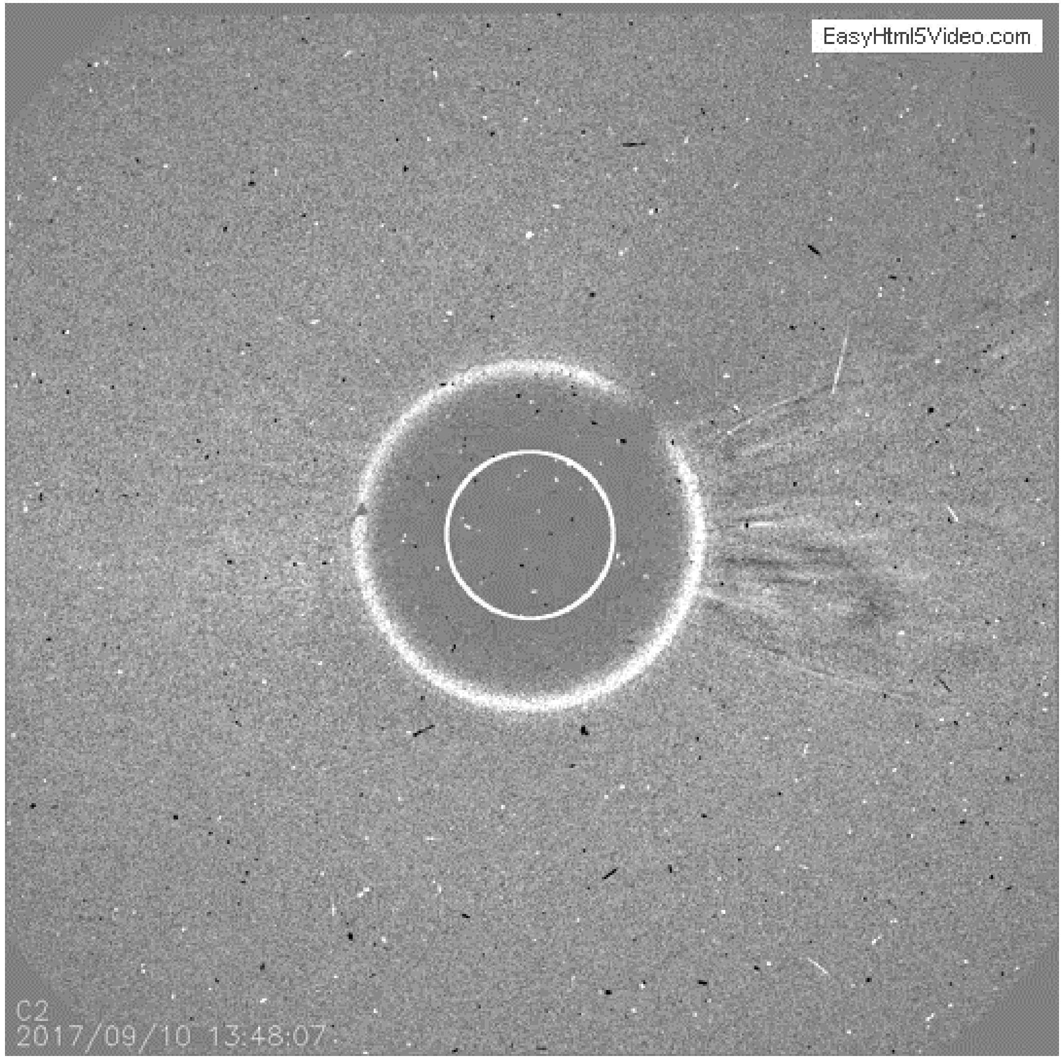
Dale Gary and Tim Bastian

Some EOVSA Results

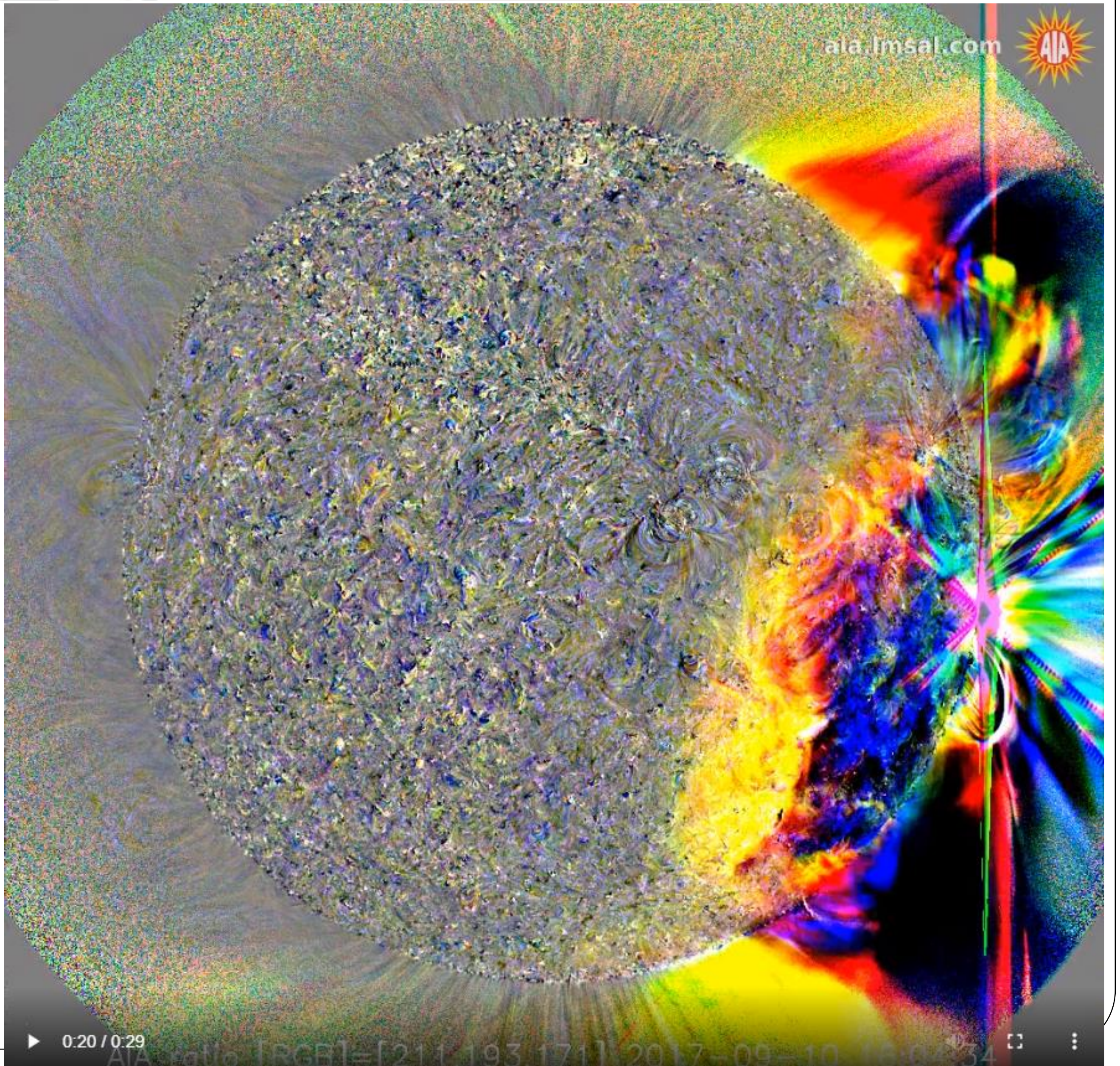
- To give a flavor of the power of FASR for flare studies, I present some in-depth results for one of the largest flares of the previous solar cycle.
- This introduces the main science problems presented by flares, which are broadly applicable to astrophysics.
- I will show that the measurement of spatially resolved microwave spectra open a broad new approach in attacking these problems.
- EOVSA is merely a demonstrator for the science that can be done with FASR—we need FASR's higher-quality/higher-dynamic-range imaging, as well as its wider frequency coverage to fully address the potential shown by EOVSA.

A Heliosphere-Wide Impact

- Here is a "running ratio" movie of EUV emission from a large solar flare in 2017.
- The eruption and coronal mass ejection was associated with a massive particle event, including ground-level neutrons, and > 100 MeV gamma rays for hours after the event.
- The event caused a heliosphere-wide disturbance, yet the entire process is initiated by an ill-understood engine close to the solar surface.



Still Frame of Global Impact



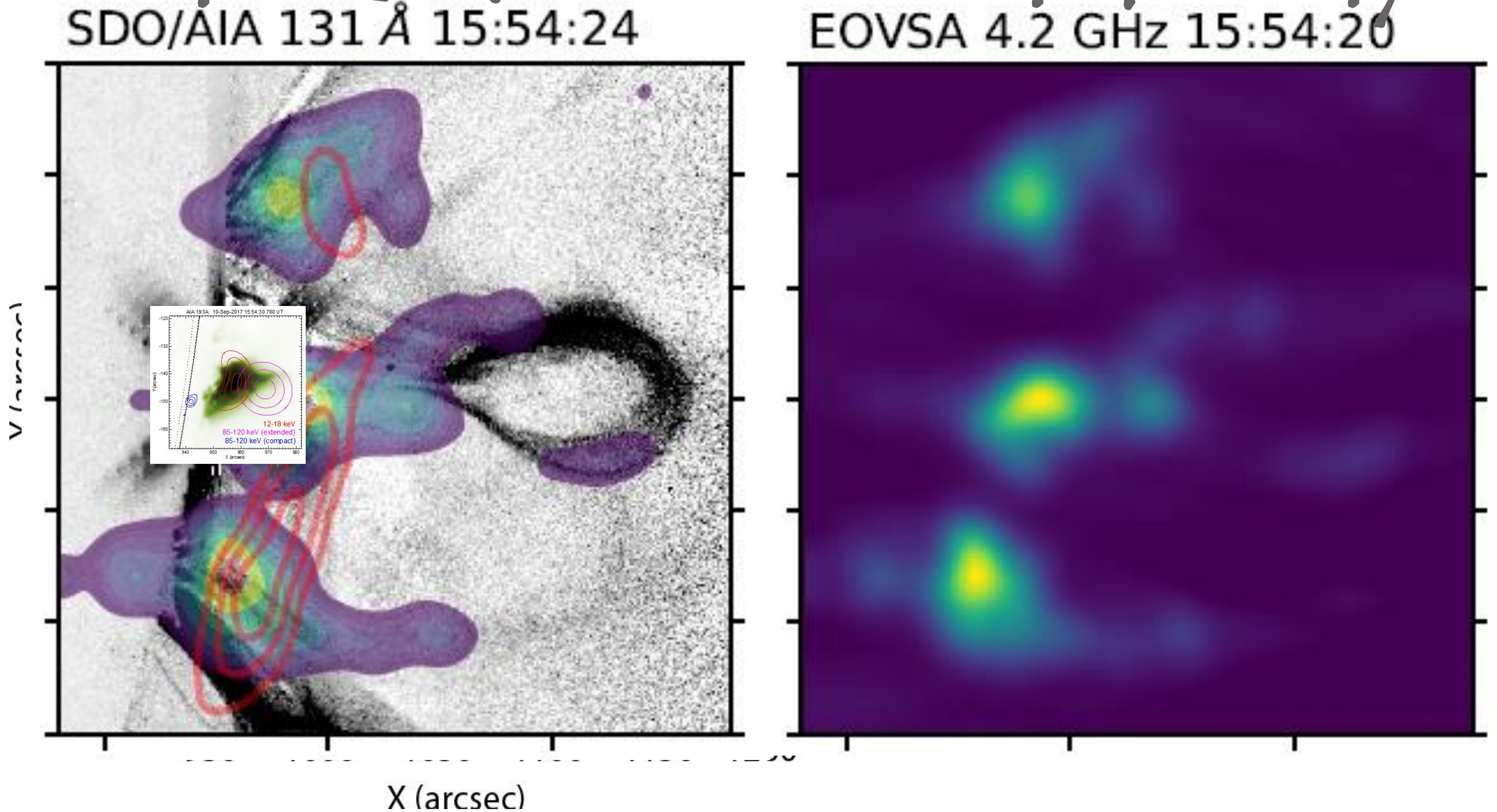
Astrophysics of Solar Flares

- Such events result from magnetic reconnection, a process that is pervasive in astrophysics yet is poorly understood.
- The subsequent destabilization and eruption of magnetized plasma is a complex problem in MHD that has direct bearing on many astrophysics environments.
- The associated rapid conversion of magnetic energy into high-energy charged particles through turbulence and shock acceleration is also key to many astrophysics problems.
- The system-wide effects of such events are of interest to exoplanet habitability, and indeed that of our own planet.
- The wide-spread effects on technological systems on Earth and in the near-Earth environment make this a topic of extreme societal relevance.

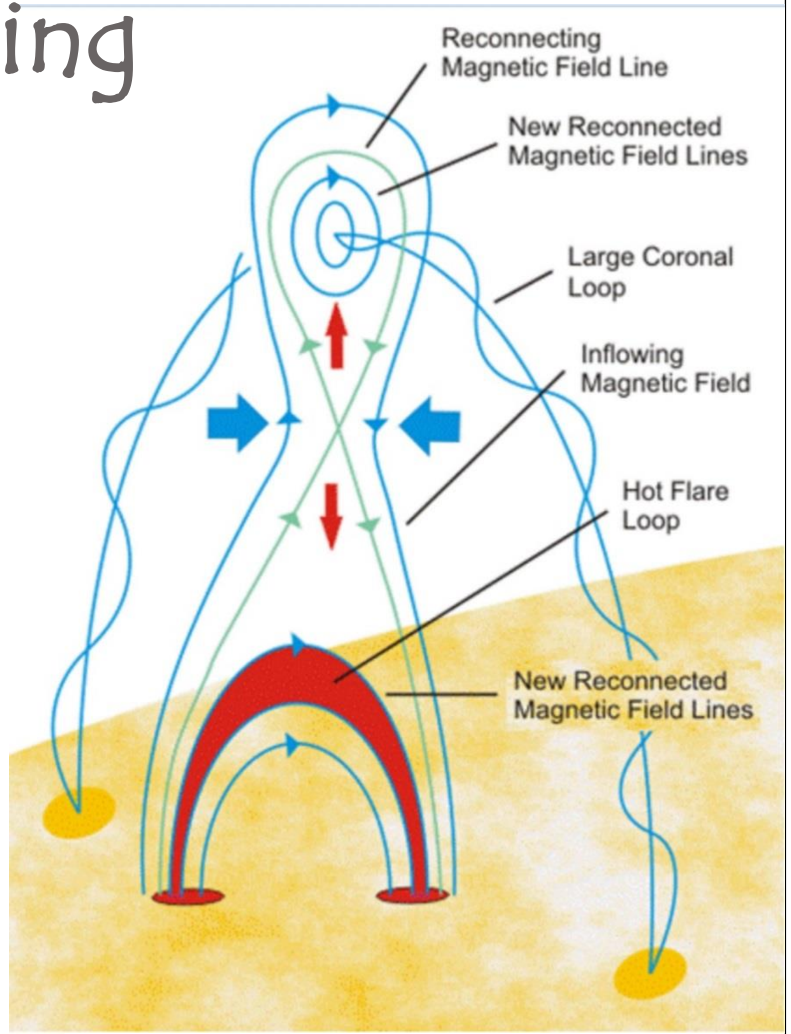
EOVSA—FASR A Demonstrator

- The 13-antenna Expanded Owens Valley Solar Array (EOVSA) is providing demonstrator science for the FASR A (2-20 GHz) array.
- We briefly present the results from each phase of the development of this iconic flare, to demonstrate the FASR science from broadband microwave spectra of solar flares.
- A brief mention of full-disk imaging in this range is presented at the end.

Flare Context with Hard X-ray Imaging



- Hard X-rays reveal high-energy particles (< 100 keV) only where density is high.
- Microwaves reveal particles (>300 keV) everywhere that the magnetic field strength is high enough—no density needed. The particles are everywhere!



