EOVSA Update: Science Highlights and Future Outlook

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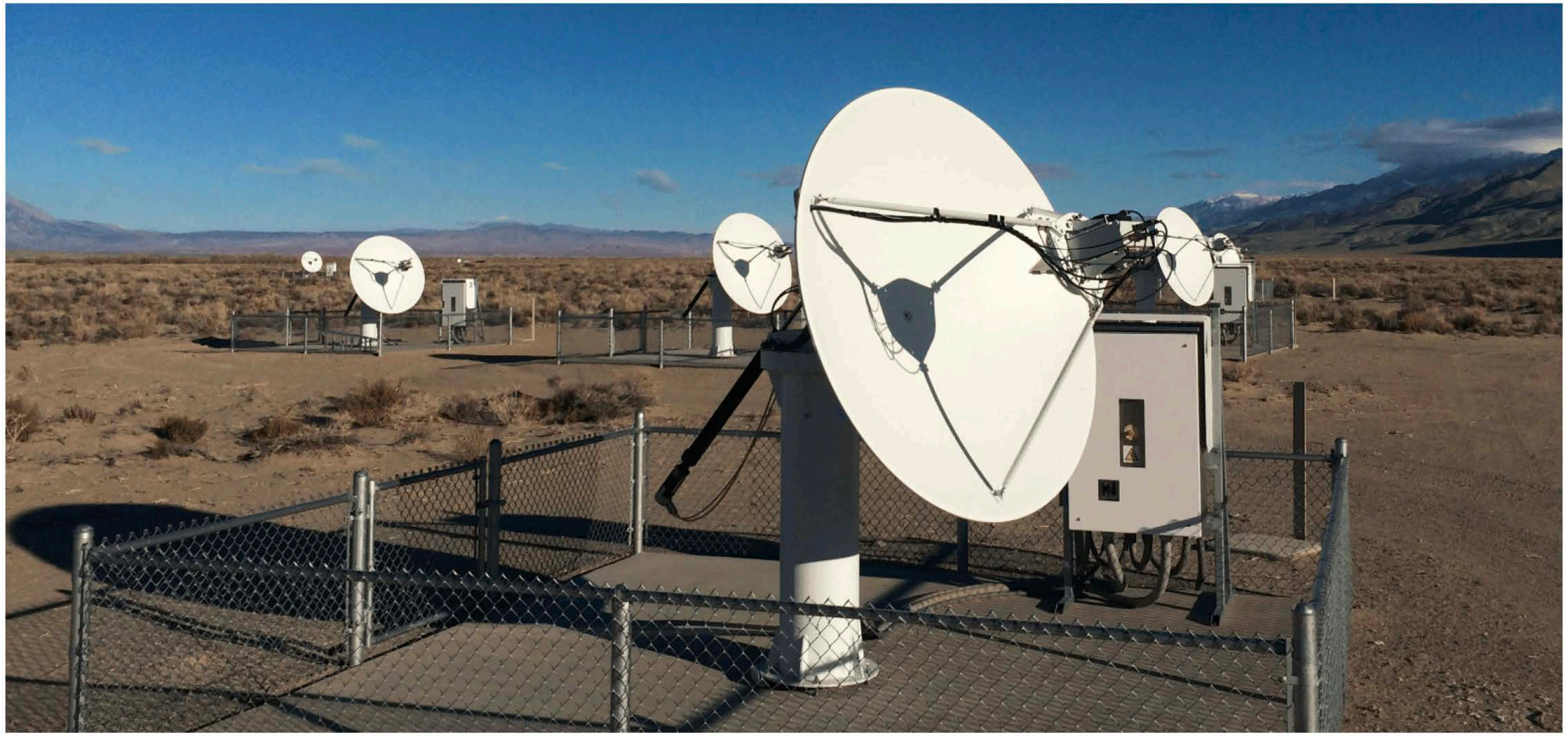
Center for Solar-Terrestrial Research
New Jersey Institute of Technology

RHESSI-20 Workshop
July 7, 2021

EOVSA Overview

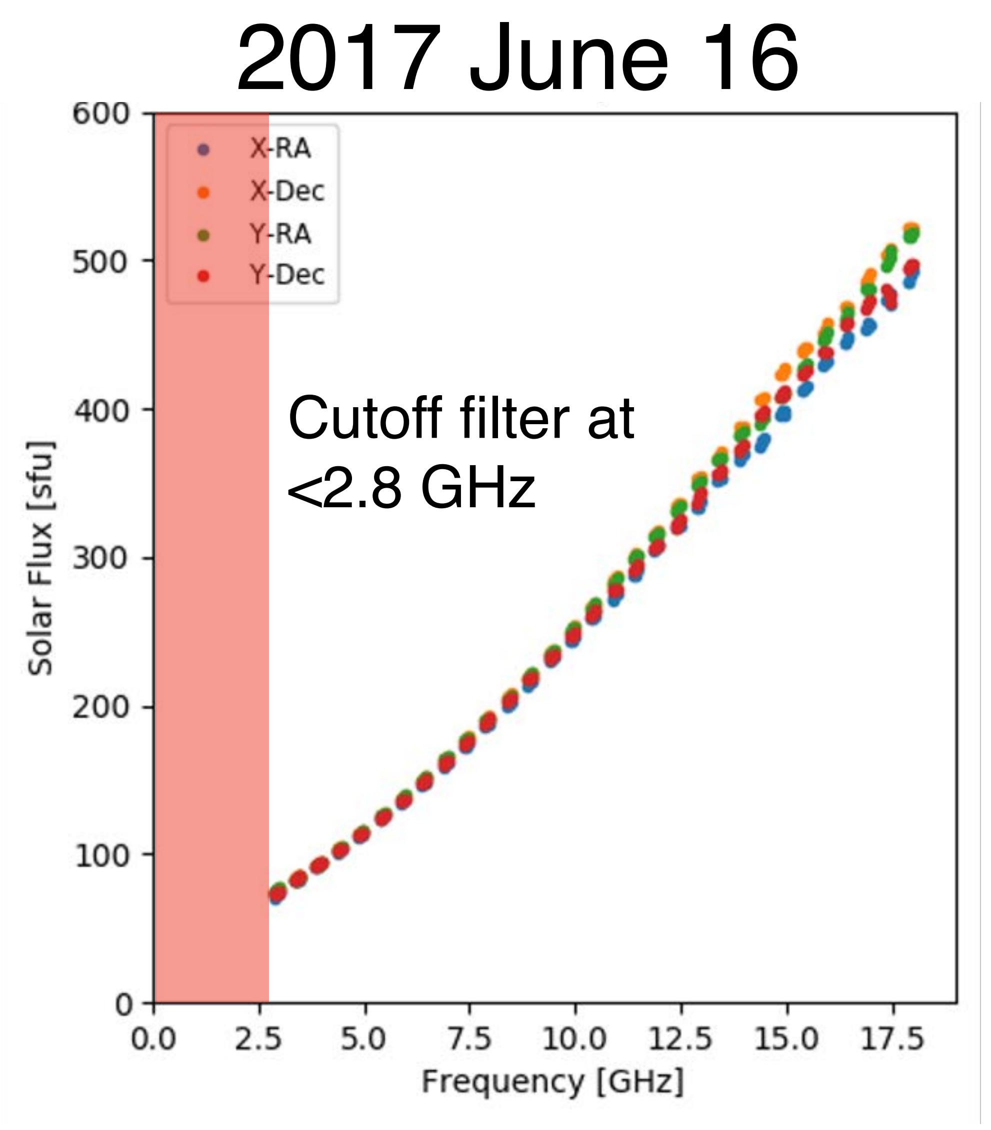


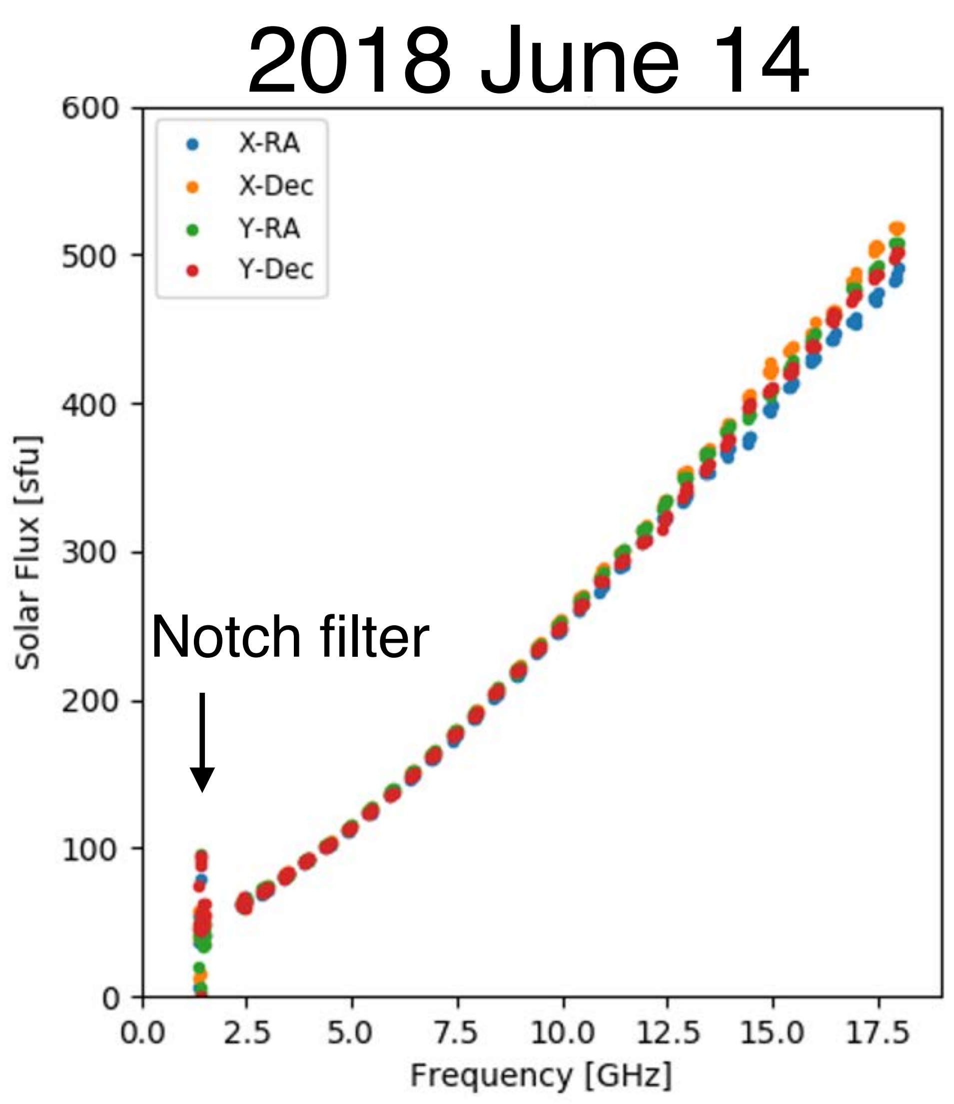
- ◉ The Expanded Owens Valley Solar Array is a solar-dedicated imaging array consisting of **13 2.1-m antennas**
- ◉ Frequency agile, sweeping the microwave range **1–18 GHz** with 50 frequeny bands **every second**.
- ◉ Each frequency band is 325 MHz wide, sampled by 8-30 science spectral channels; that is, **451 independent spectral measurements**
- ◉ Longest baseline ~1 km, offering an angular resolution of $\sim 60''/\nu_{GHz}$ (inversely proportional to frequency; highest resolution is $\sim 3''$)