Standard Solar Flare Model

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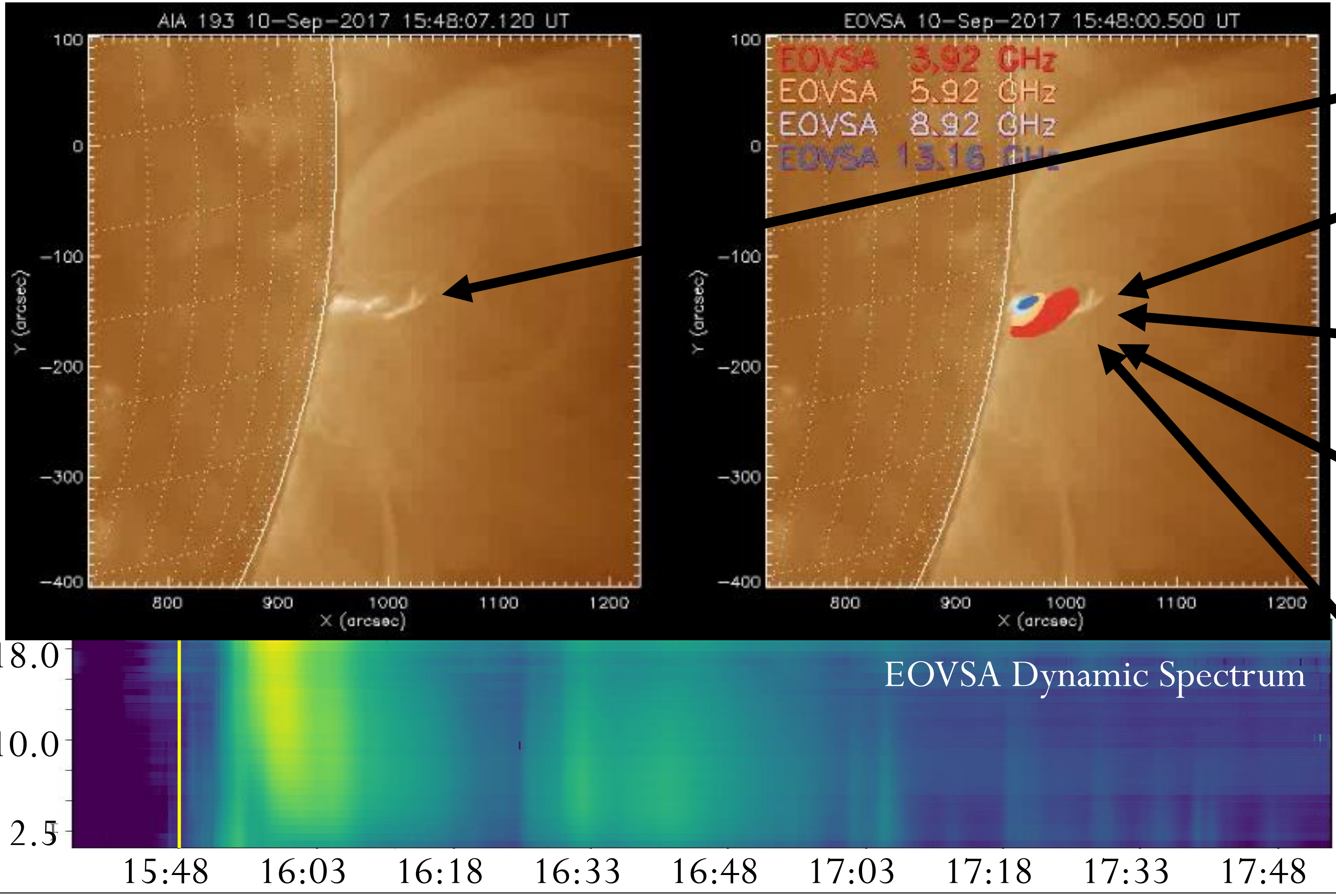
AIA 193 EOVSA



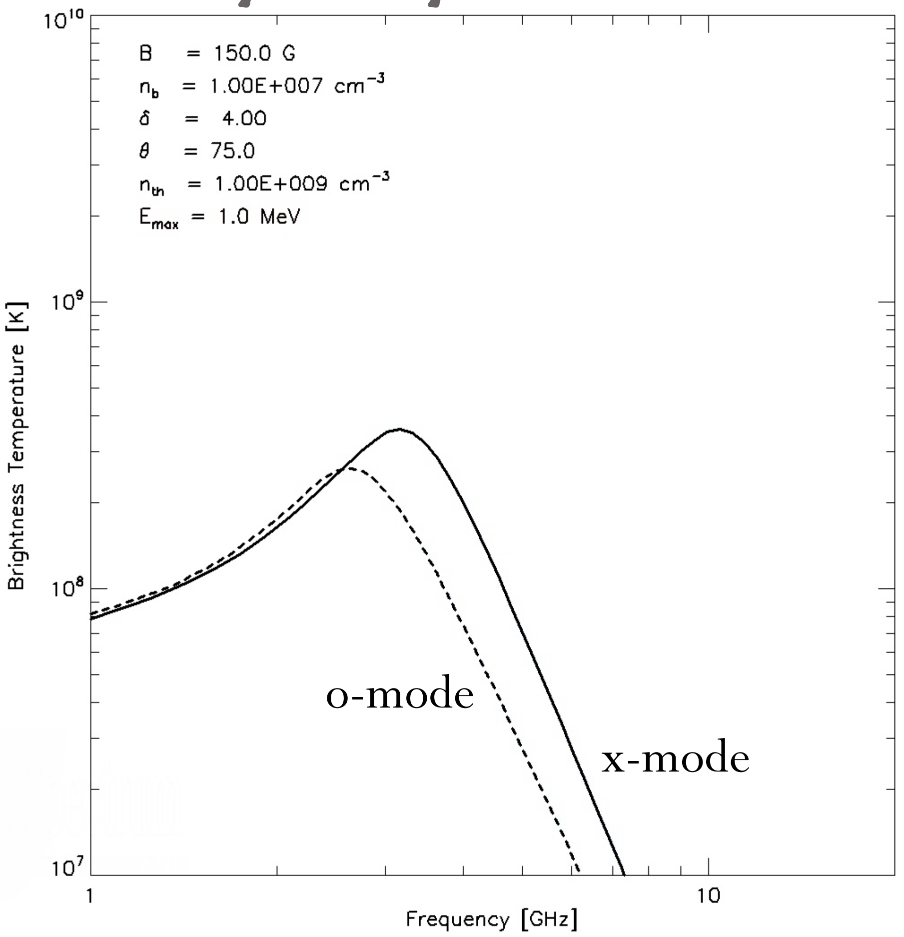
Dynamics!

- Filament and flux-rope eruption.
- Current sheet lights up in radio.
- Loops form and rise with time.
- Bifurcation of source by dense plasma sheet.
- Pulsations followed by thermal emission.

Incoherent Emission Diagnostics: Gyrosynchrotron

- Emission is due to nonthermal electrons gyrating in coronal magnetic field
- Microwave spectra provide sensitive diagnostics of magnetic field strength and energy distribution of nonthermal electrons, and in some cases, thermal electron density

Spatially resolved gyrosynchrotron spectra can be used to derive **maps** of **coronal magnetic field** and **nonthermal electrons**



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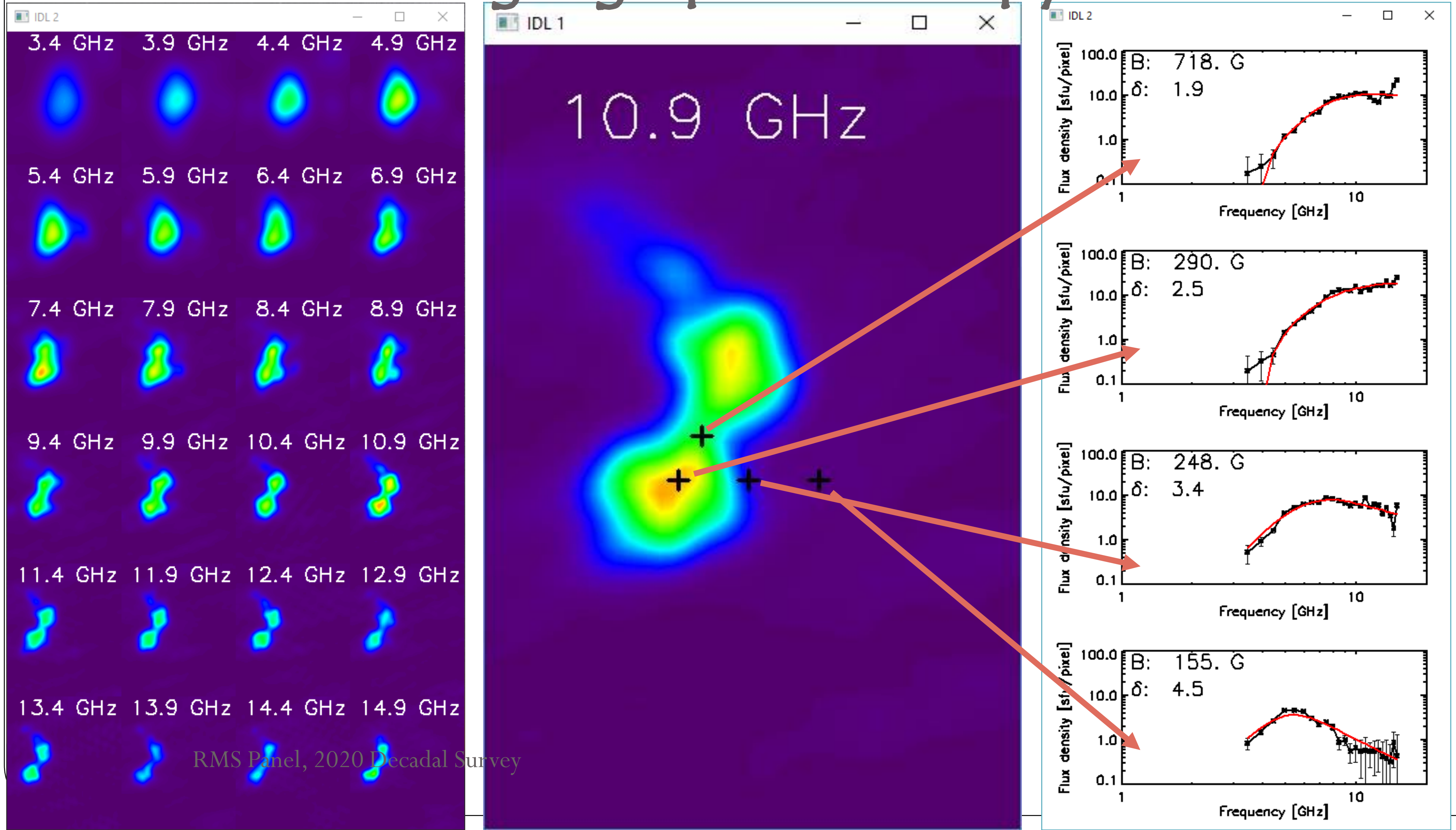
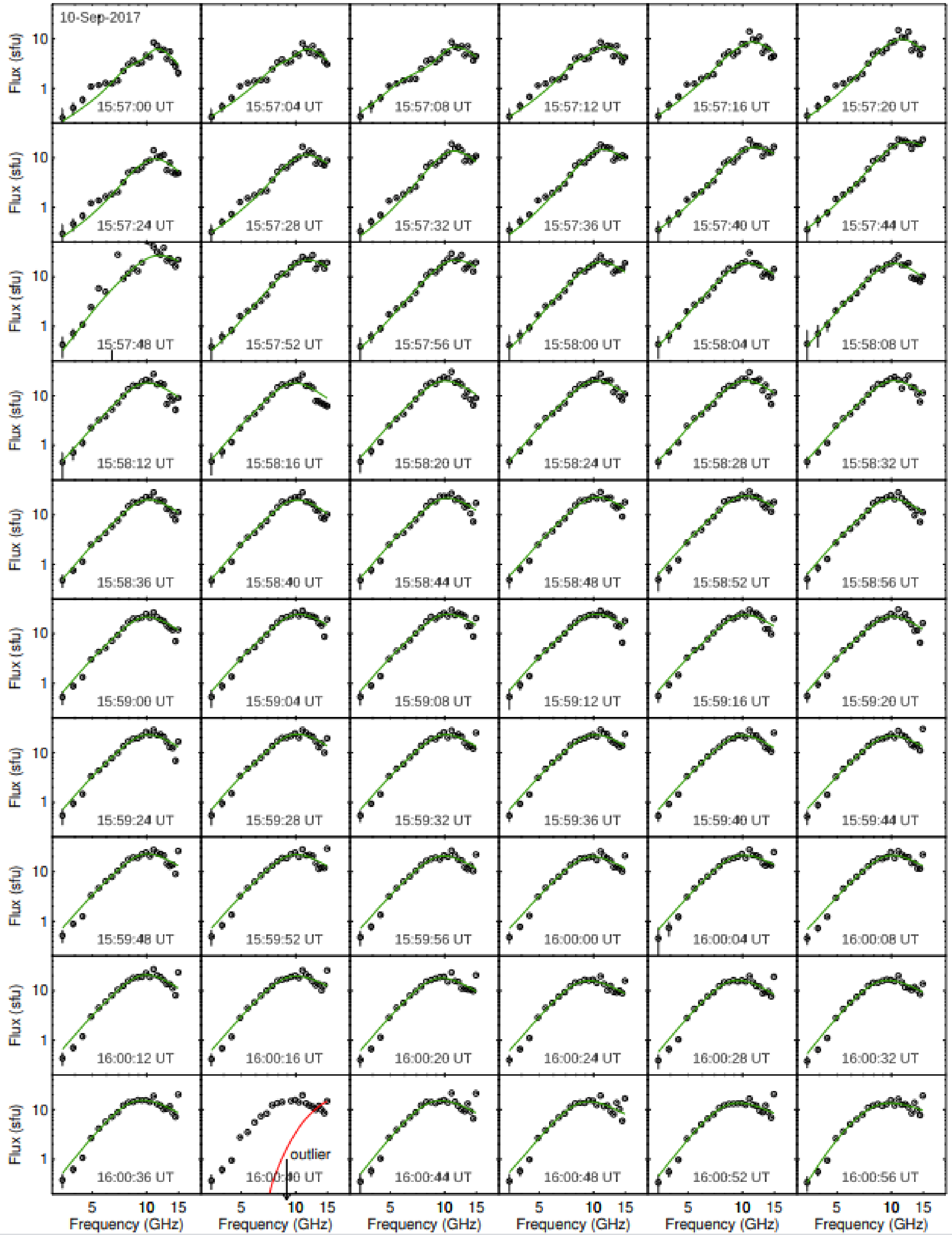
EOVSA Imaging Spectroscopy Method



- Magnetic field values are fairly consistent with time.
- Possible increase of electron spectral index at lower heights.
- We can make parameter maps and <u>movies</u> over the entire emitting region.