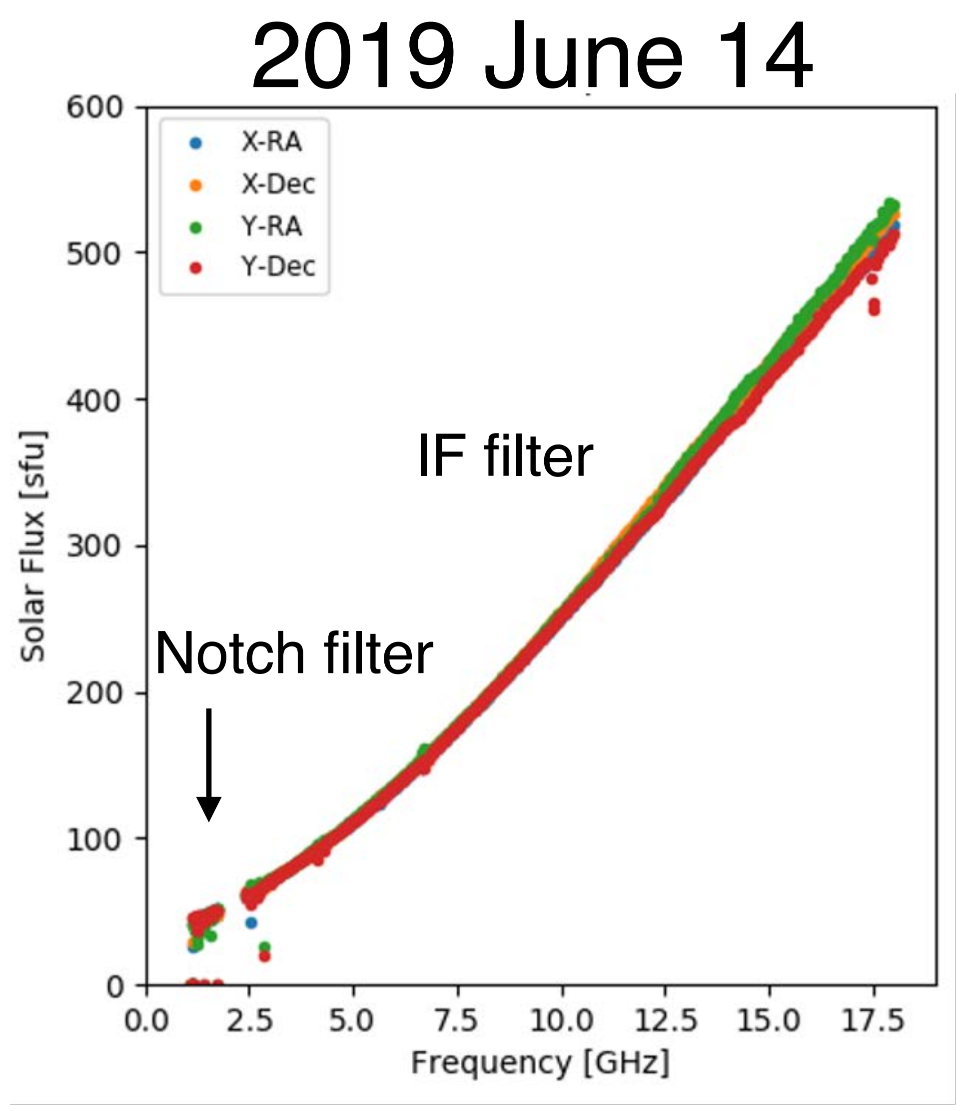
EOVSA Upgrades

Frequency Parameter	2017	2018	2019–
Number of bands	34	34	52
Instantaneous Usable BW	160 MHz	160 MHz	325 MHz
Bandwidth gaps	340 MHz	340 MHz	None
# of science frequency	134	167	451
Frequency Range	2.84-18 GHz	1.34-18 GHz	1.10-18 GHz
Cadence—full spectrum	1 s	1 s	1 s

Total Power Spectrum



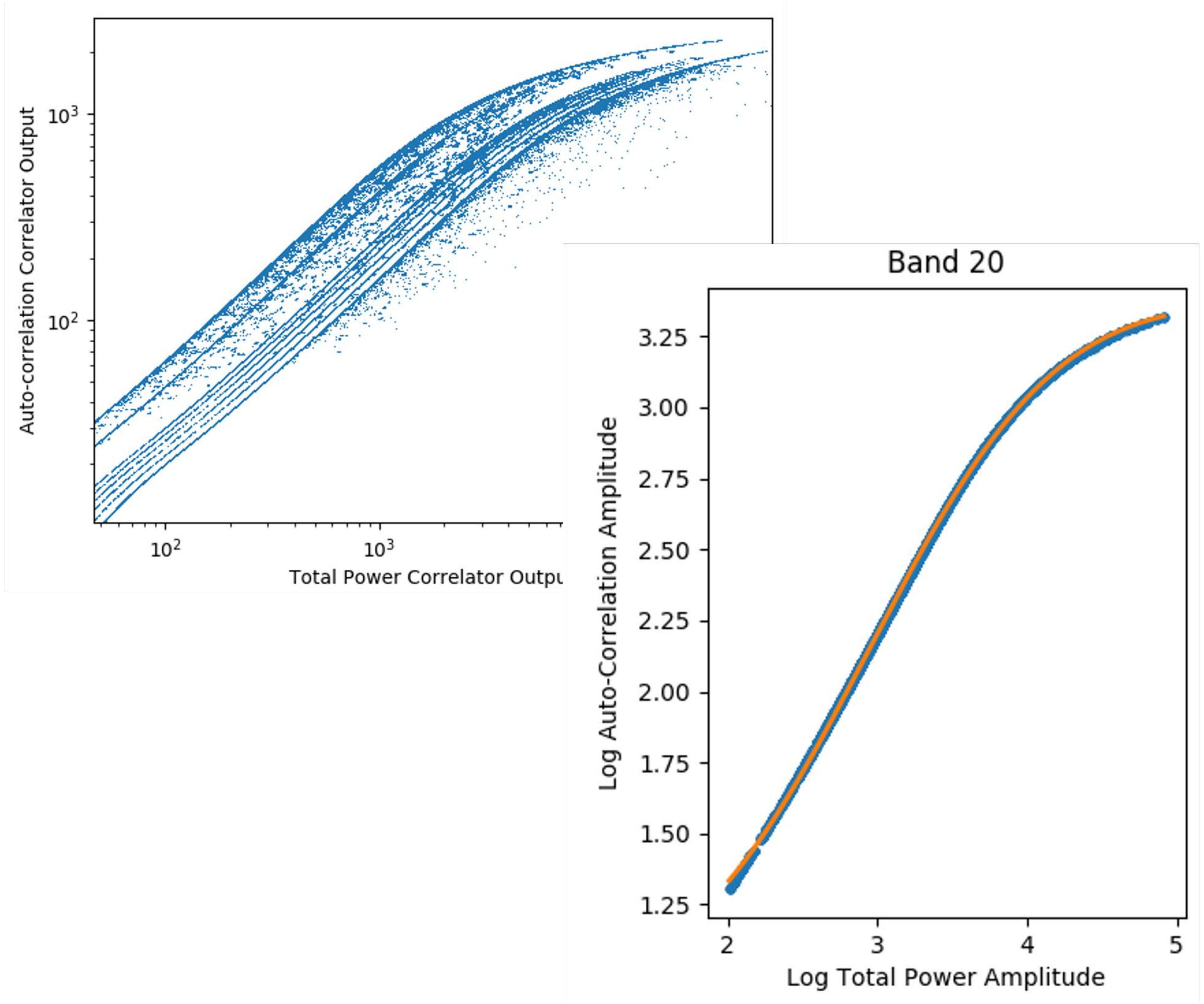




Desaturation of Visibility Data

(and other improvements)

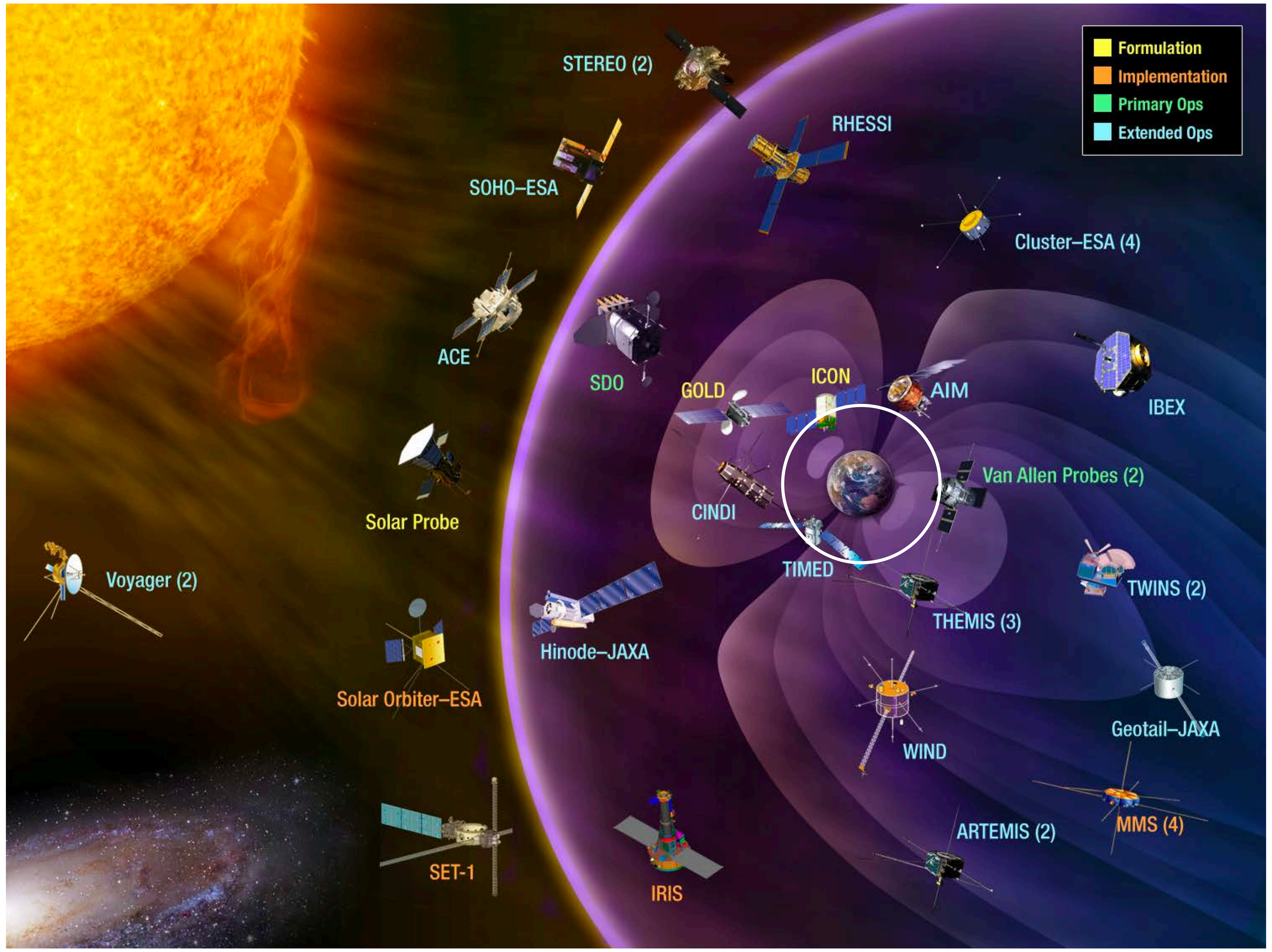
- The correlator samples total power with high bit-resolution and auto-correlations with 4-bit resolution. The cross-correlations are based on this 4-bit resolution data.
- When the auto-correlation is plotted against total power, we see evidence of saturation at the highest power levels.
- We analyzed this behavior and determined that a single functional form fits the data with high precision (orange curve) for all bands at all times.
- We have implemented a function that applies this desaturation correction, so that the auto-correlation (and by extension the cross-correlation) matches the total power.
- We also devised a way to monitor the ADC levels and adjust the IF gain to better maintain the linearity, and we made other improvements in the total power calibration