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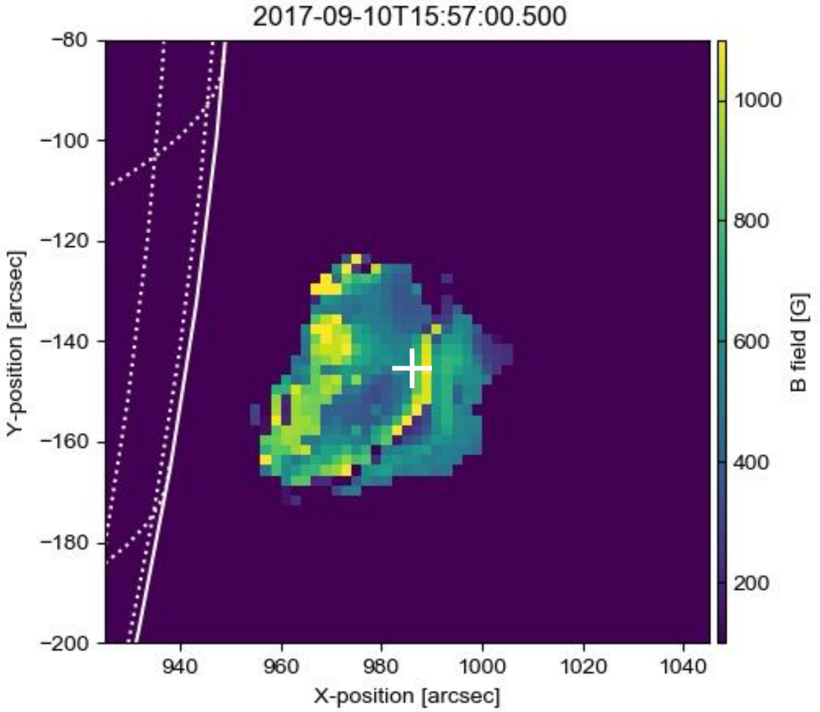
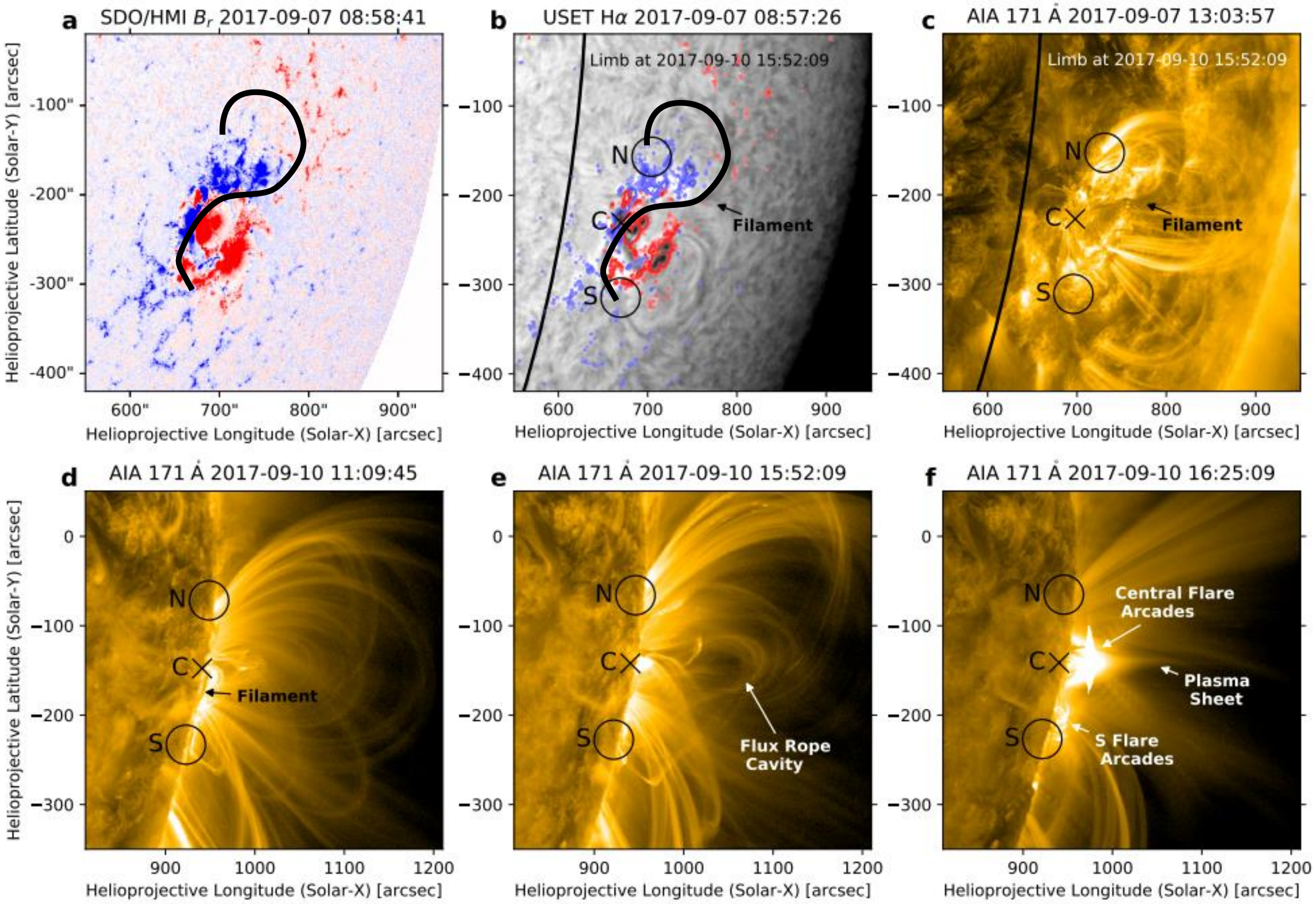
Fleishman et al. (2020), Science, 367, 278.



- Spectral fits every 4 s from location with + symbol.
- The spectrum grows brighter, broadens, and the peak frequency shifts lower with time.

Initiation of the 2017 Sep 10 Event

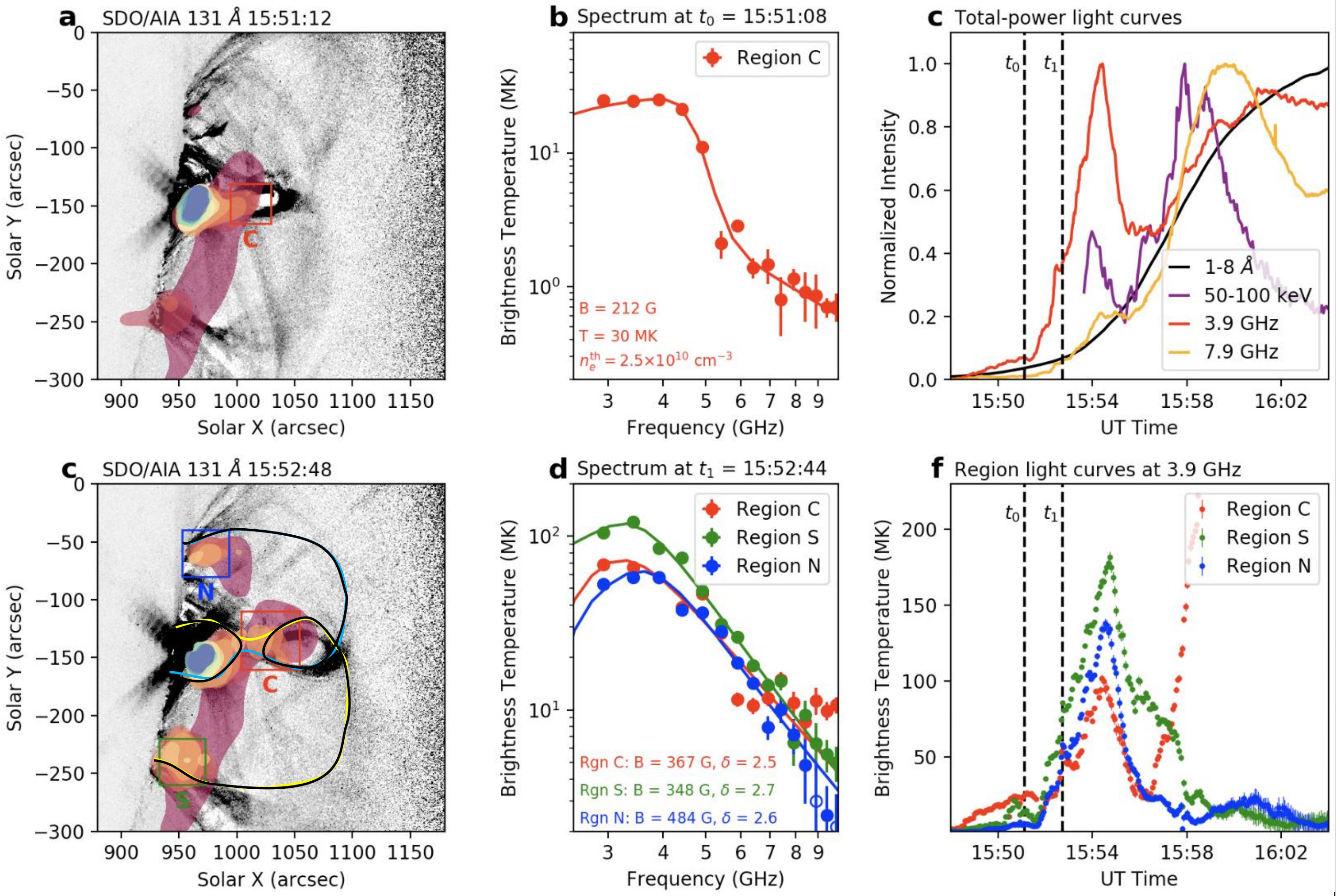
- Because the event occurred at the limb, we have to look several days earlier to understand the geometry of the event.
- The magnetic neutral line (between opposite polarity surface fields) winds N-S, then E-W, then N-S.
- A filament also traces this path.
- On the day of the event, these surface features were slightly past the limb.



Chen et al. (2020b), in preparation.

Outlier Sources Appear to be Ends of Flux Rope

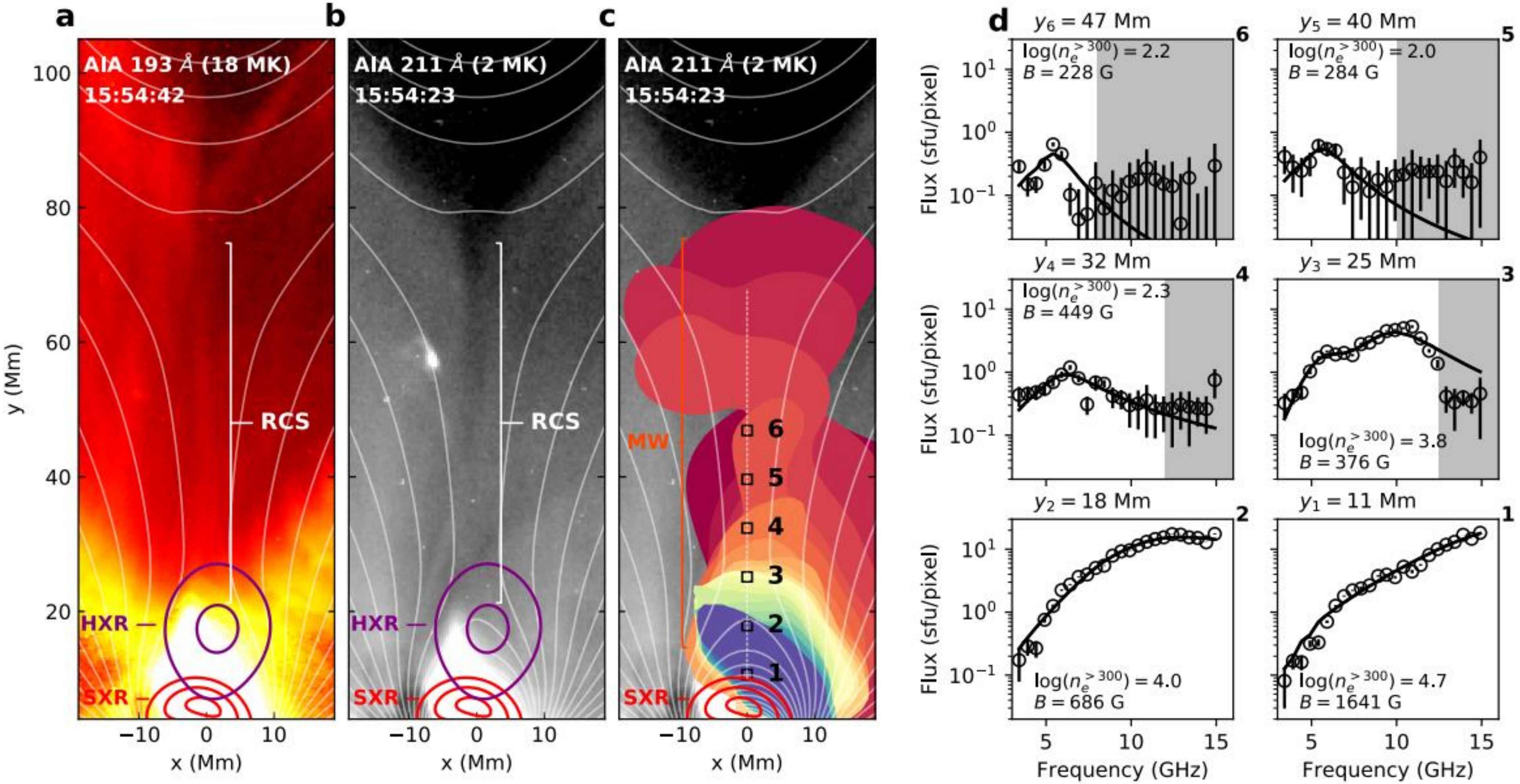
- The radio spectrum at the start of the radio emission (t_0) is consistent with super-hot thermal (30 MK).
- At later time (t_1) the outliers appear and all three sources (center, north and south) have similar, nonthermal spectra, with $T_b \sim 10^8$ K and $B \sim$ 350-480 G.
- All three sources brighten and fade together, until central source takes off toward 10^9 K around 15:58 UT.
- Conclusion is that the outlier sources are the ends of the flux rope.



Chen et al. (2020b), in preparation.

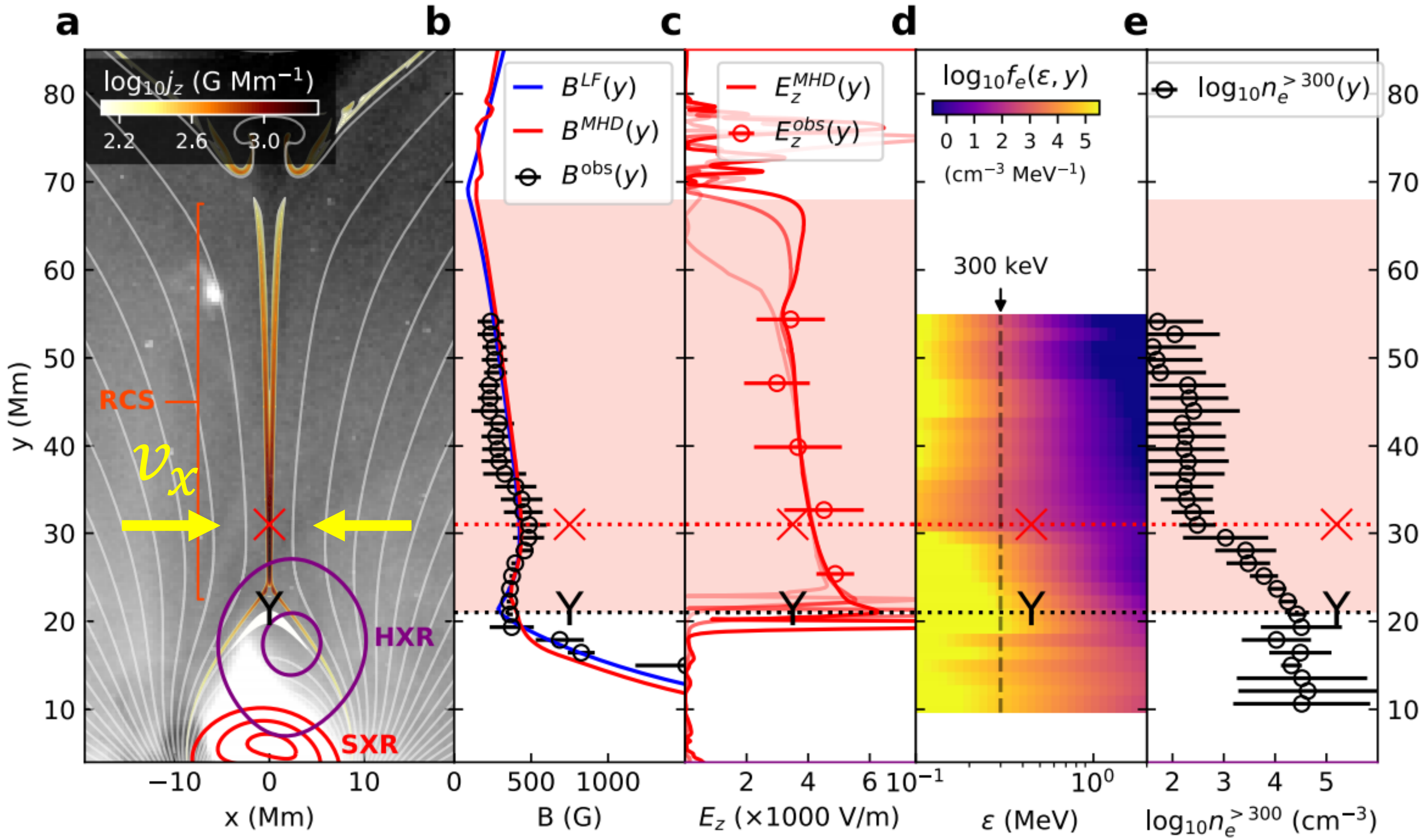
Spectral Fits Along Current Sheet

EUV diagnostics show a hot current sheet—bright at 18 MK, dark at 2 MK.



Chen et al. (2020a), Nature Astronomy, in review.

Fits and Height Profile of B, E, and Energetic Electrons



2.5-D dynamic MHD model comparison of magnetic and electric fields with those derived from observations, and location of nonthermal electrons.

$$E_z \approx v_x B_y / c$$

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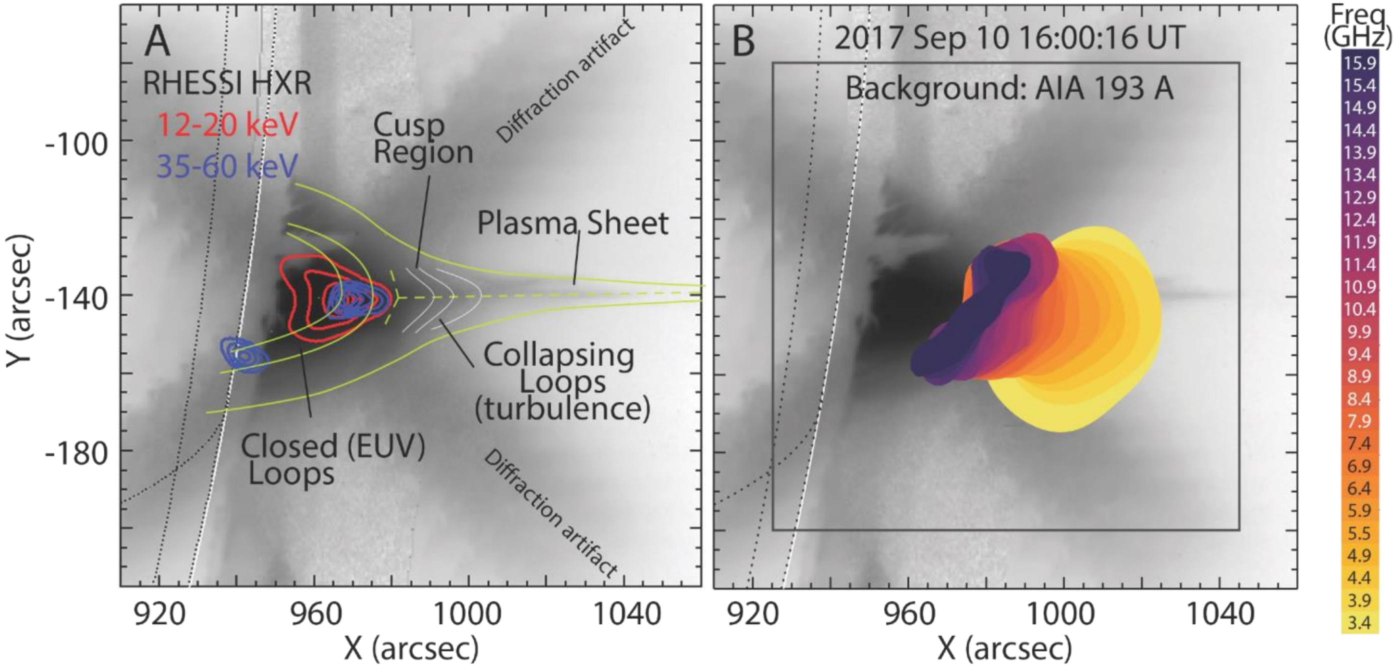
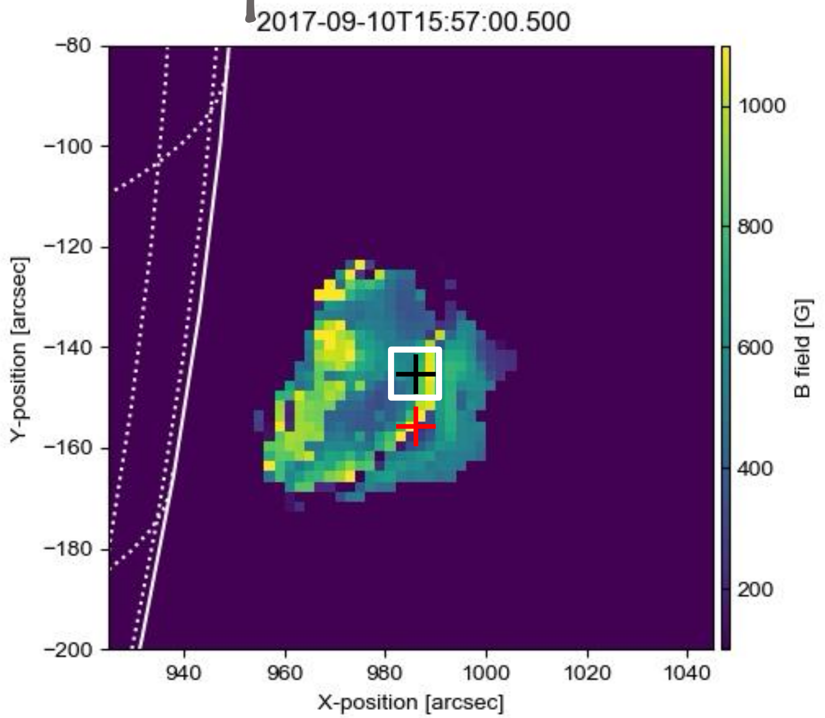
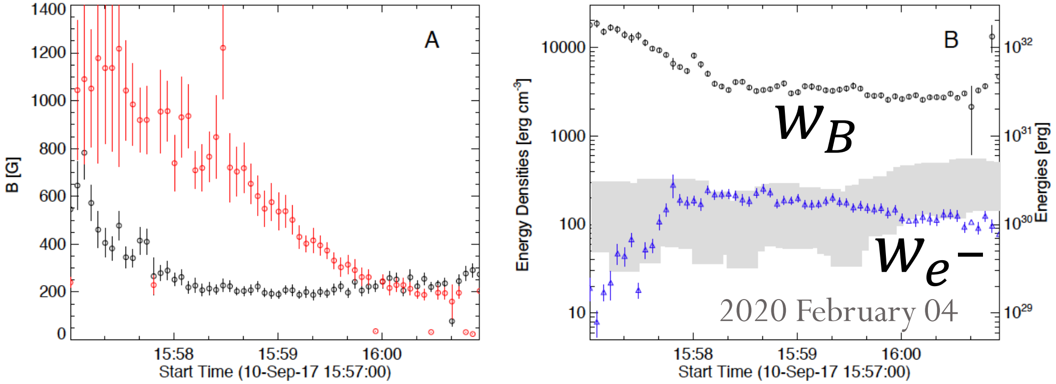
Fast Decaying Magnetic Field in Flare Loops





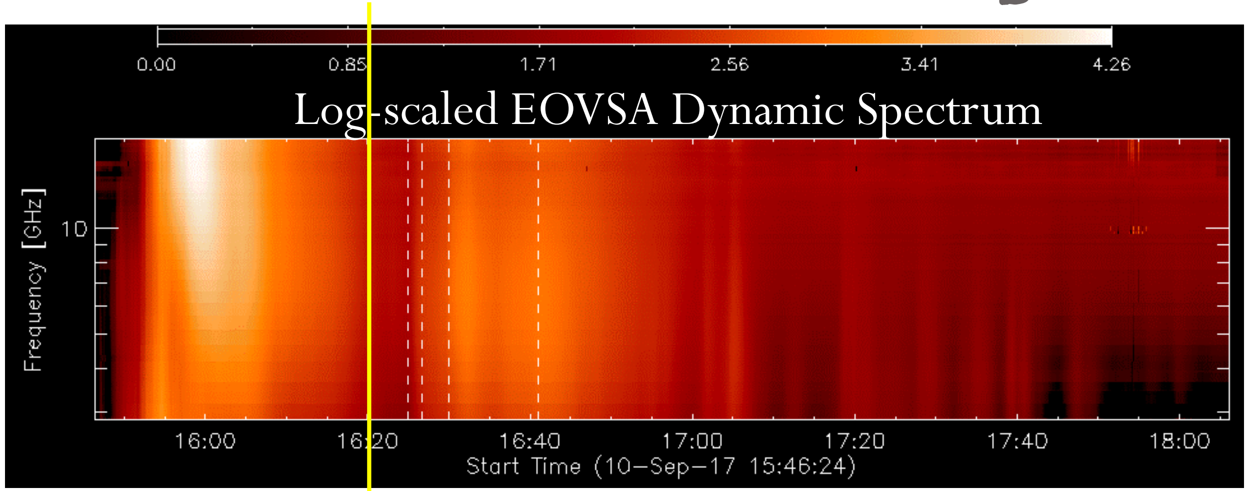
- Magnetic field decays rapidly in the cusp region at a rate of 5 G/s
- Strong electric field of ~2000 V/m
- Sufficient magnetic energy decrease to power electron acceleration and plasma heating



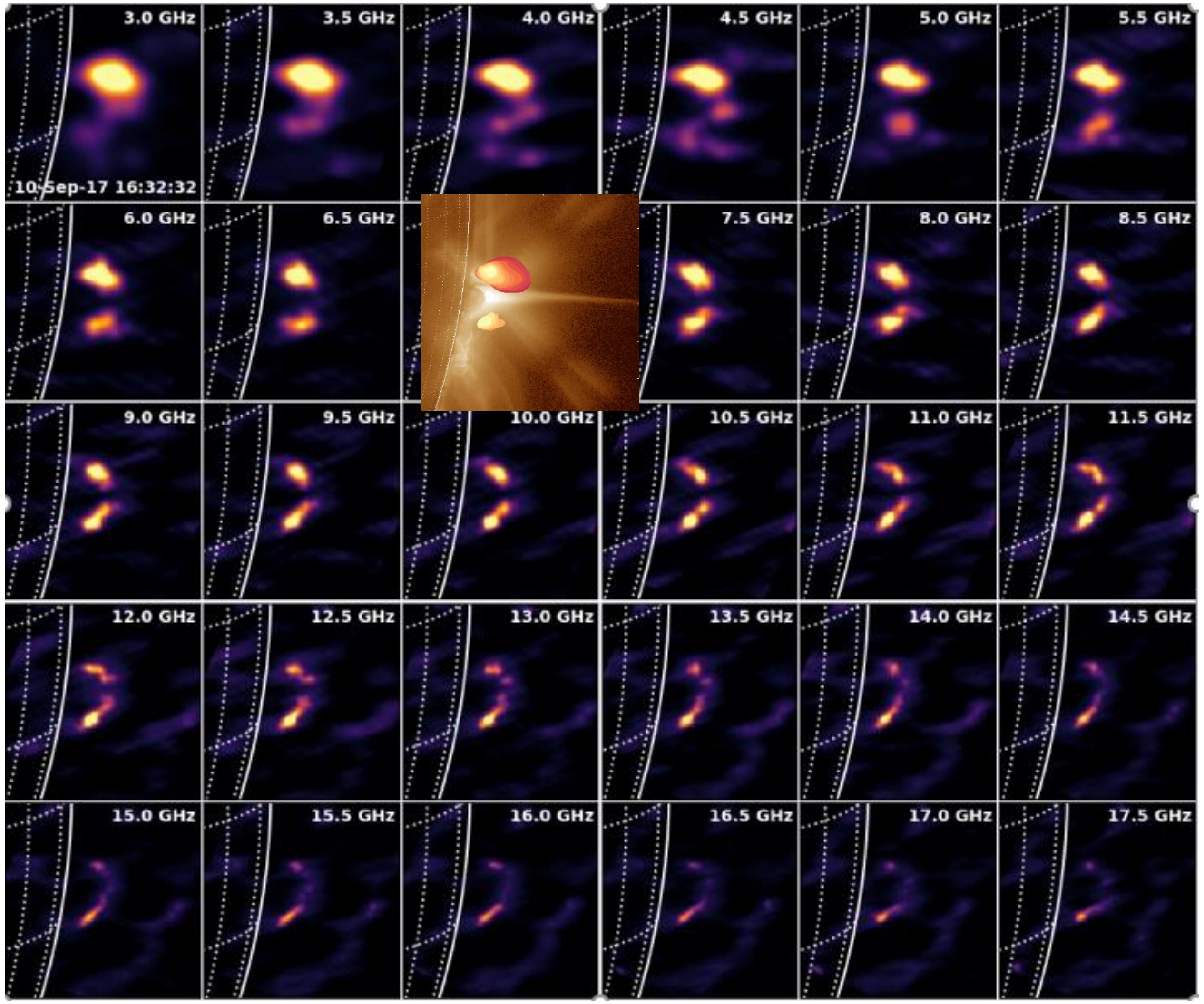
2020 February 04

Fleishman et al. (2020), Science, 367, 278.

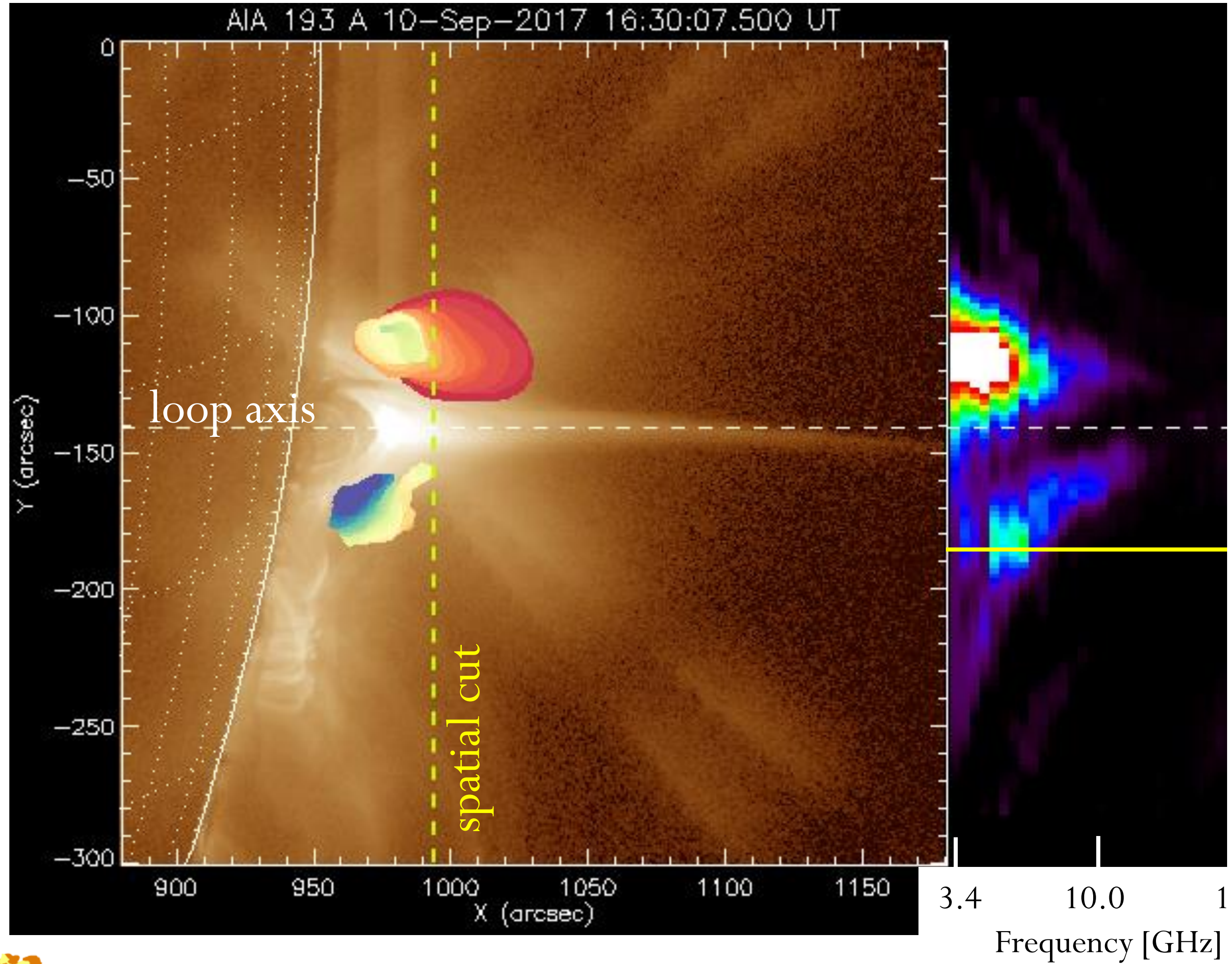
Secondary Component Movie of EOVSA Images

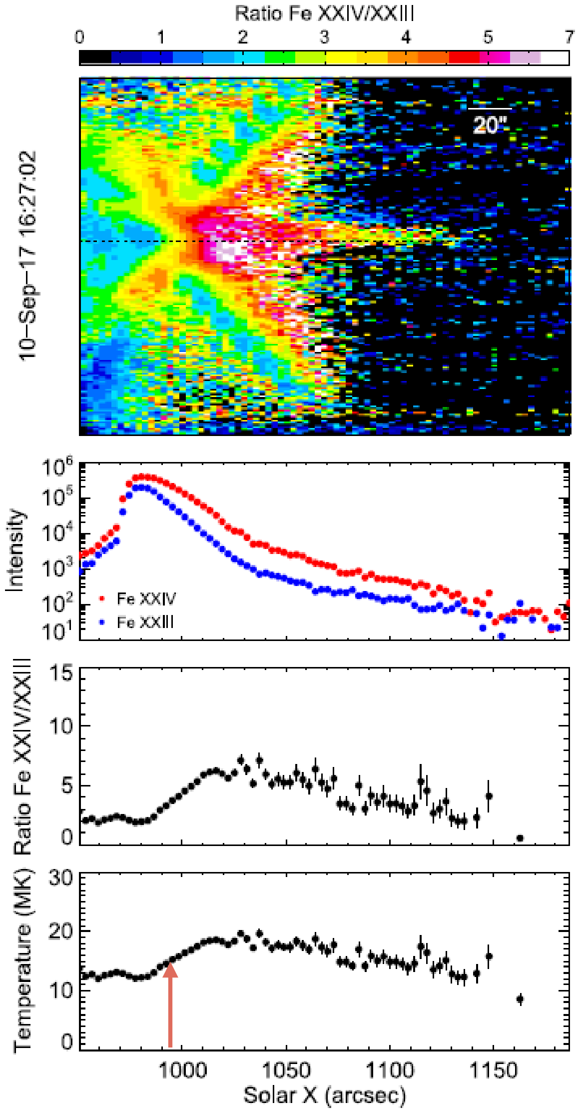


- The gyrosynchrotron emission in microwaves is split into a northern and southern lobe.
- The Northern lobe encroaches over the plasma sheet while the southern lobe appears to peek out from behind the plasma sheet.
- We investigate whether the gap may be due to free-free absorption of the microwave emission.