Coordination with Other Facilities

EOVSA

BBSO

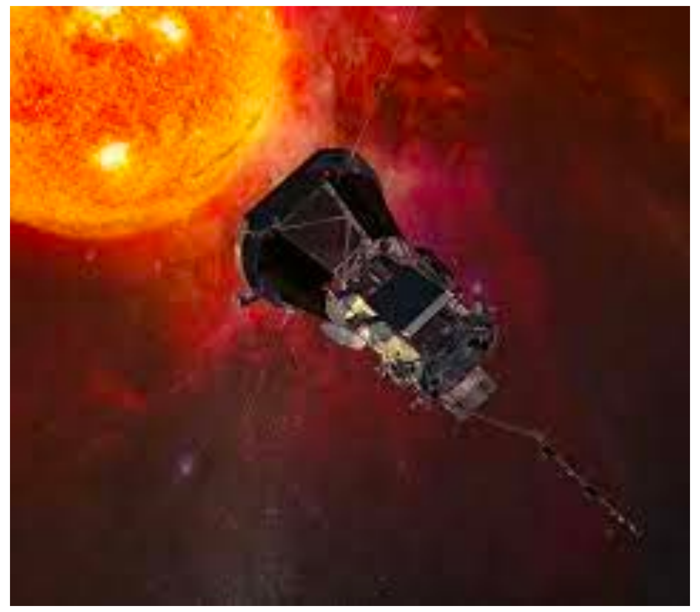


Heliophysics Systems Observatory

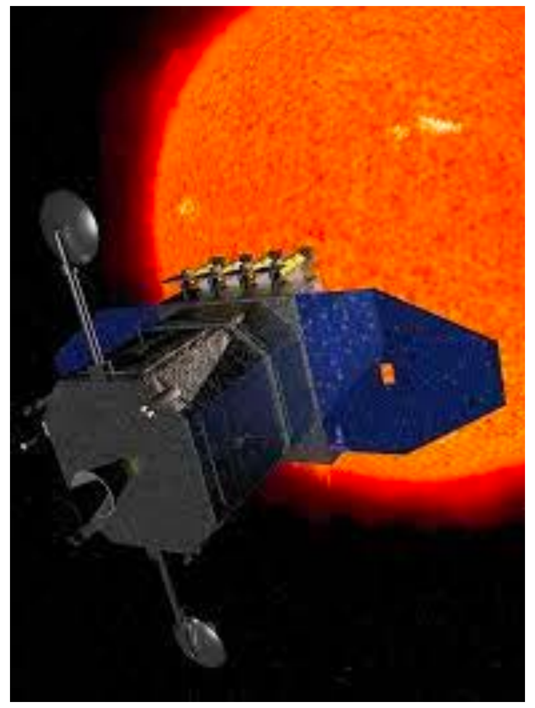
RHESSI

Hinode & IRIS

PSP



SDO

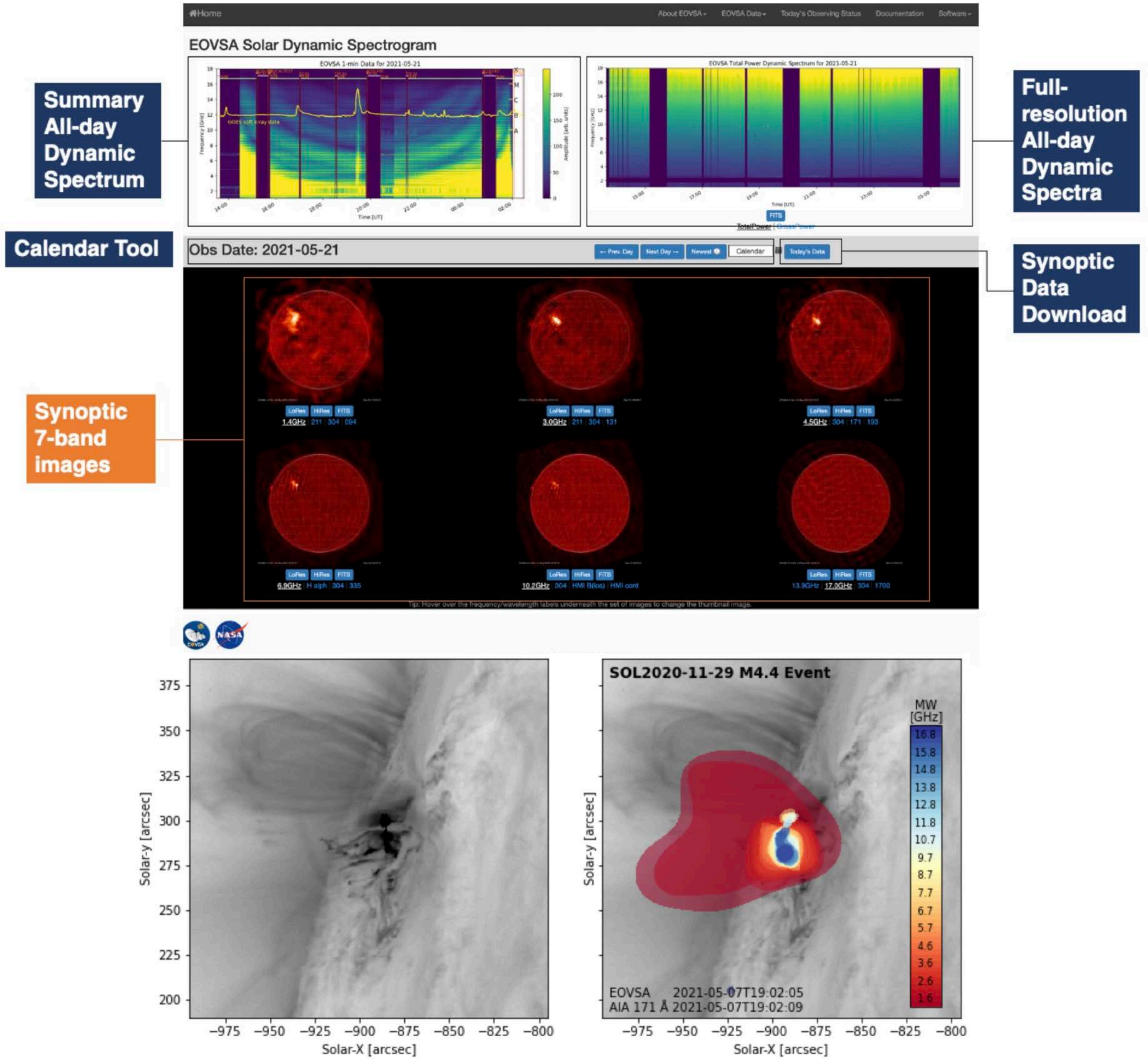


Solar Orbiter

Using EOVSA Data

- EOVSA's data are completely open. Let's do science together!
- Yesterday's EOVSA tutorial included extensive discussions on how to browse, reduce, and analyze the data. Scan QR code on the right to access the Jupyter notebook
- Our team is trying to make things better, but the community's help is very welcome!