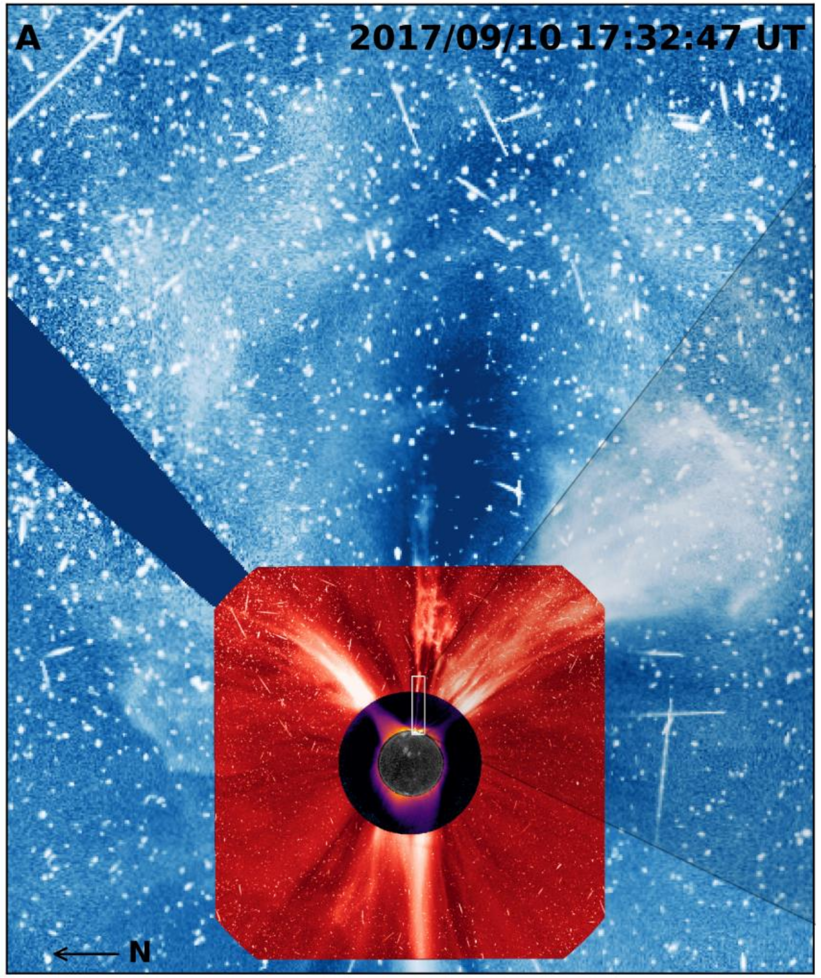
Spectra Along Spatial Cut Across Plasma Sheet





- The $\tau = 1$ frequency depends on column emission measure and plasma temperature $n_e^2 L/\sqrt{T}$.
- EOVSA results are NOT consistent with EUV diagnostics (T~15 MK), but require a lower temperature (T~5 MK).
- This may be due to non-equilibrium ionization (ions are over-ionized relative to electrons).

Late Phase and MW / X-ray Sources



Extremely Long Thin Plasma Sheet (extend to ~2.5 R_{sun})

Looptop HXR source

Looptop and Loopleg Microwave Sources

Why a Solar-Dedicated Instrument?

- **The Sun is whopping bright.** The brightness temperature in this event exceeded 10^9 K, flux exceeded 20,000 sfu (2×10^8 Jy).
- **The spectrum changes fast.** The entire spectrum has to be measured on fast (1 s or faster) cadence.
- **The power level changes fast.** To follow the dynamic range of this event, the EOVSA system automatically detected power level changes and inserted 20 dB in 2 dB steps (attenuation inserted within 1 s). Stepped attenuation is a <u>must</u>!
- **The Sun is unpredictable.** Solar-dedicated operation every day/all day is needed.
- EOVSA's innovations in rapid frequency switching (1 ms dead time, 20 ms sample time) and attenuation switching were absolutely REQUIRED to do the science shown here.

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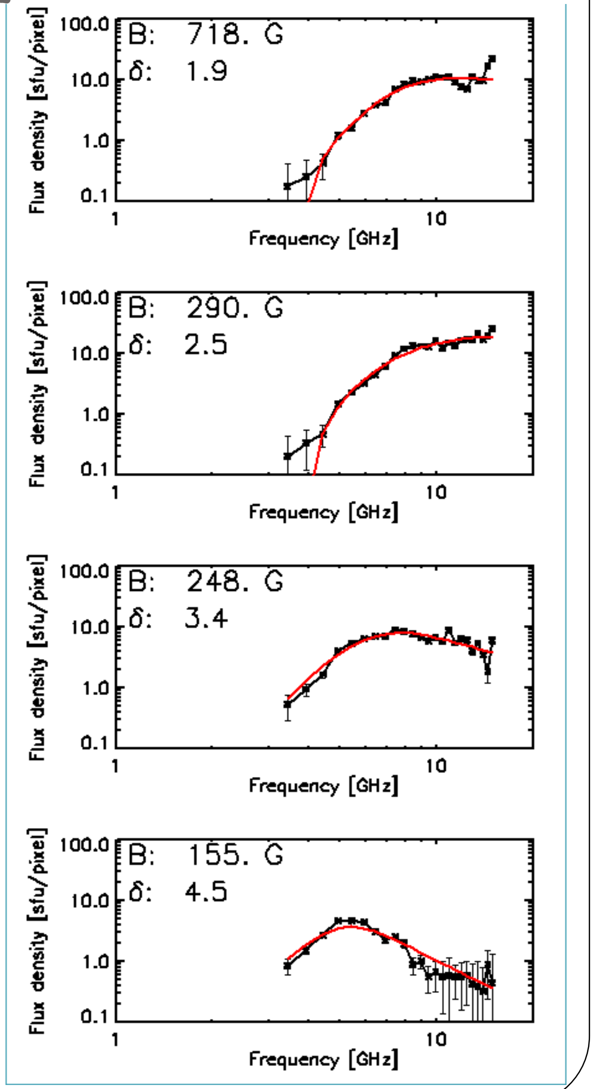
Why FASR? The Problem of Sparse Arrays

- This was a bright flare whose brightest part of the spectrum could be well fit, but the lower brightness parts have large error bars due to limited dynamic range.
- Only the strongest flaring sources can be seen, while weaker ones are lost in the sidelobes produced by imaging with a sparse array.
- The spectral fits assume <u>isotropic pitch angles</u>, <u>single-powerlaw</u> energy spectra, and <u>homogeneity along the line of sight</u>. Subtle changes in spectral shape can reveal violations of these assumptions, and lead to more physical models that can be compared with theory. FASR image quality and dynamic range are needed.
- The emission from weaker events competes with the rest of the solar active region and disk sources, which cannot be imaged in snapshot mode. FASR will image the entire disk instantaneously.



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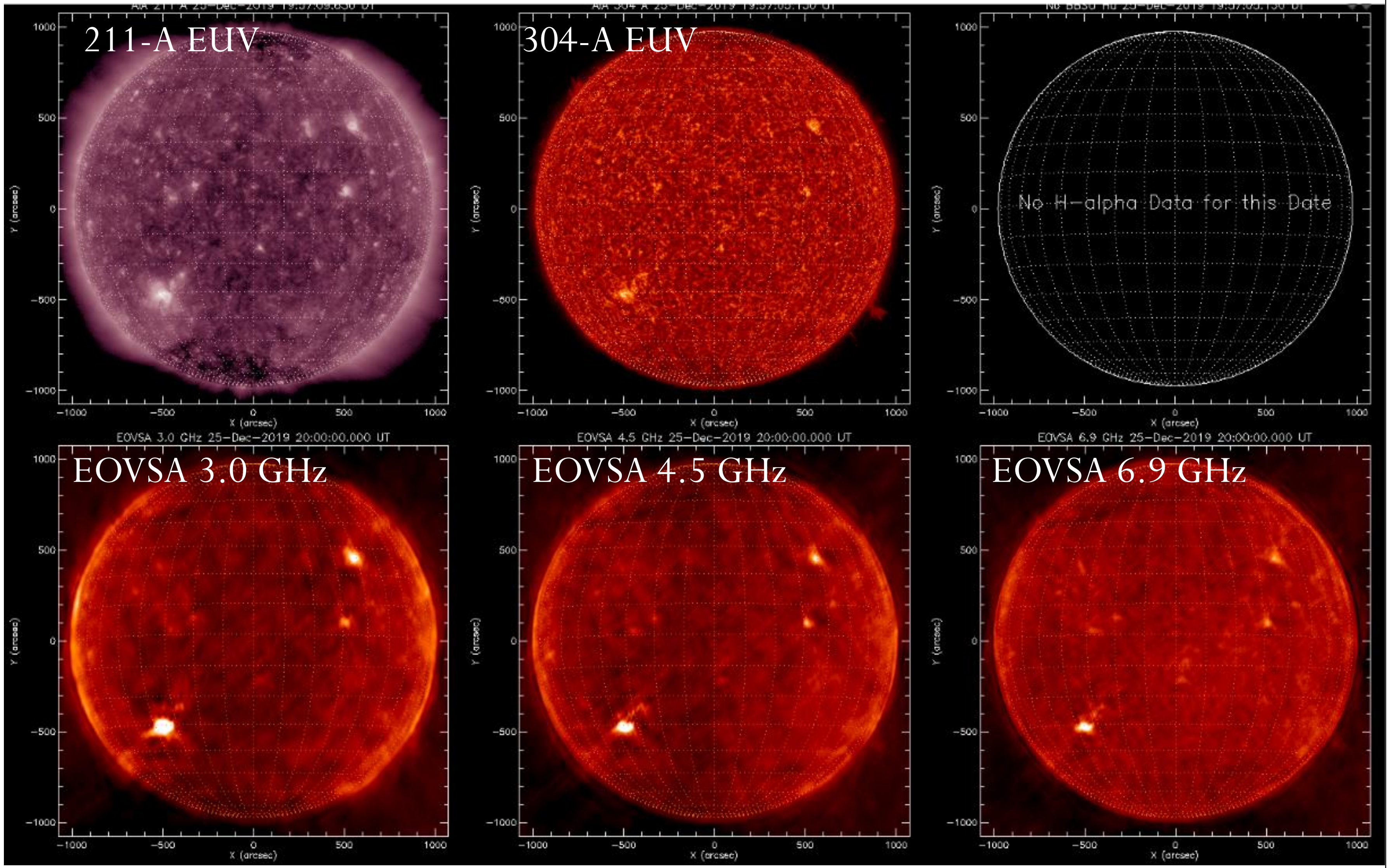
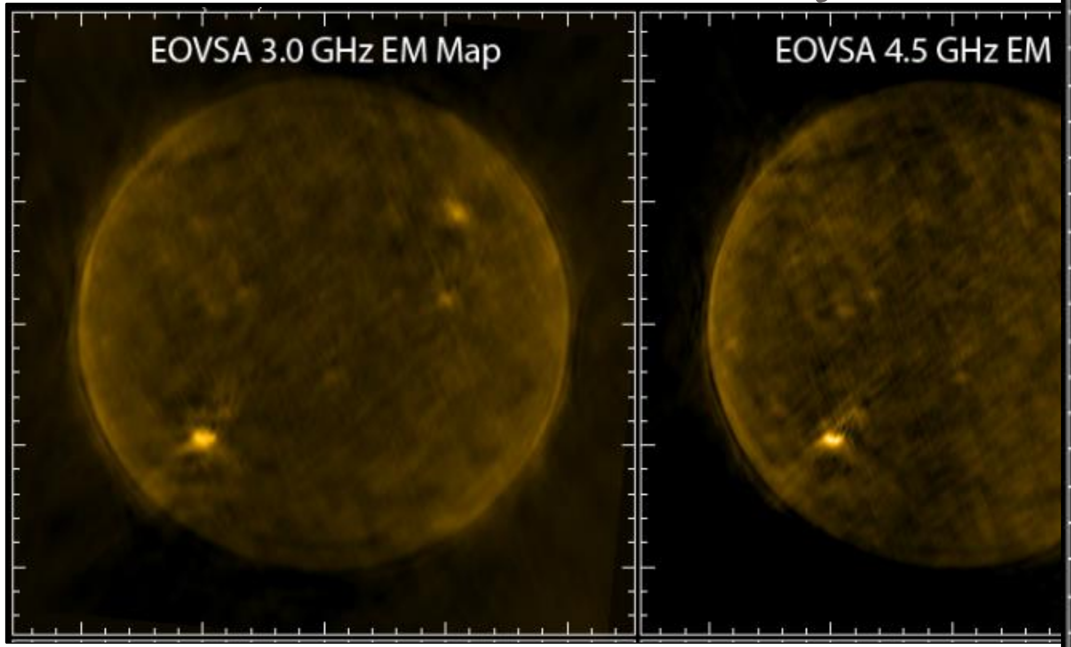
All-Day Quiet Sun Maps

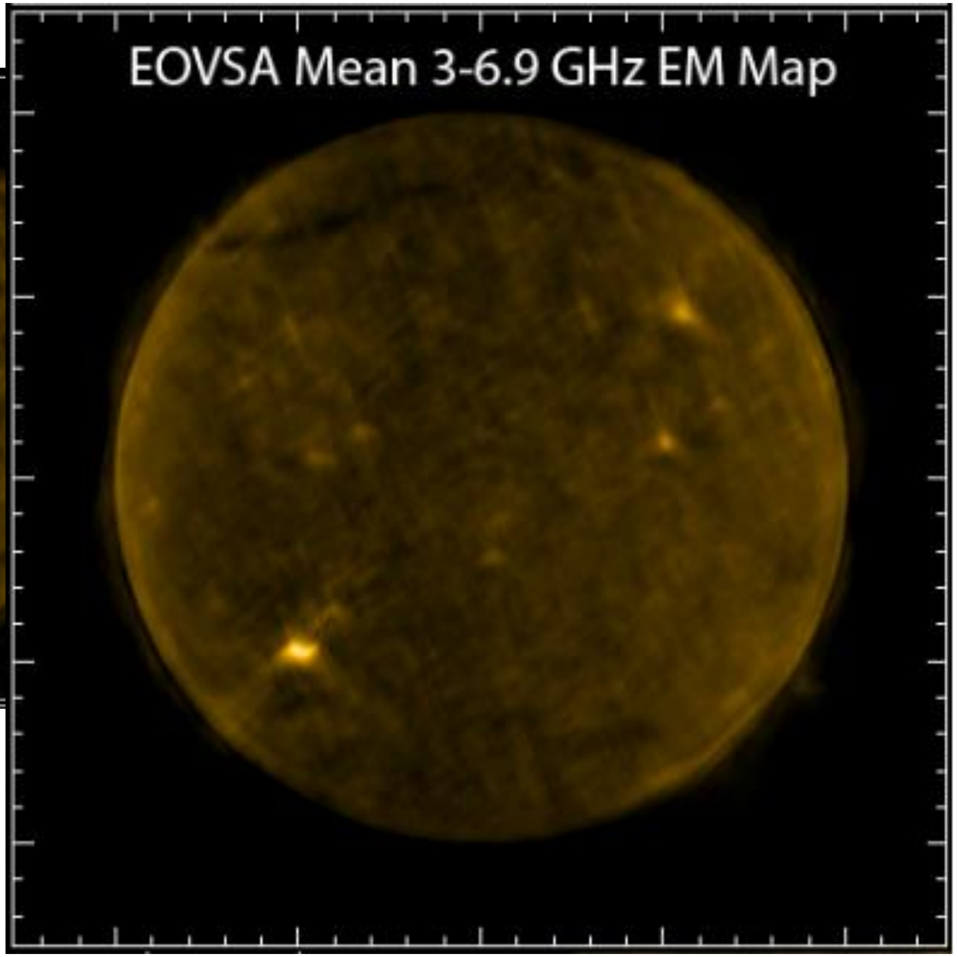
- EOVSA's sparse array does not allow snapshot images of the full disk.
- However, an all-day (8-hour) synthesis does <u>for the first time</u> reveal the multi-frequency quiet Sun.