EOVSA Tutorial

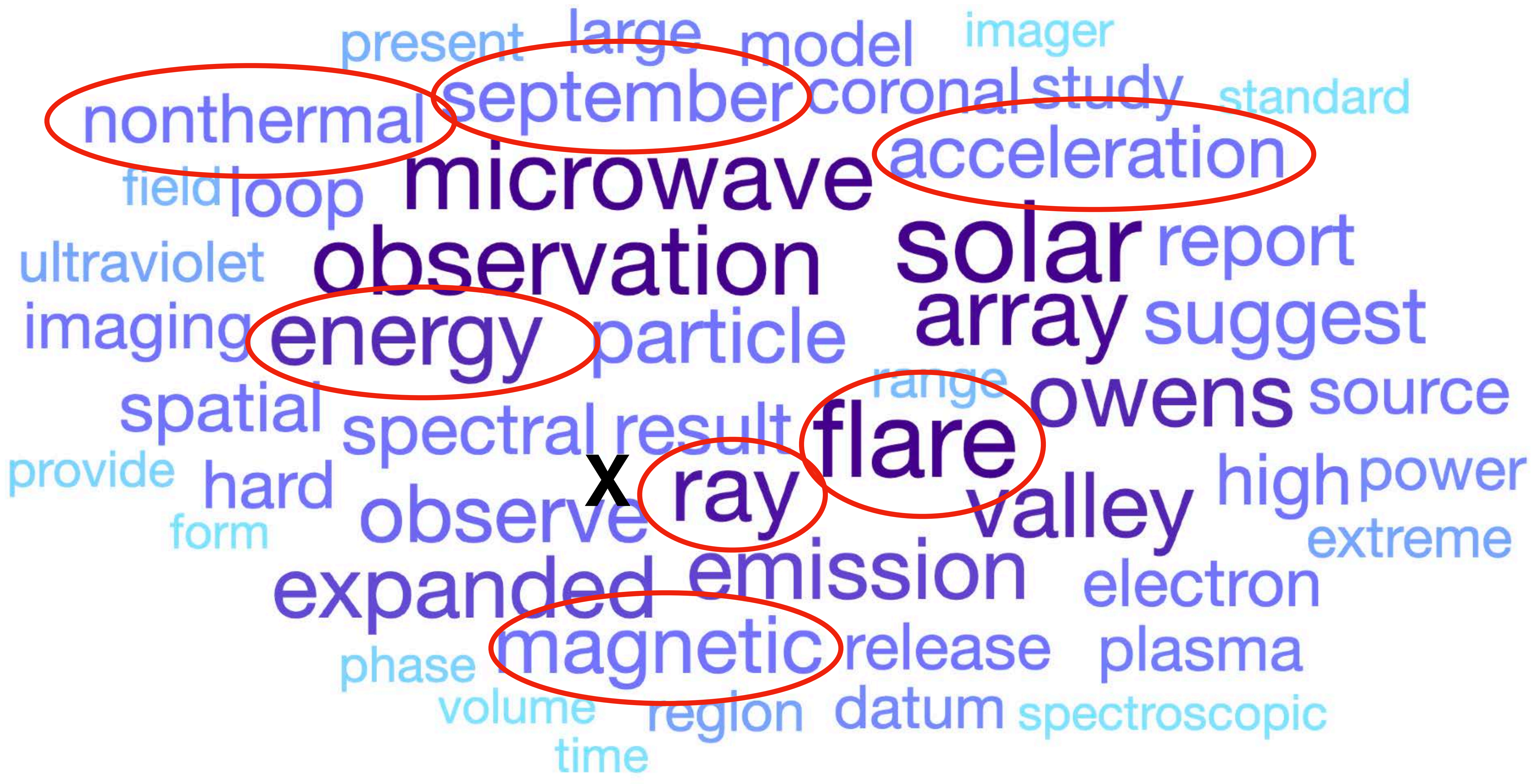


Science Highlights

Published Studies: 2020–2021

- Chhabra et al. (2021), ApJ, 906, 132 Imaging Spectroscopy of CME-Associated Solar Radio Bursts
- Chen et al. (2021), ApJL, 908, L55 Energetic Electron Distribution of the Coronal Acceleration Region: First results from Joint Microwave and Hard X-ray Imaging Spectroscopy
- Kocharov et al. (2021), ApJ, 915, 12 Multiple Sources of Solar High-energy Protons
- Shaik & Gary (2021), ApJ, in press Implications of Flat Optically Thick Microwave Spectra in Solar Flares for Source Size and Morphology
- Fleishman et al. (2020), Science, 367, 278 Decay of the coronal magnetic field can release sufficient energy to power a solar flare
- Karlicky at al. (2020), ApJ, 889, 72 Drifting Pulsation Structure at the Very Beginning of the 2017 September 10 Limb Flare
- Glesener et al. (2020), ApJL, 891, 34 Accelerated Electrons Observed Down to <7 keV in a NuSTAR Solar Microflare
- Kuroda et al. (2020), Frontiers, 7, 22 Evolution of Flare-accelerated Electrons Quantified by Spatially Resolved Analysis
- Chen et al. (2020a), ApJL, 895, 50 Microwave Spectral Imaging of an Erupting Magnetic Flux Rope: Implications for the Standard Solar Flare Model in Three Dimensions
- Chen et al. (2020b), Nature Astronomy, Jul 27, 2397 Measurement of magnetic field and relativistic electrons along a solar flare current sheet
- Yu et al. (2020), ApJ, 900, 17 Magnetic Reconnection During the Post Impulsive Phase of the X8.2 Solar Flare: Bi-Directional Outflows as a Cause of Microwave and X-ray Bursts
- Reeves et al. (2020), ApJ, 905, 165 Hot Plasma Flows and Oscillations in the Loop-top Region During the September 10 2017 X8.2 Solar Flare

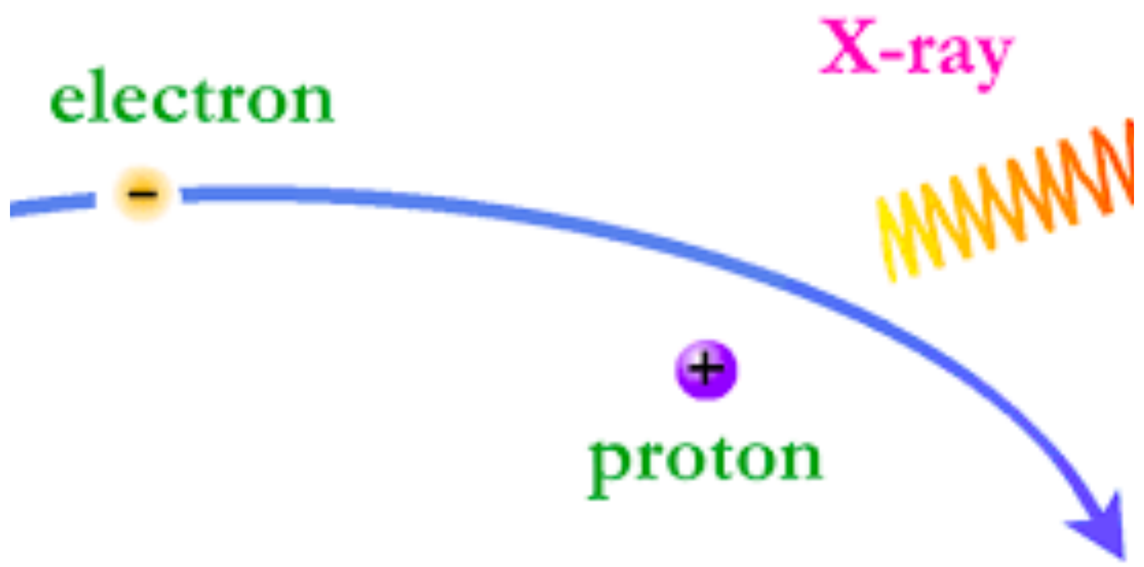
More studies in the "pipeline" (later this talk)



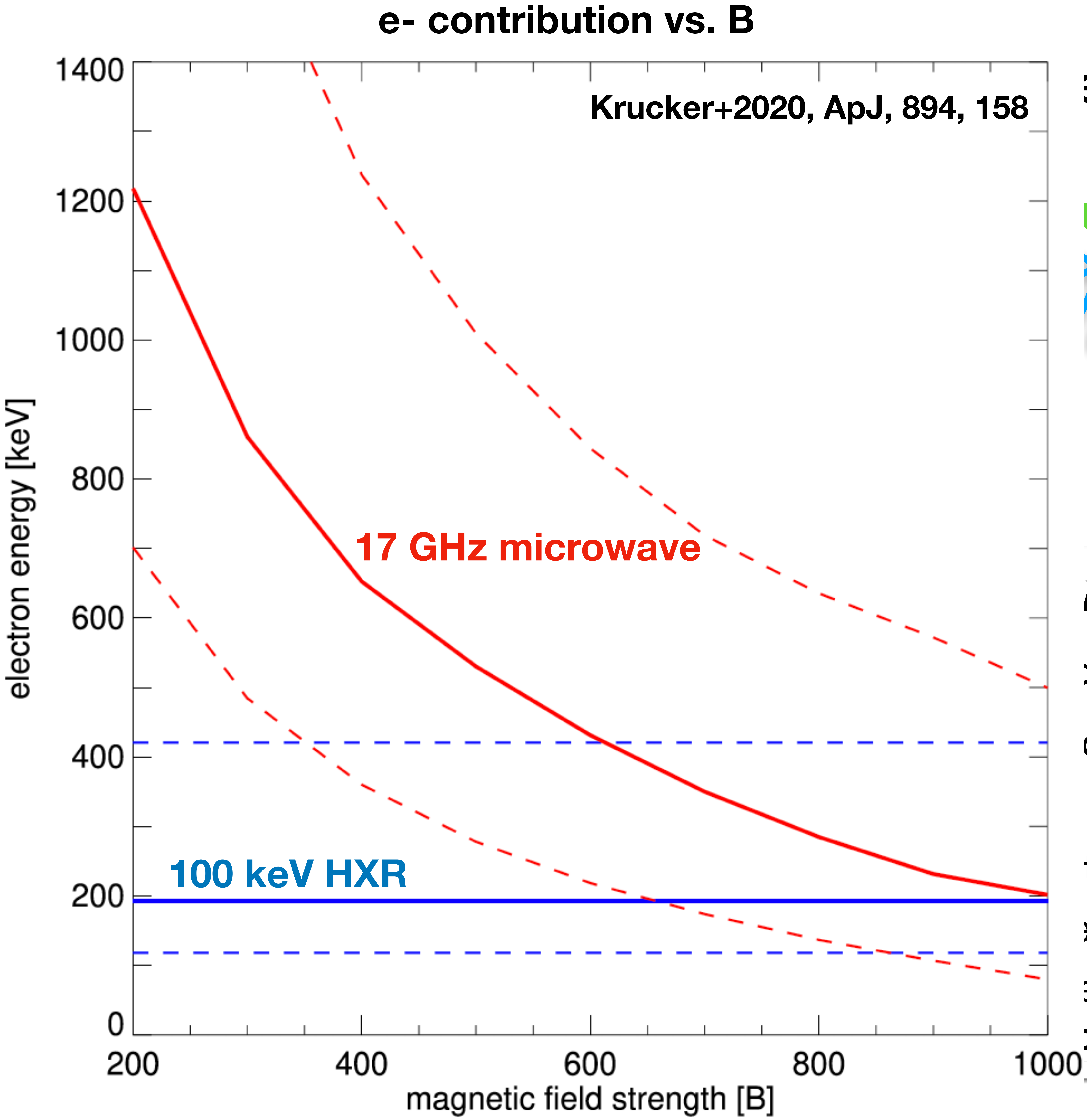
For more published studies using EOVSA data, please visit this ADS library.

Microwave & HXRs: Complementary Diagnostics for Nonthermal Electrons

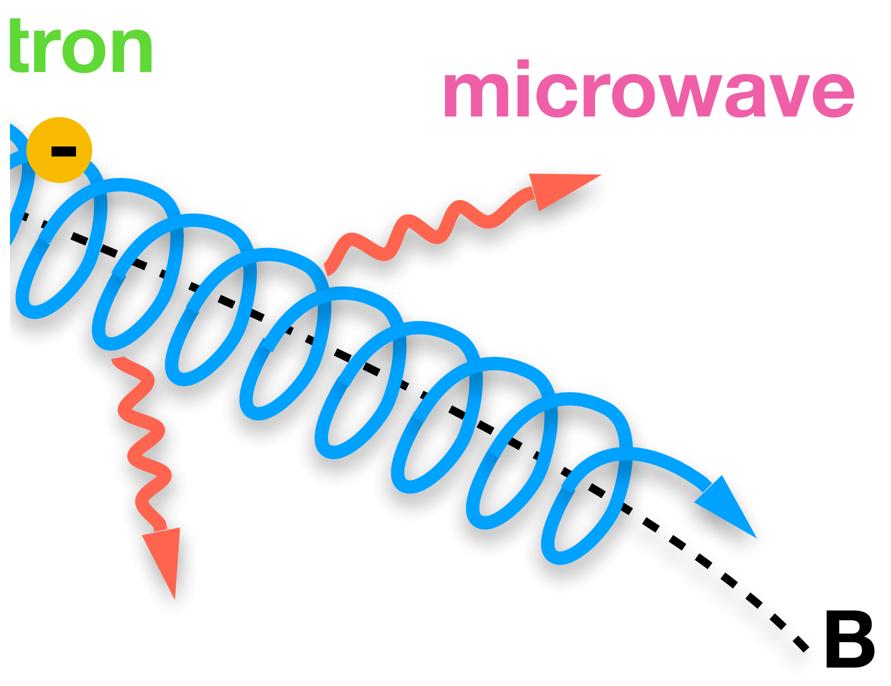
HXRs: bremsstrahlu



- Emission straightforwardly relatec **density** $n_{\rm nth}$ (or flux)
- **Emissivity highly weighted by b density** $n_{\rm th}$
- Generally sensitive to **trans-relati** few x 100 keV), because higher-e smaller in number



es: (Gyro)synchrotron



B, δ, and in some cases, $n_{\rm th}$

ł **by both B and** $n_{\rm nth}$

or optically thin emission with $\delta = 4$

energetic e- (>~ 100 keV)

tic (~100 keV)