$$\boxed{T_b = T_{\mathrm{chrom}} + \tau T_{\mathrm{cor}}}$$



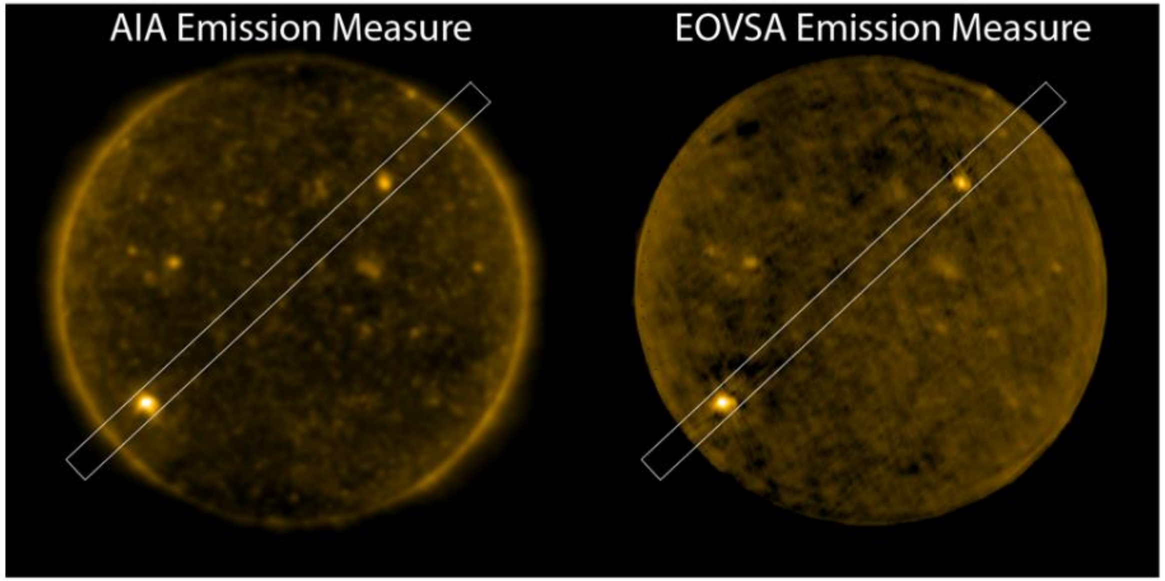
Emission Measure Maps

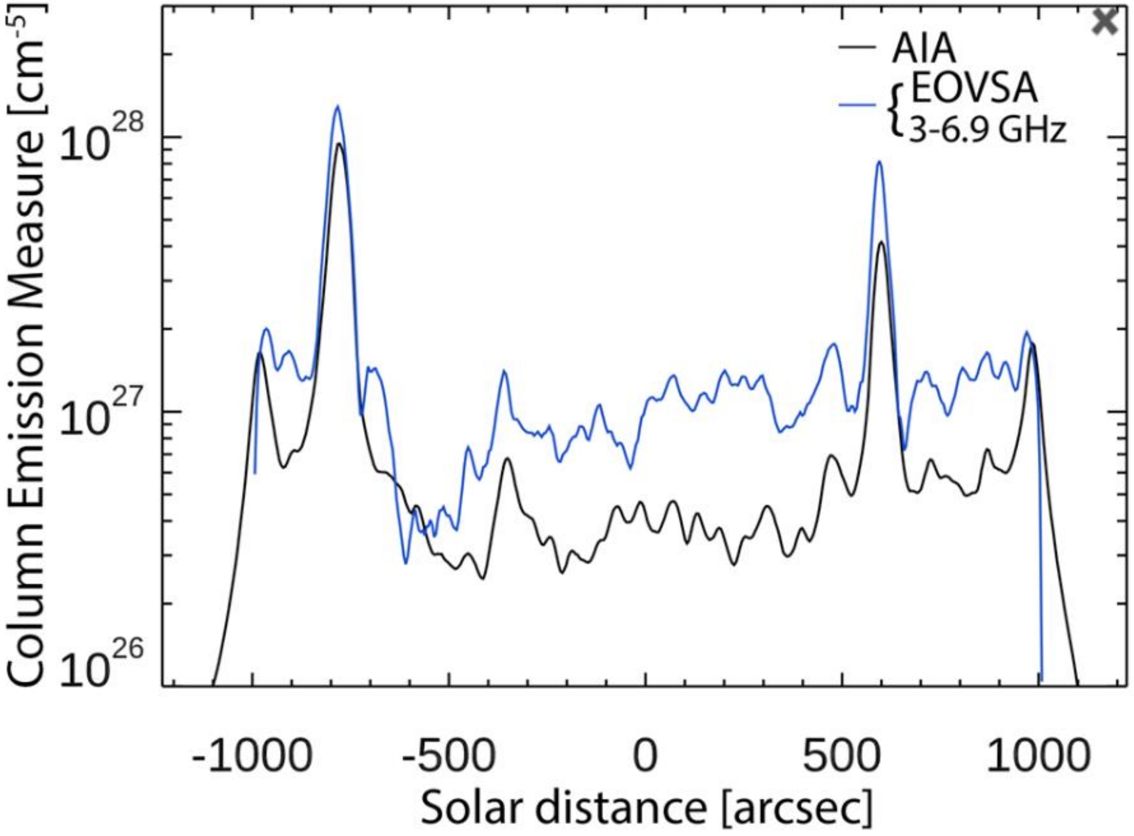




$$\frac{EM}{\sqrt{T_6}} = 1000\,\nu^2\,\frac{T_b(\nu) - T_{\mathrm{chrom}}}{\zeta}$$

Ion-Based vs. Electron-Based Emission Measure

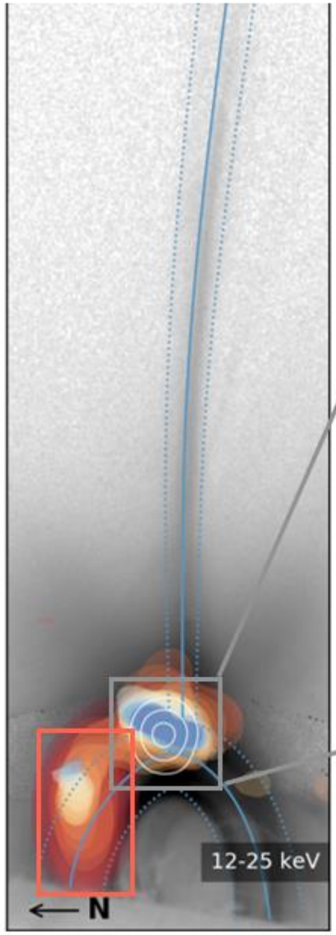




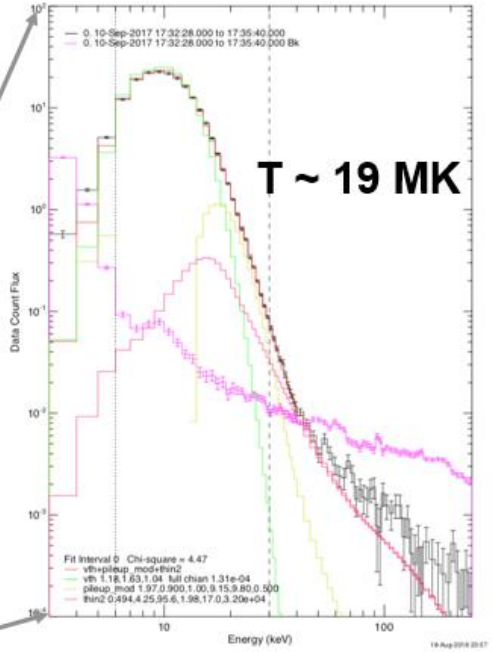
Backup Slides

Episodic Reconnections Power Nonthermal Source

- Looptop source is static, entirely thermal (superhot, 19 MK)
- Loop leg source comes and goes, triggered by episodic reconn-ections, highly nonthermal.

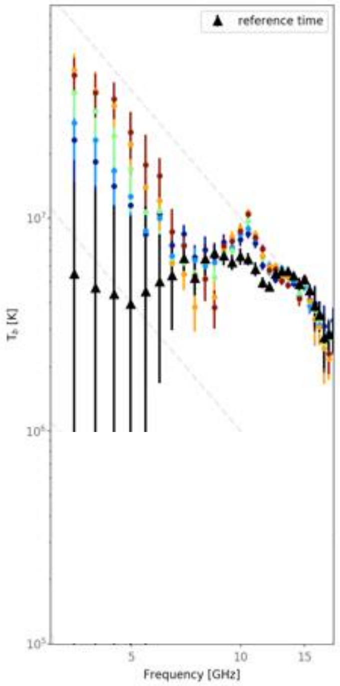


Looptop HXR Source



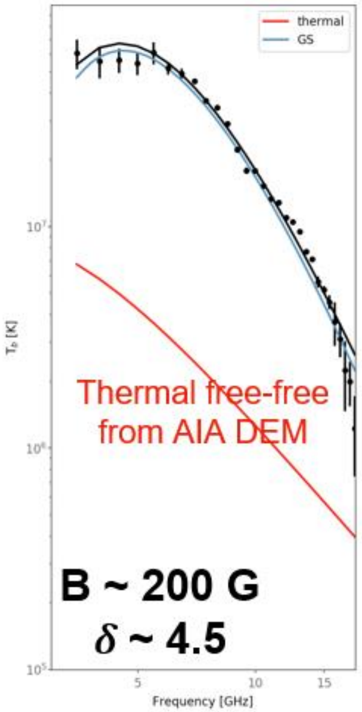
Thermal (no detectable nonthermal component)

Looptop MW Source



Possibly thermal (needs further investigation)

Loopleg MW Source



Very likely nonthermal

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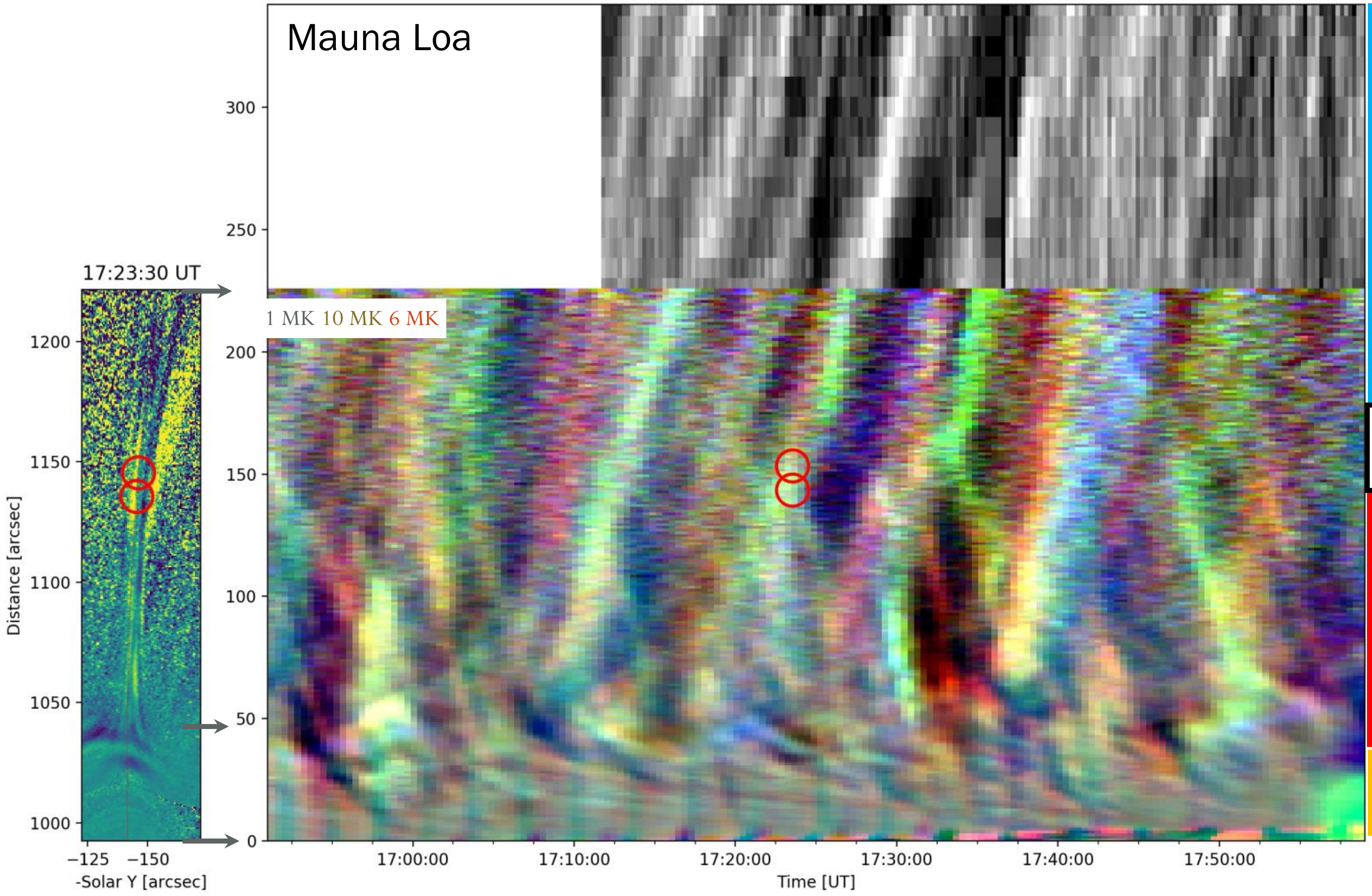
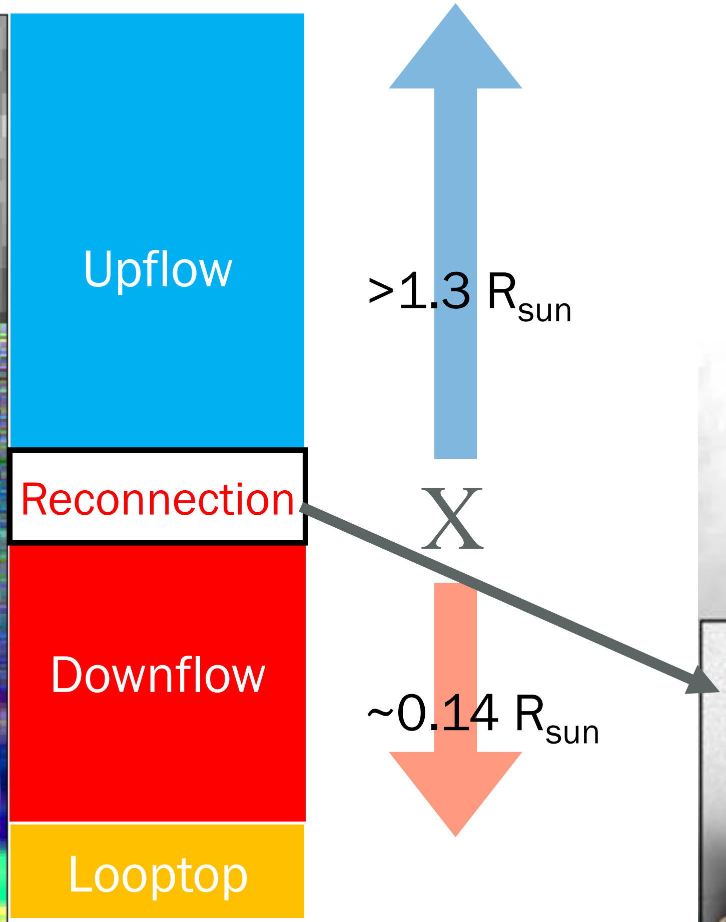
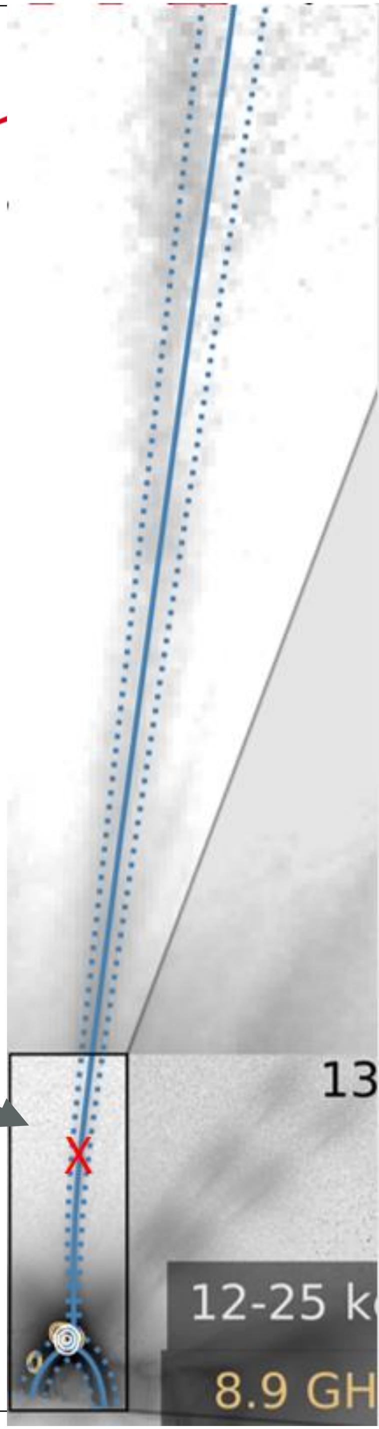
Bi-Directional Outflows and Extremely Low Reconnection Site