ɜV and above)

ɘ spectrum also provides diagnostics for

ɔf **keV)** and **thermal electrons**

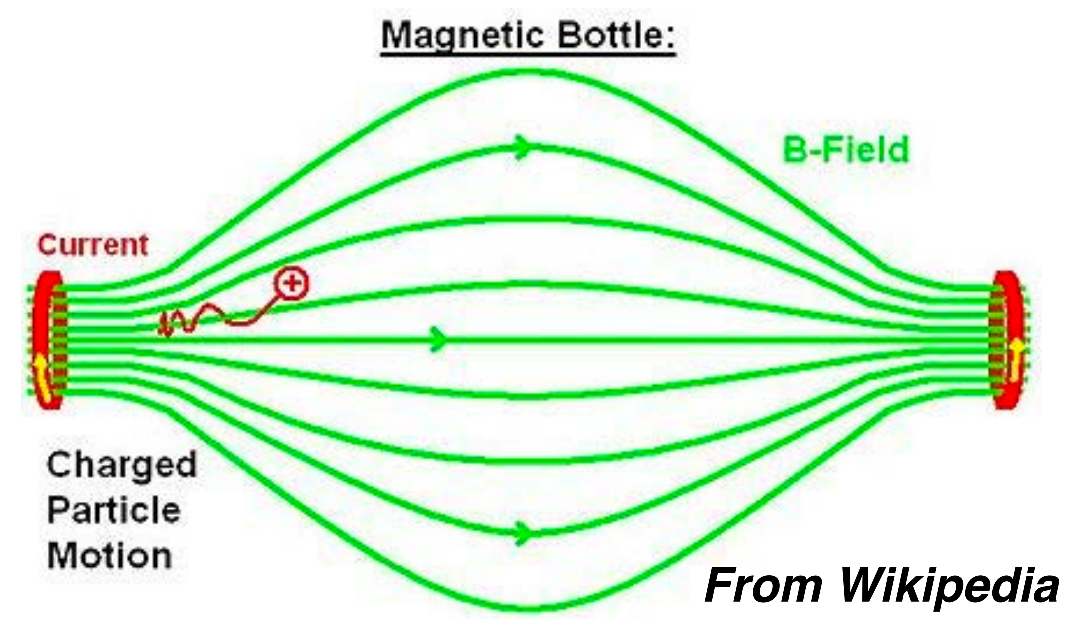
More Studies of the SOL2017-09-10 Event

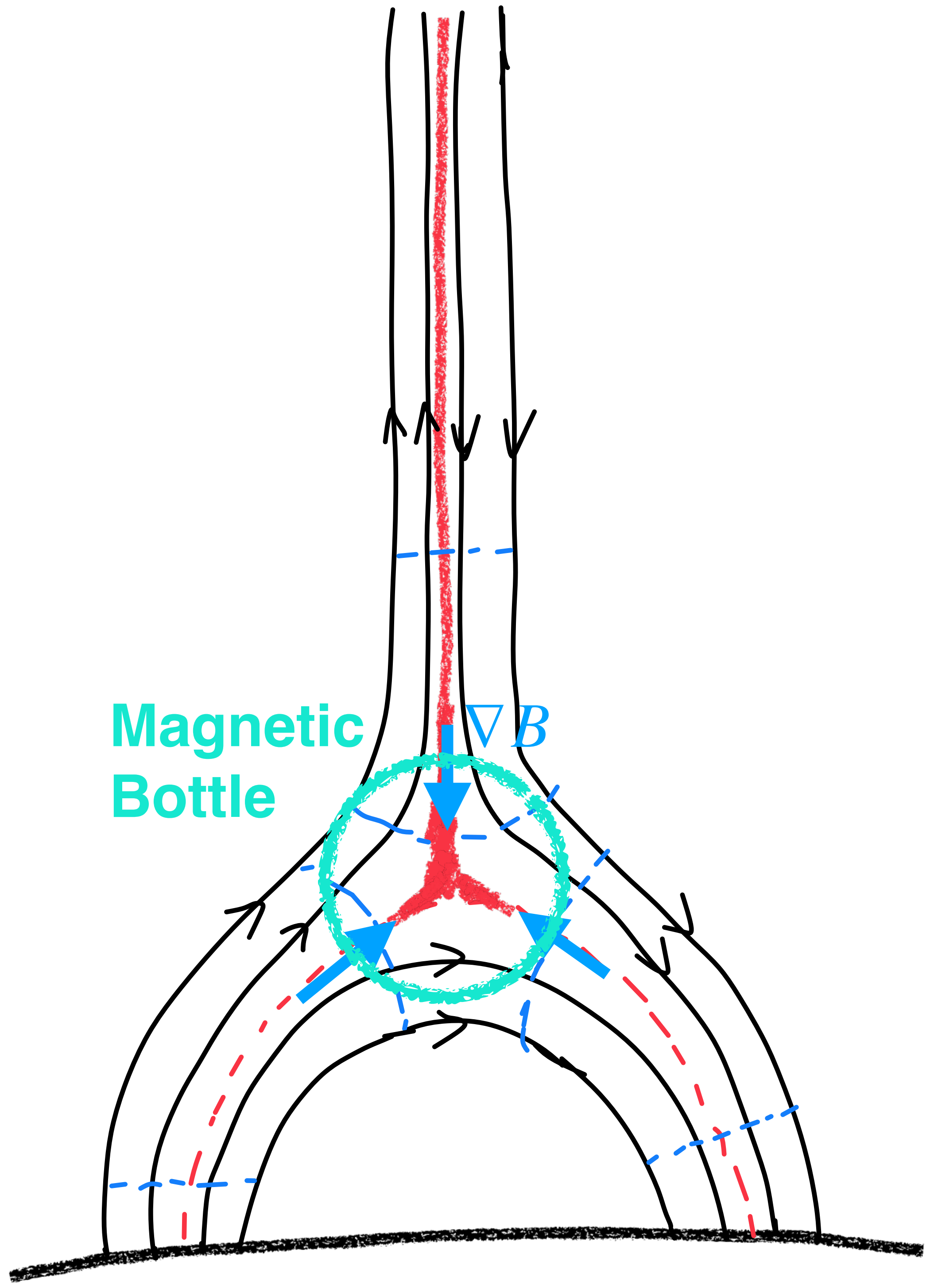
From Lin & Forbes 2000

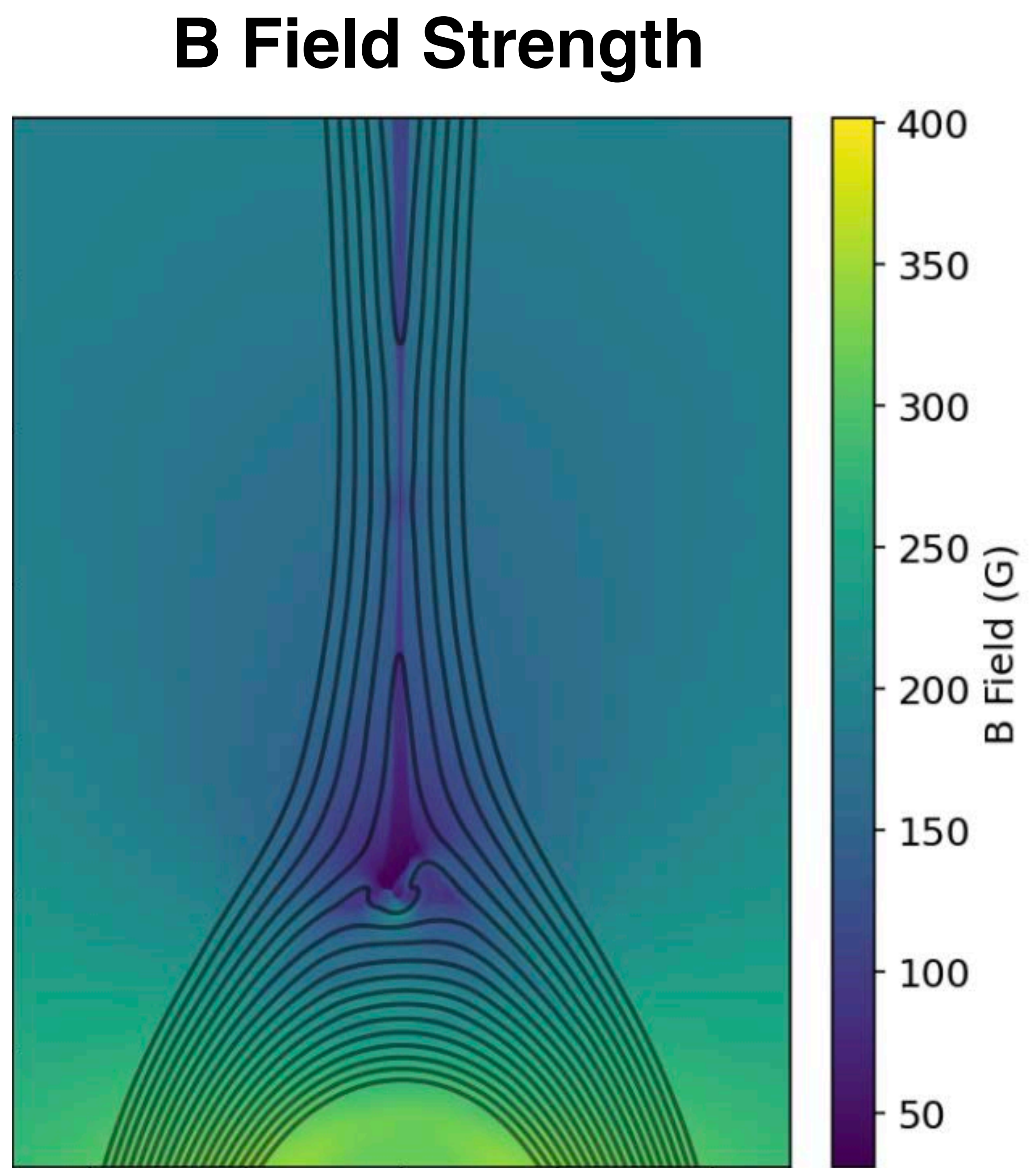
The Early Impulsive Phase

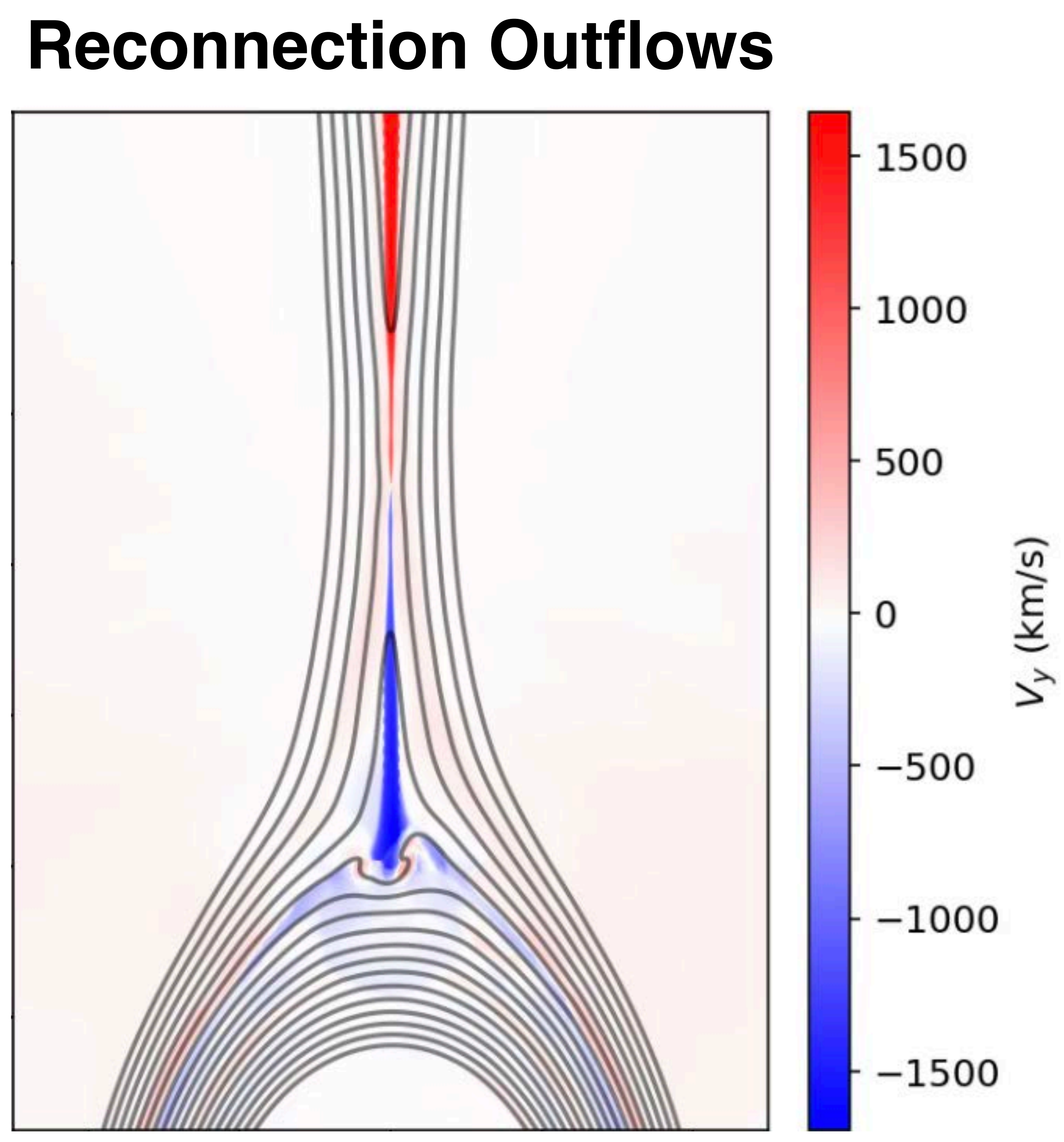
Chen+2020, Nature Astronomy

The Magnetic Bottle

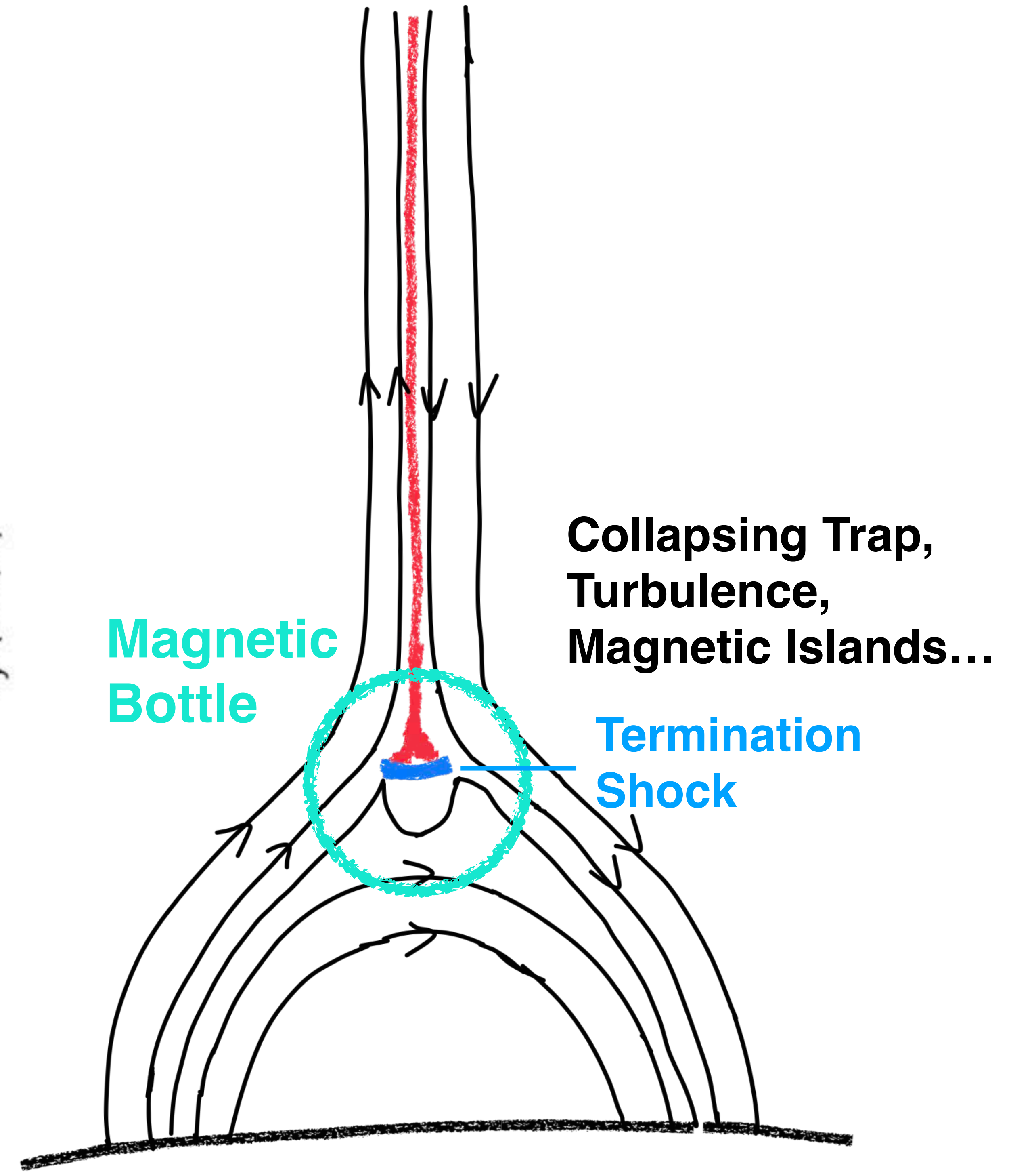




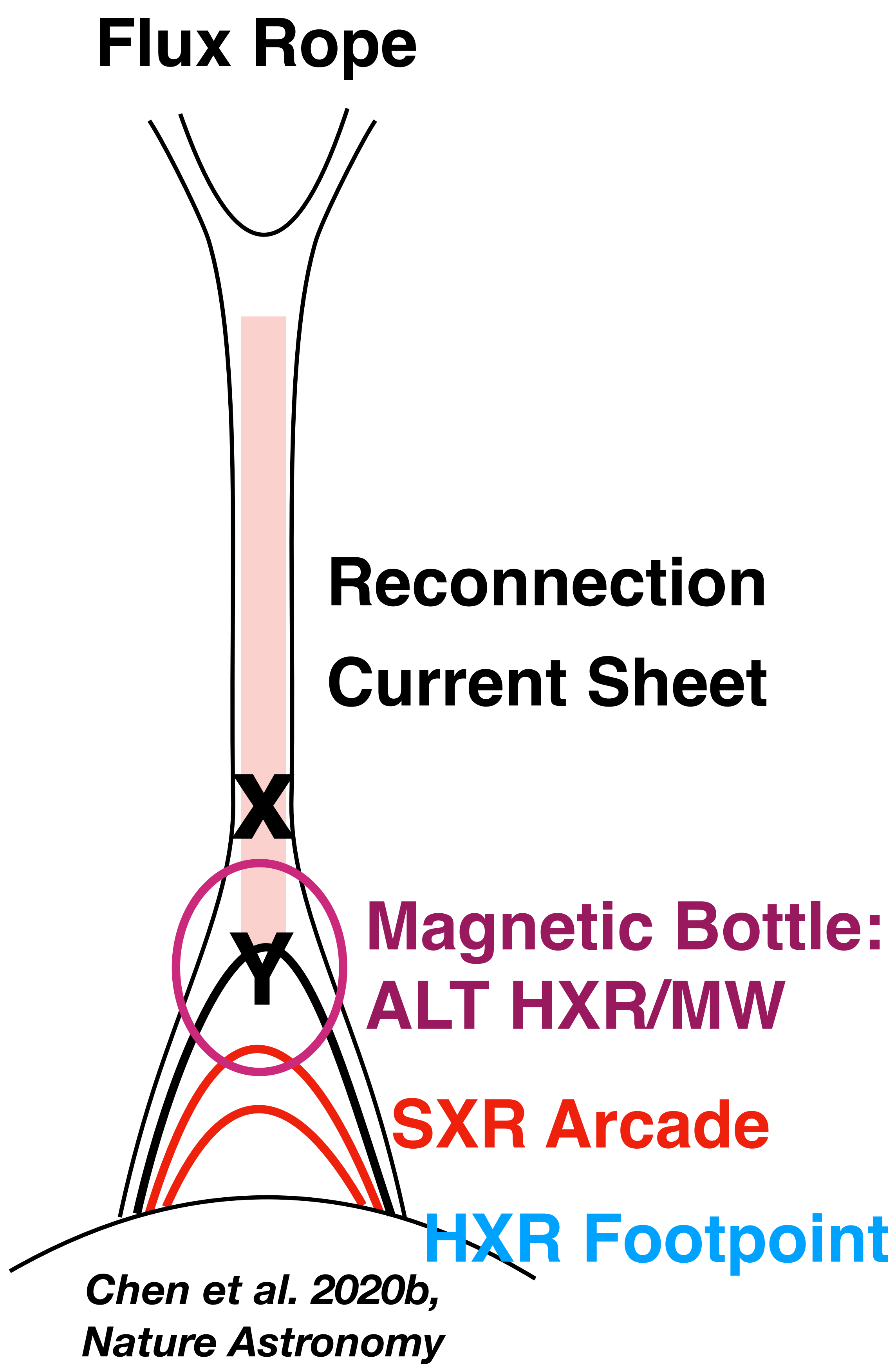




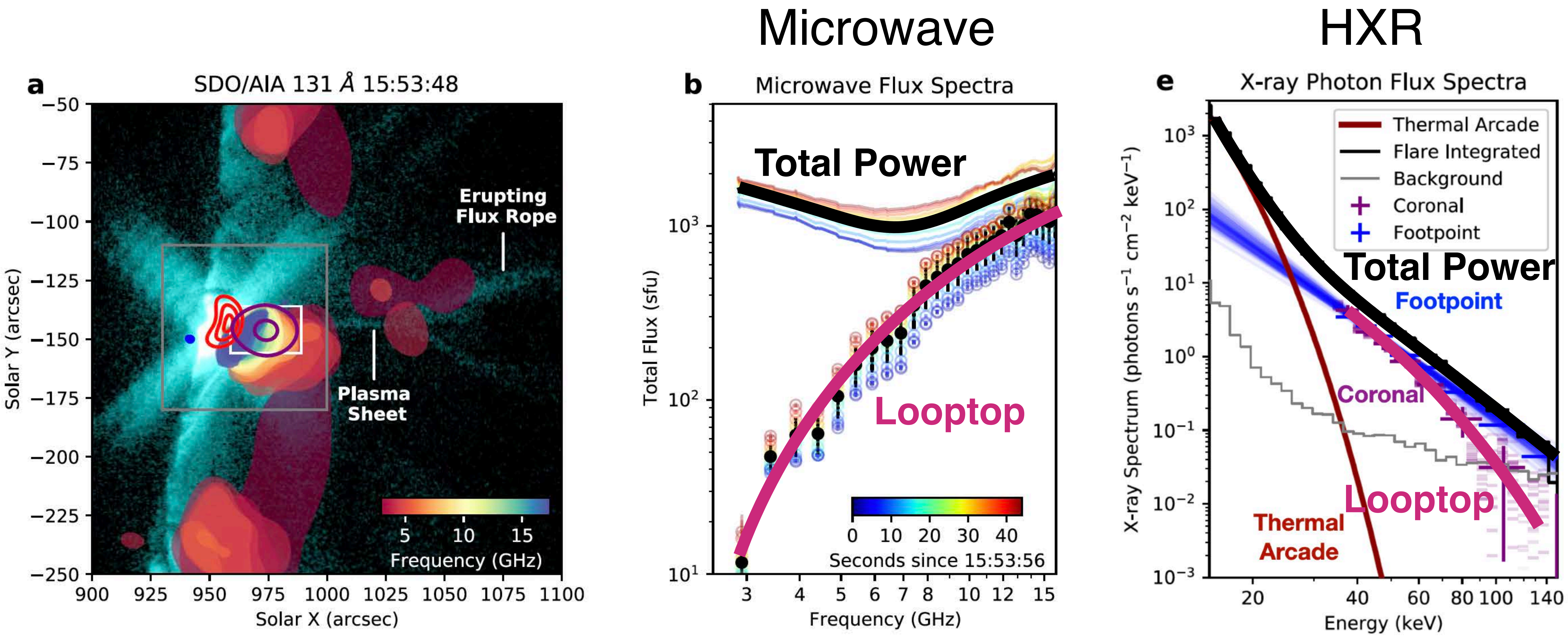
MHD model by Chengcai Shen



The Above-the-Looptop Source

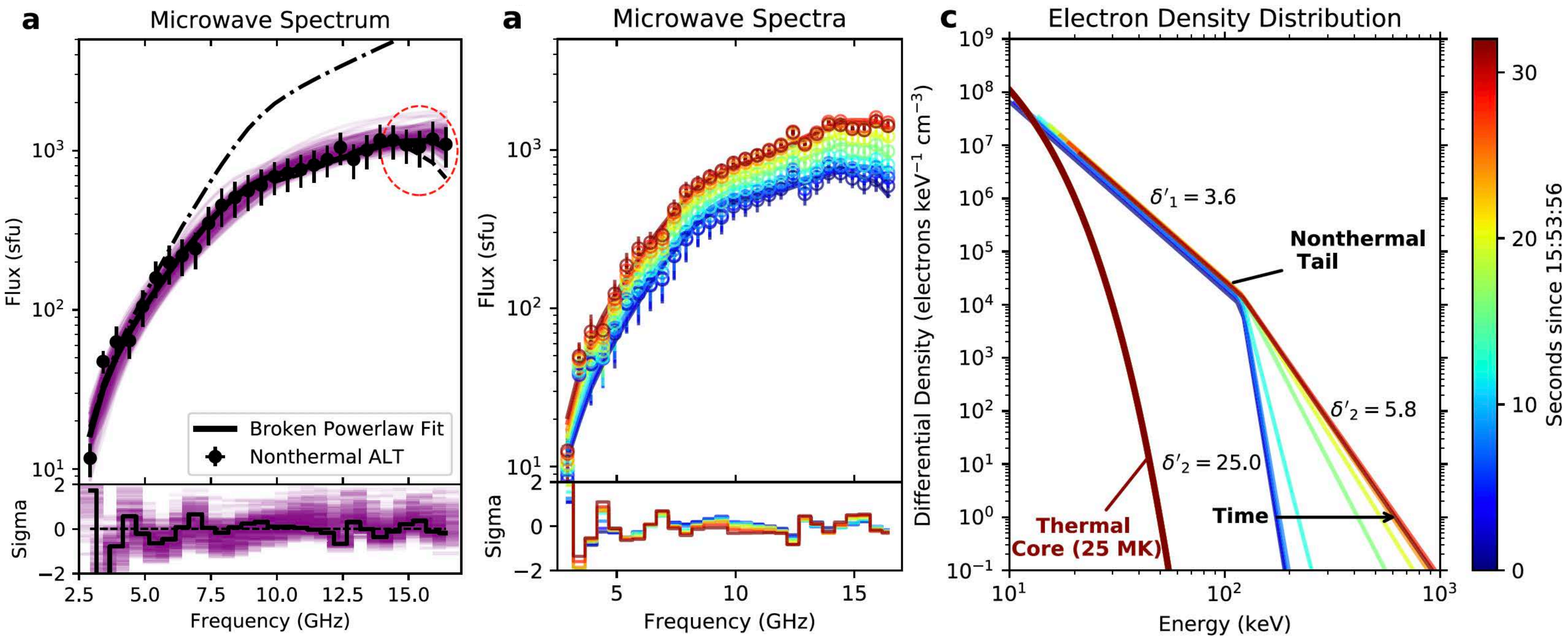


- The **above-the-looptop magnetic bottle** seems to play a vital role in trapping/accelerating electrons to high energies
- **Joint microwave and HXR imaging spectroscopy** provides further insights on the energetics of the acc'ed electrons