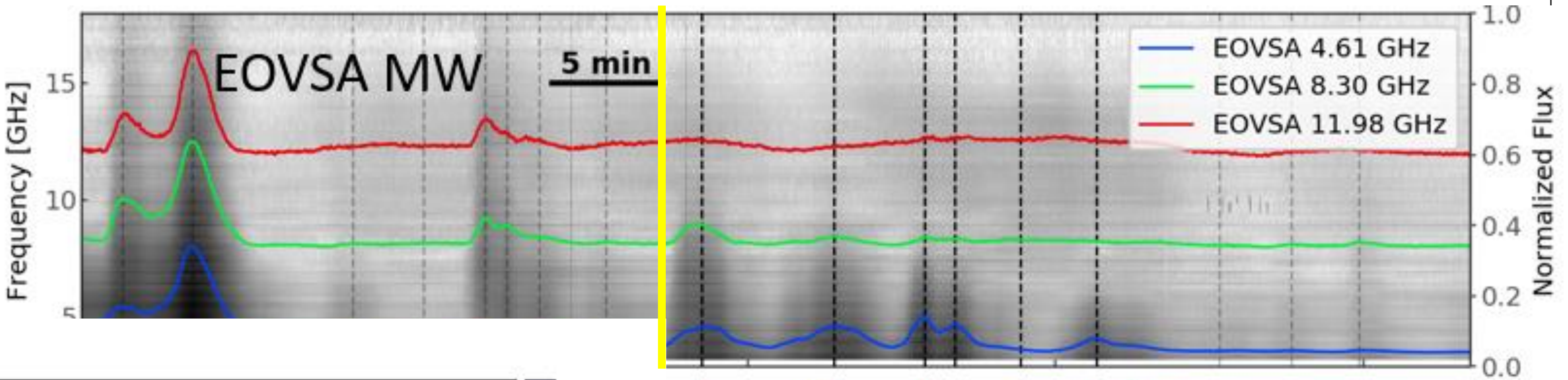
CME Core: ~10 Rsun



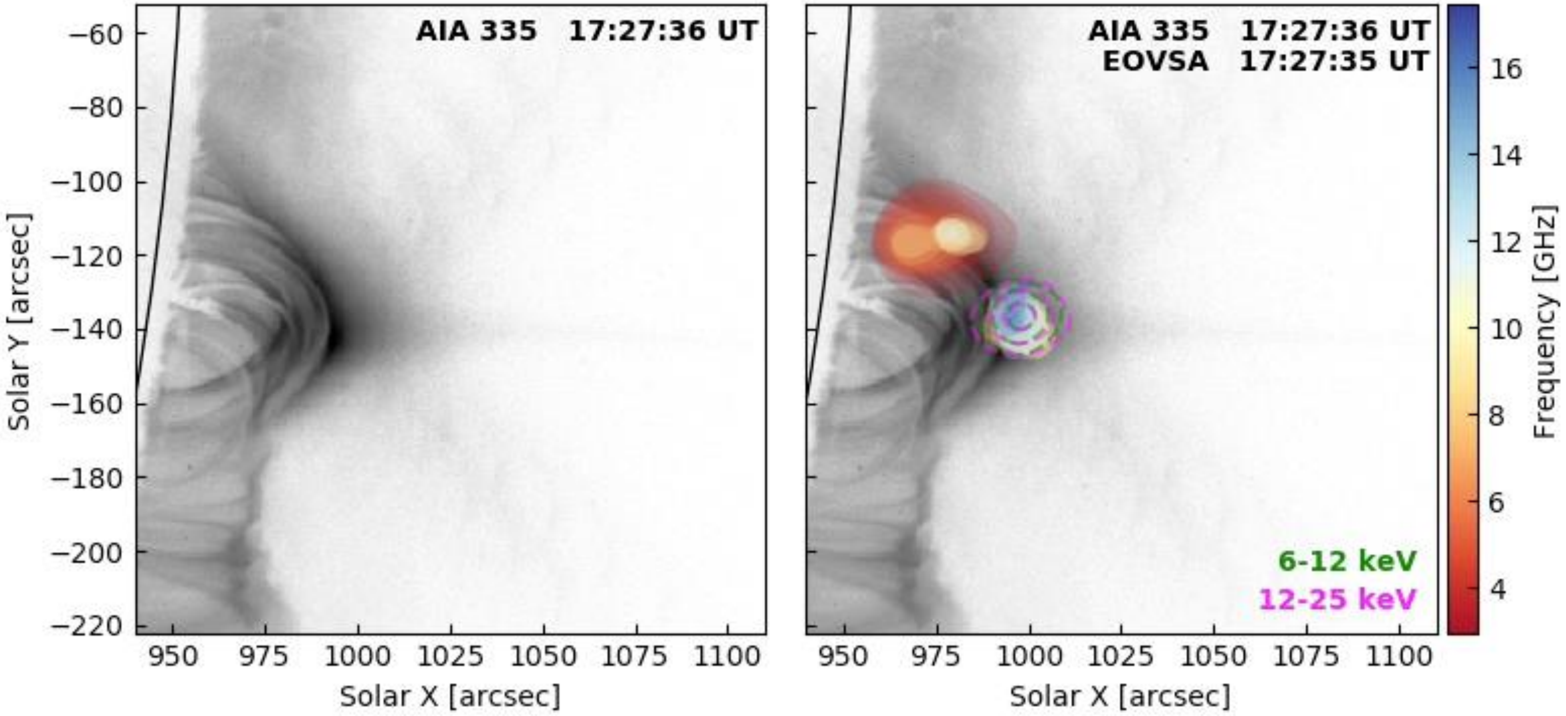


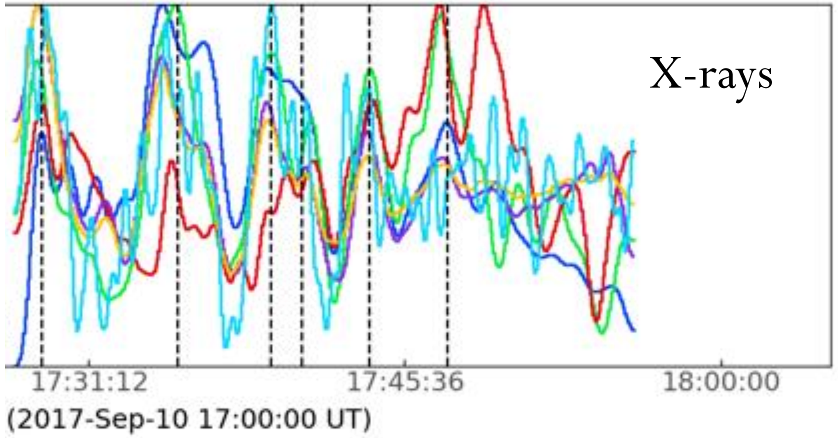


2017-SEP-10 Movie: 17:31 – 18:06 UT

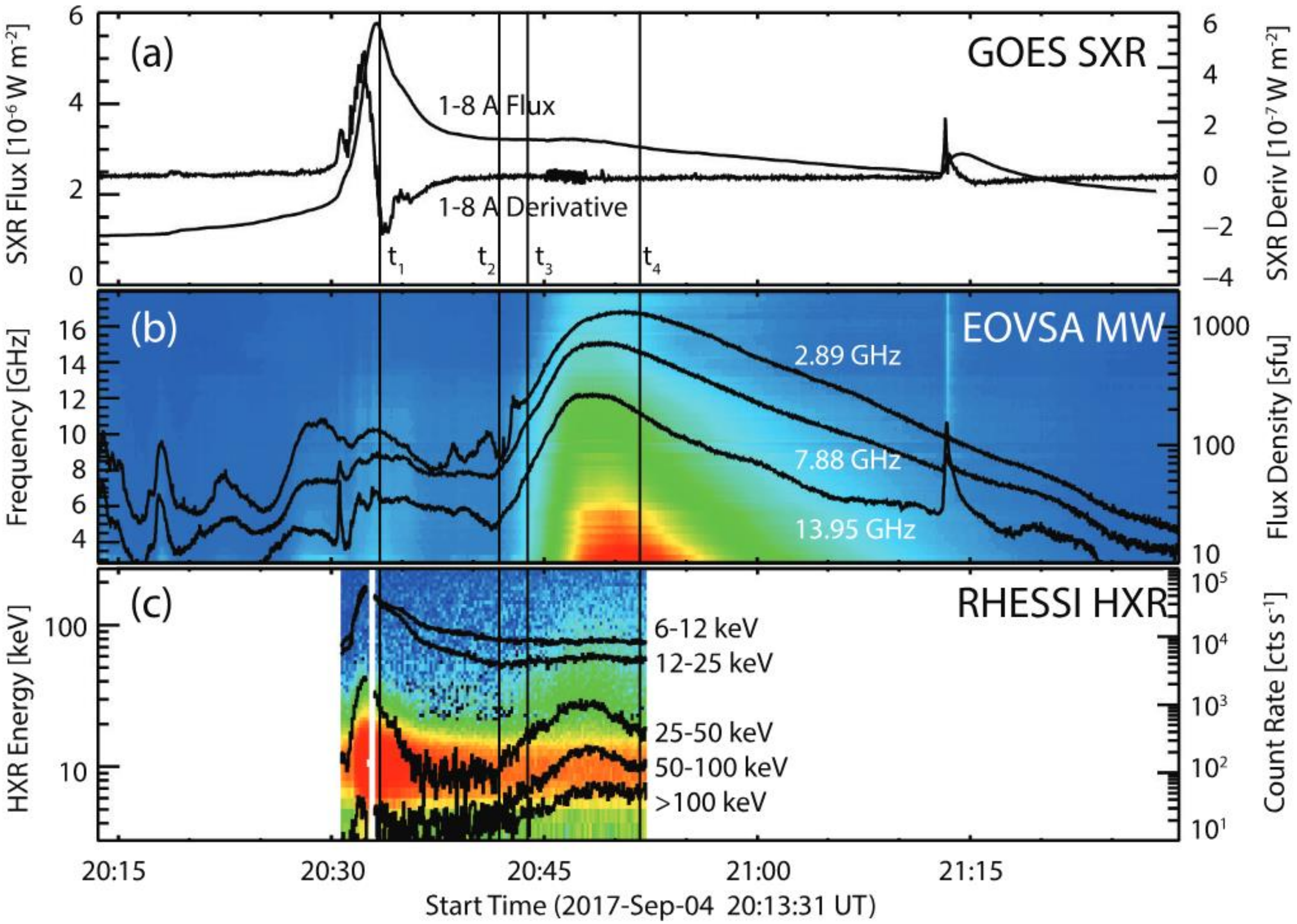


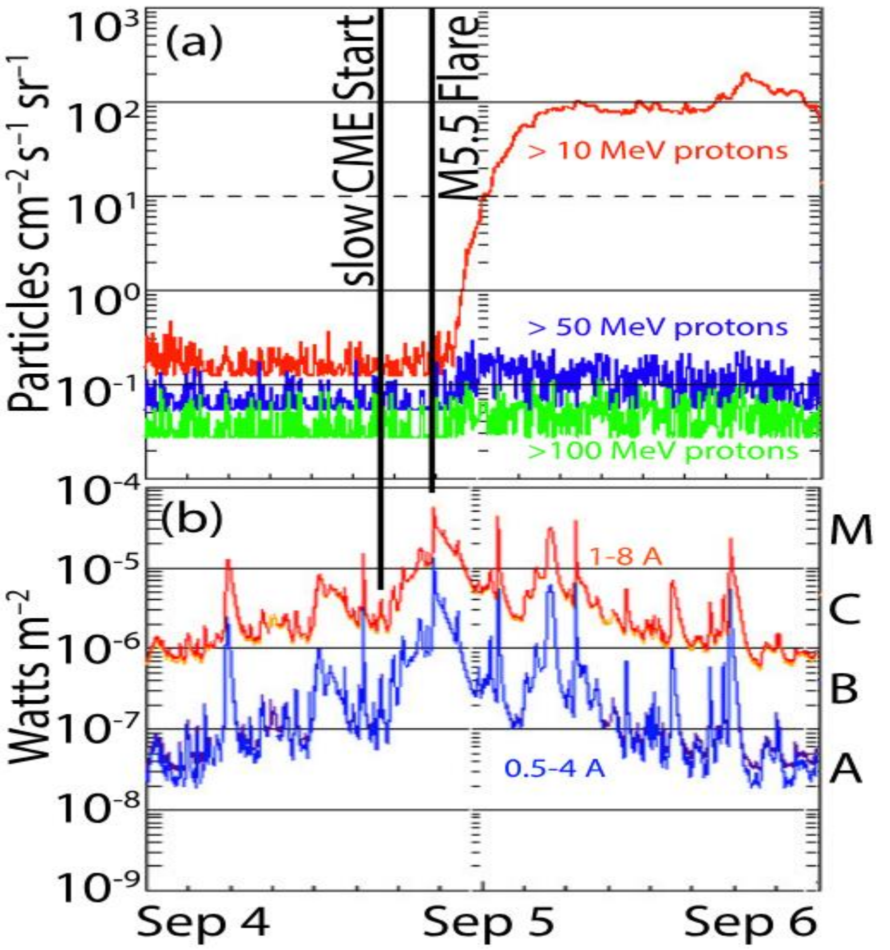
Sijie Yu, paper in preparation



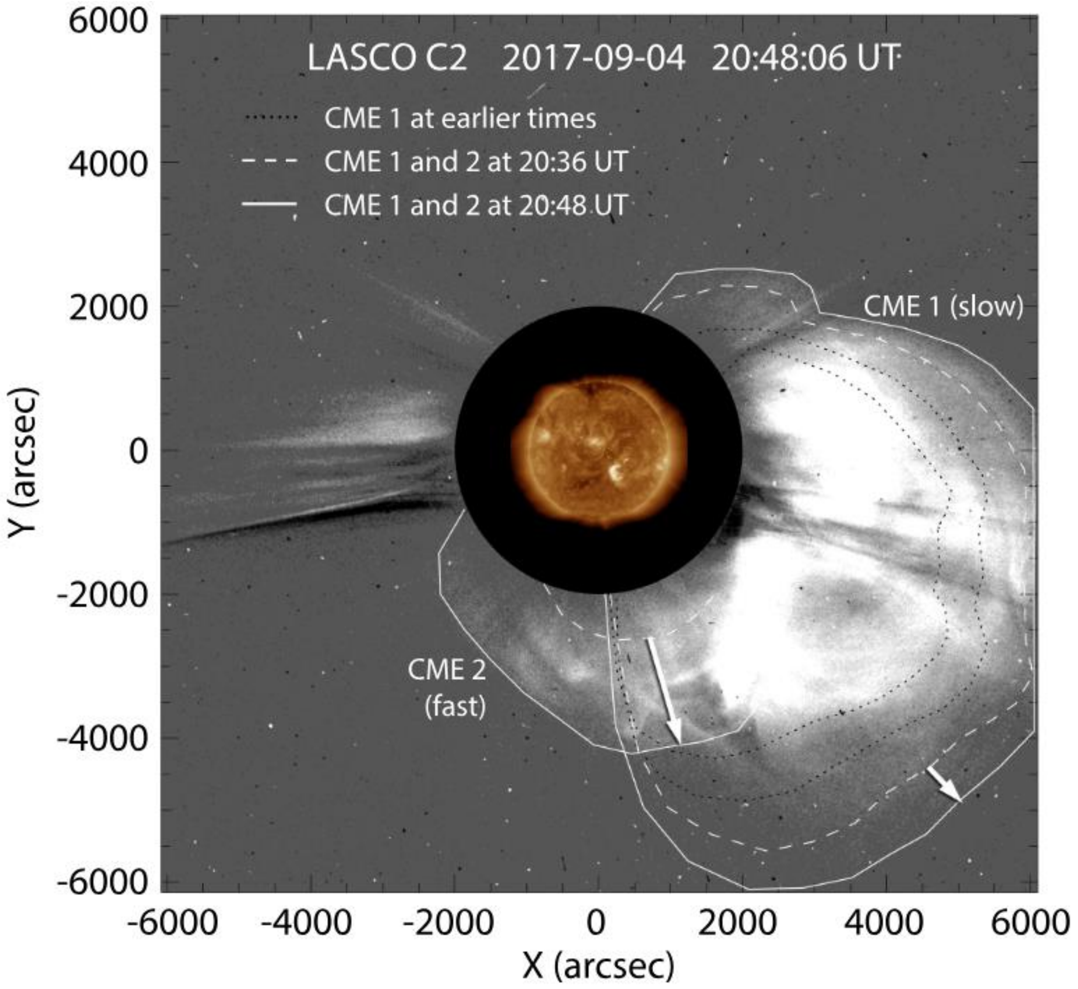


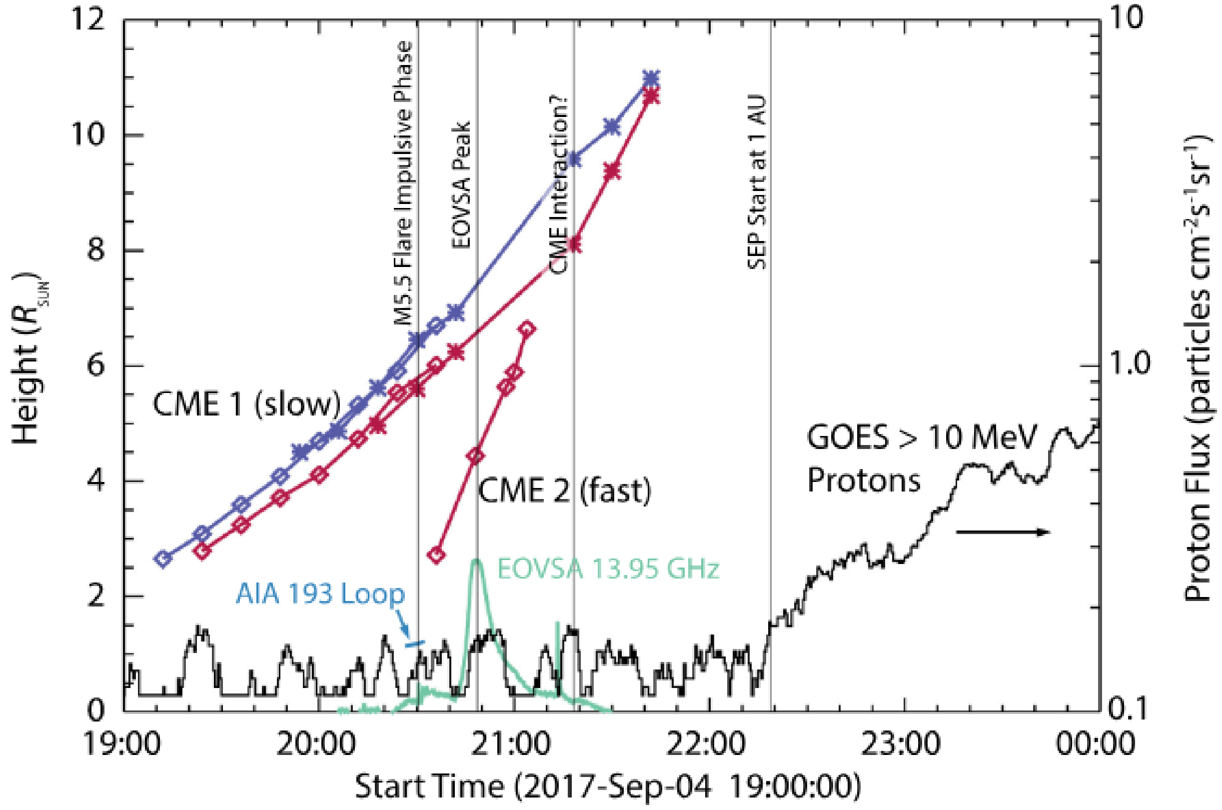
2017 September 04 SEP Event Timing



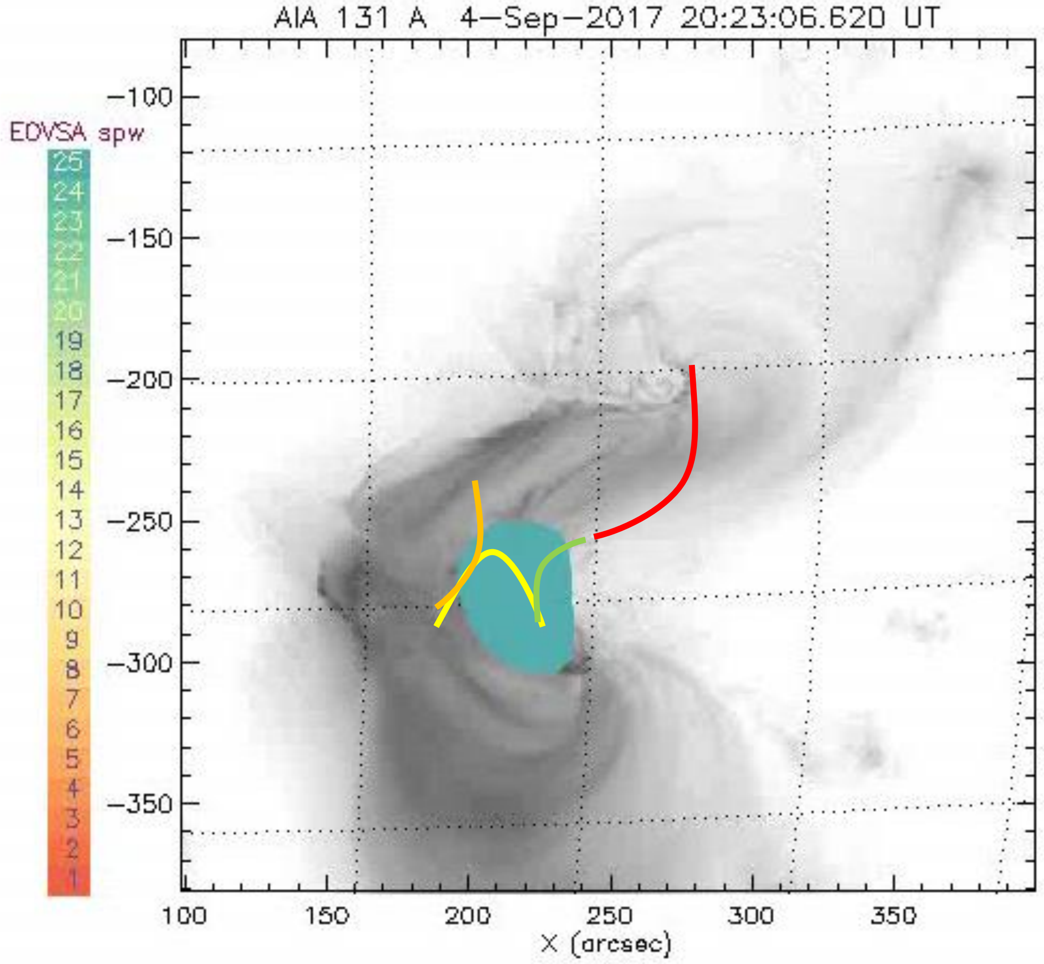


Associated CME and SEP Activity



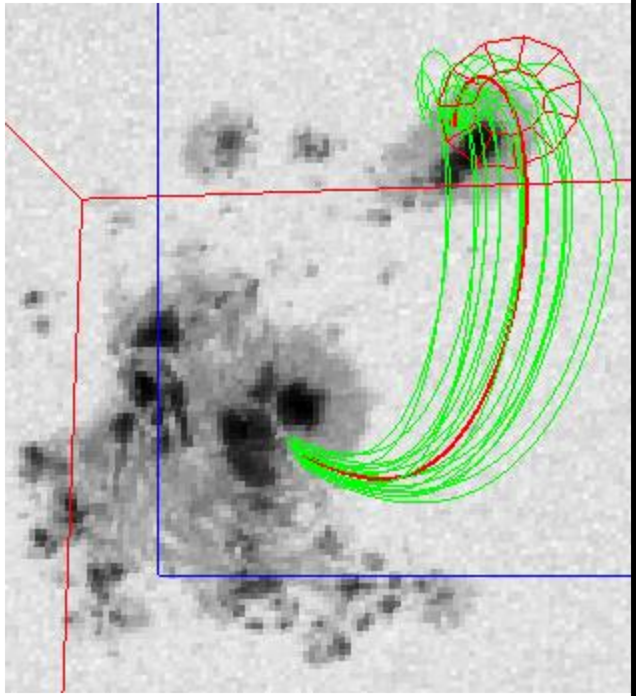


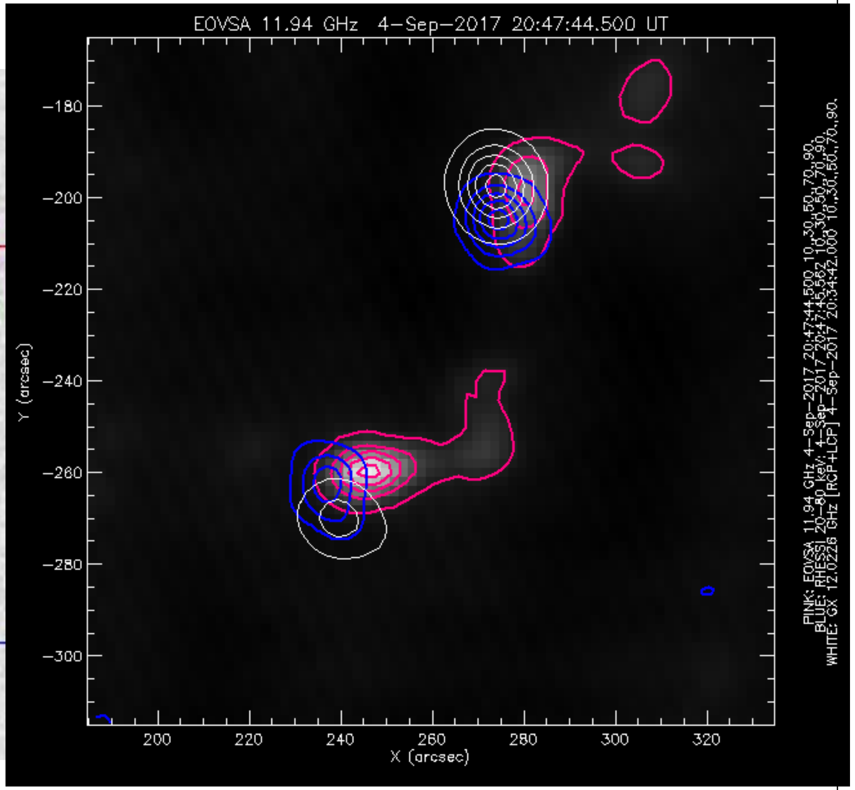
2017 September 04 SEP Event



Need For 3D Forward-Fit Modeling

- Example from 2017 Sep 04:
  - Start with magnetic field model (extrapolation or MHD)
  - Identify field line that matches source structure, and create loop