Chen+2021, ApJL

Joint HXR-Microwave Spectral Fit

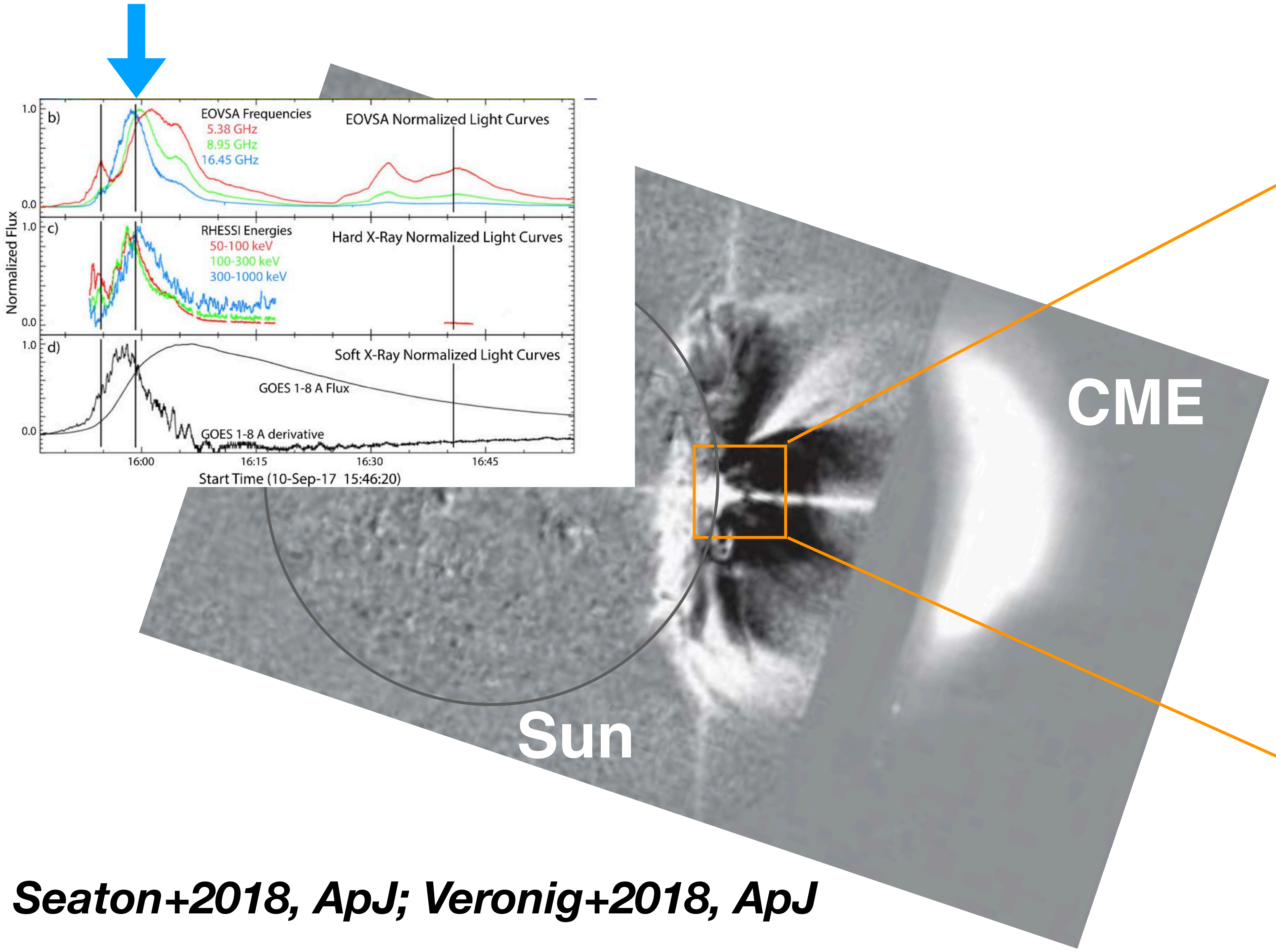


- A **~25 MK thermal "core"** by a **broken powerlaw nonthermal tail** at ~16 keV
- **Nothermal "tail"** that breaks down at ~160 keV needed to fit both X-ray and microwaves
- **Spectrum** **hardens** from >25 to ~6 **within ~20 seconds, or** **~10 Alfvén crossing times**