  - “Dress” the loop with plasma and accelerated particles (use parameters from parameter maps as a guide
  - Calculate emission from the model (microwave, hard X-ray, EUV)
  - Convolve with instrument resolution, and compare with observations.





FASR vs. EOVSA

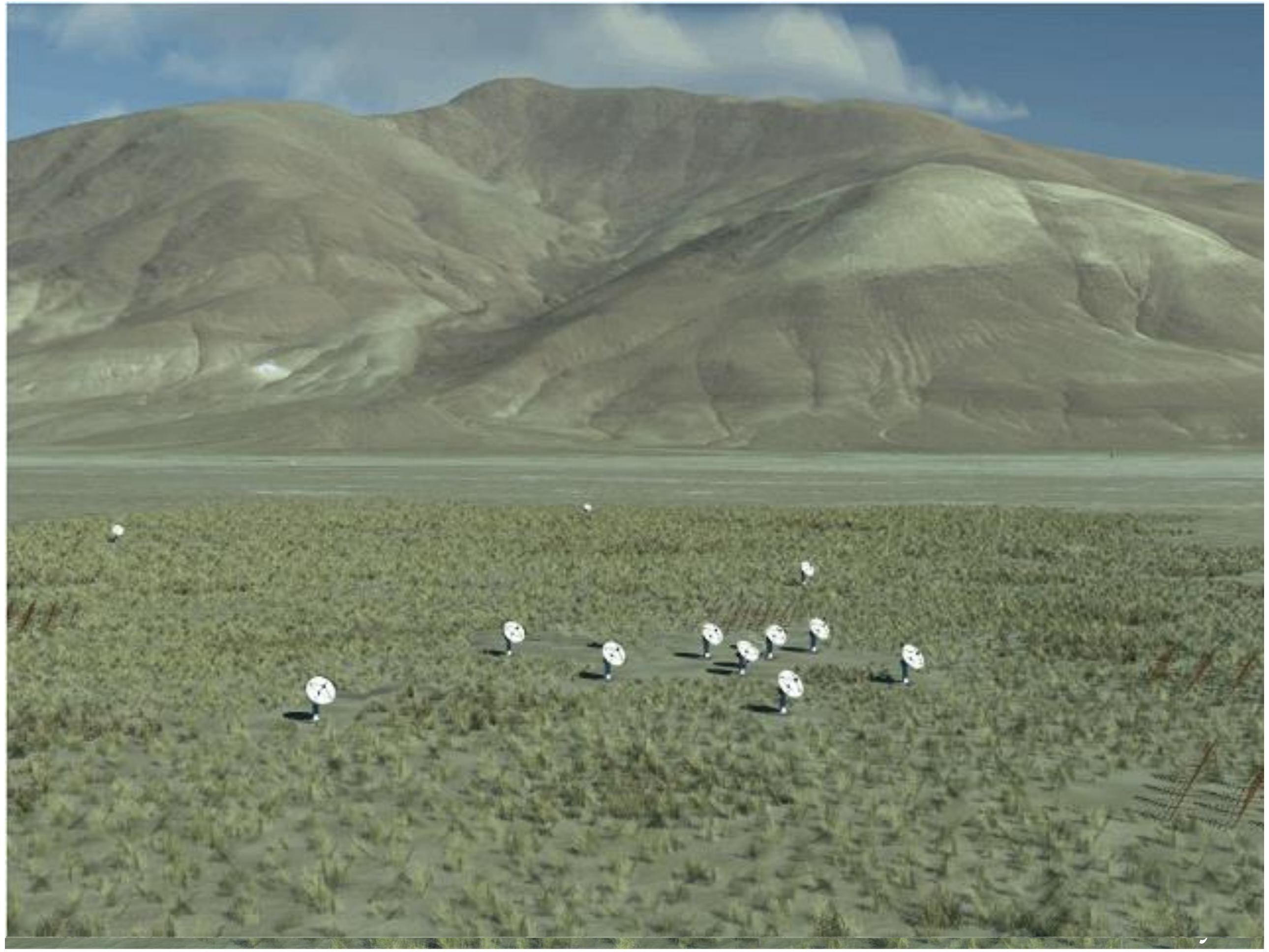


Table 1: FASR Instrument Specifications	
Angular resolution	$20/\nu_{GHz}$ arcsec
Frequency range	0.05-21 GHz
Frequency resolution	1%
Time resolution	1 s
Polarization	Stokes I & V (Q/U selectable)
Number of antennas	2-21 GHz: 15 ~~45~~ 0.2-3 GHz: 15 ~~15~~ < 0.3 GHz: 0 ~~15~~
Size of antennas	2-21 GHz: 2 m parabolic 0.2-3 GHz: 6 m parabolic < 0.3 GHz: log-periodic dipoles
Maximum antenna spacing	4.25 km
Proposed Site	Owens Valley (Big Pine, CA)