Chen+2021, ApJL

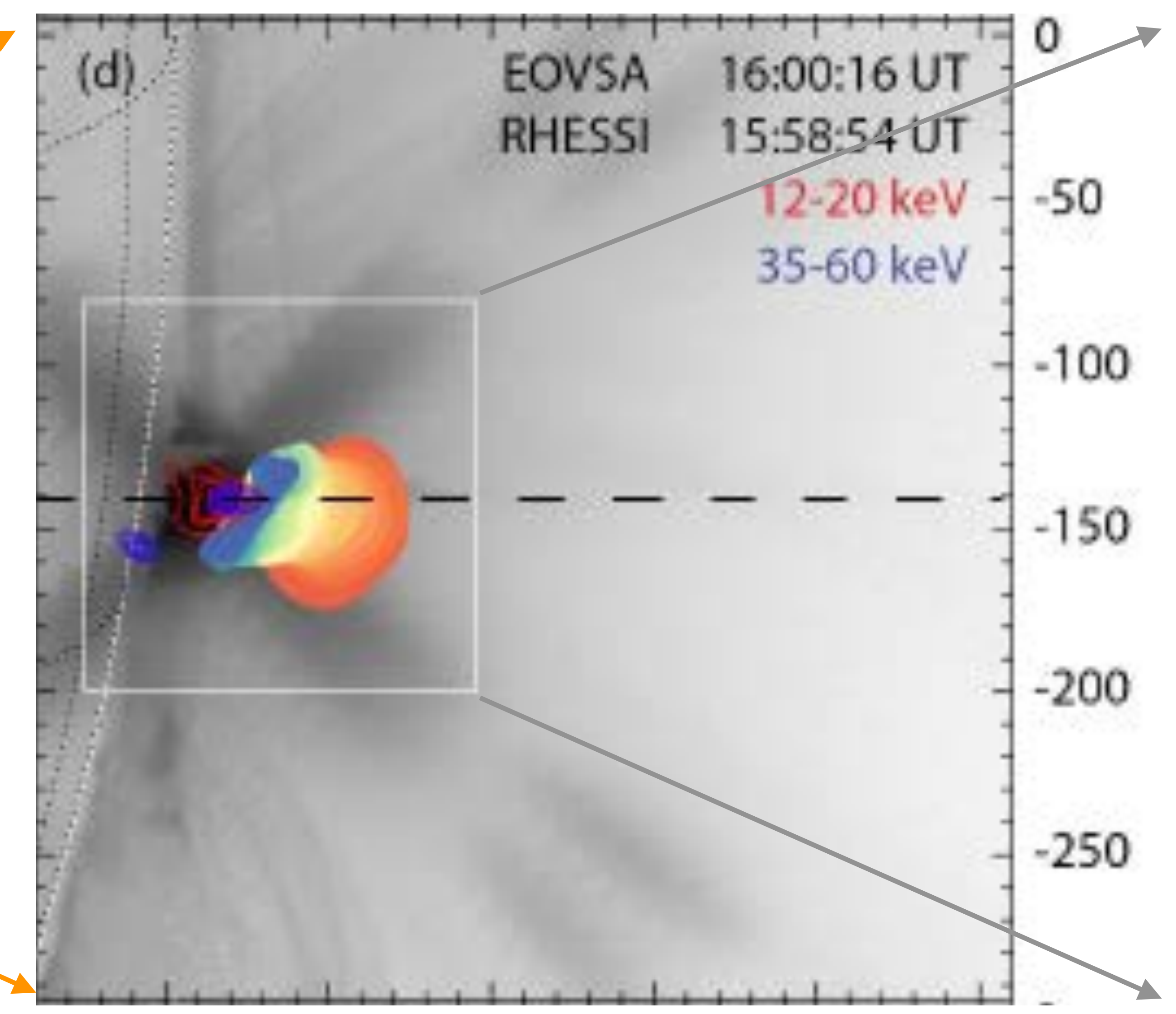
Main Impulsive Phase: Decaying B Field above the Looptop

GOES-R/SUVI + LASCO/C2 @ 1600 UT

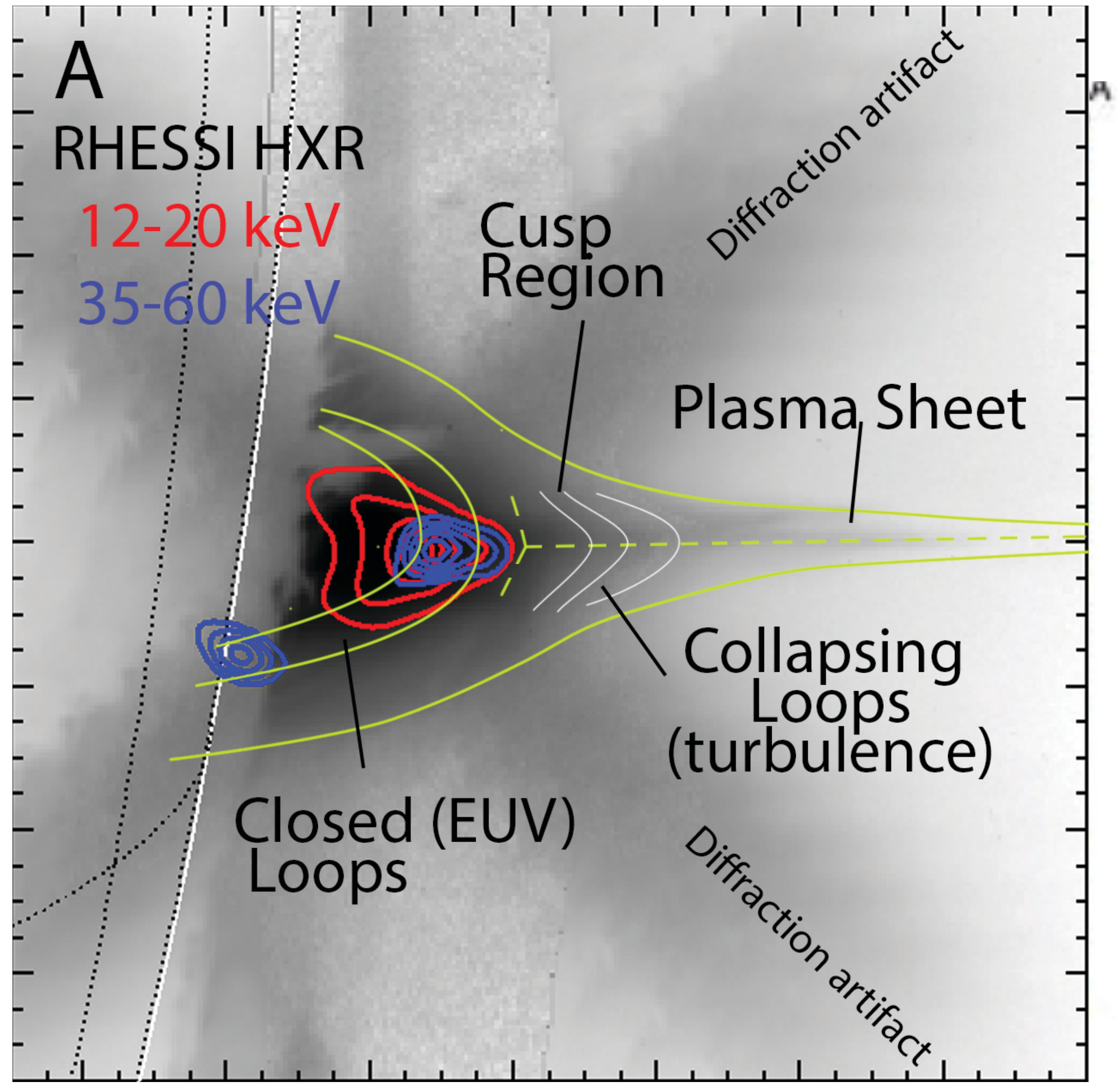


Seaton+2018, ApJ; Veronig+2018, ApJ

SDO/AIA + EOVSA + RHESSI @ 1600 UT



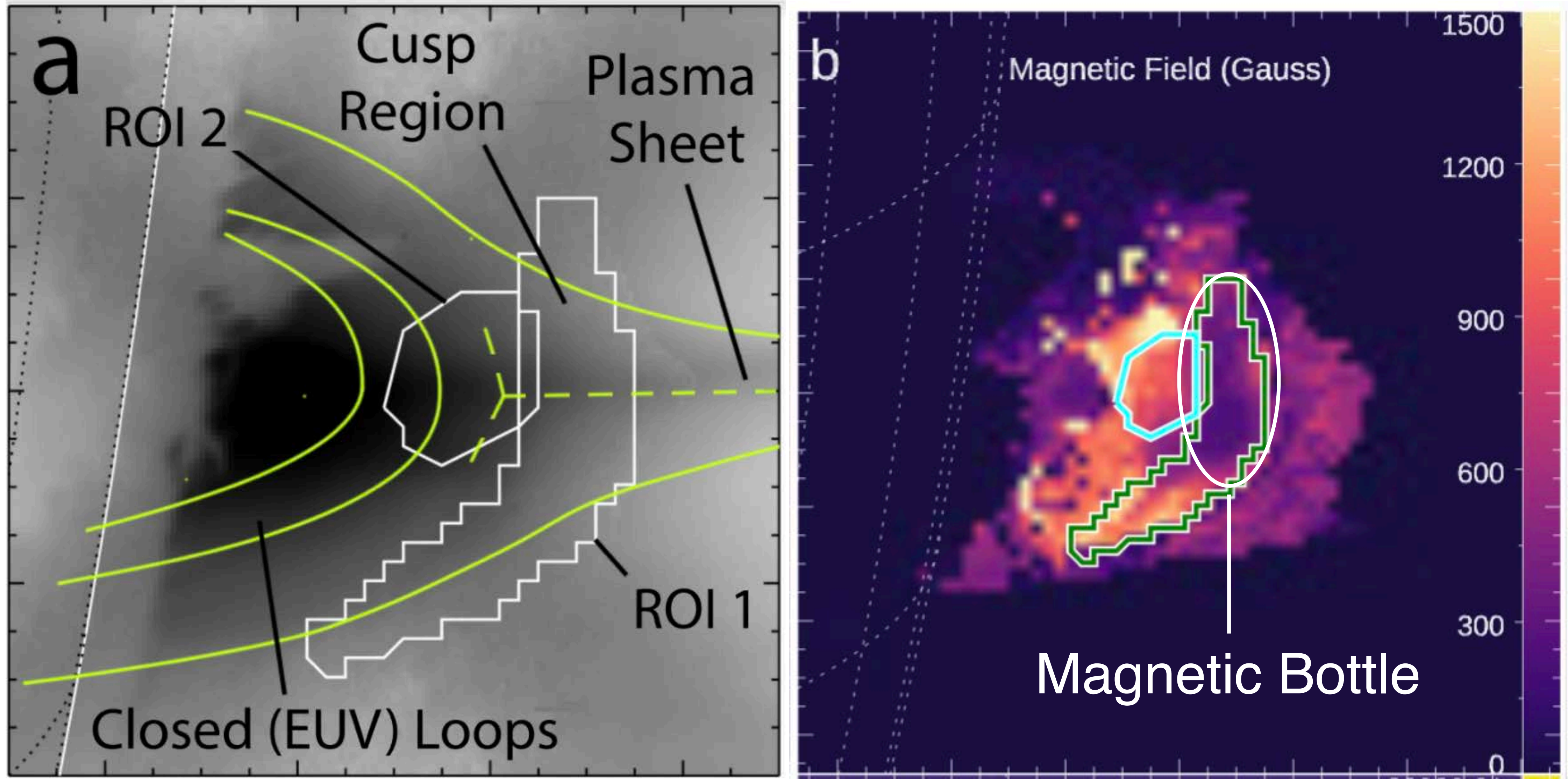
Gary+2018, ApJ



Fleishman+2020, Science

- CME is ~1 R_{sun} away with a long plasma sheet, while HXR/microwave flux peaks
- A fast decay of B field in the cusp region above the looptop

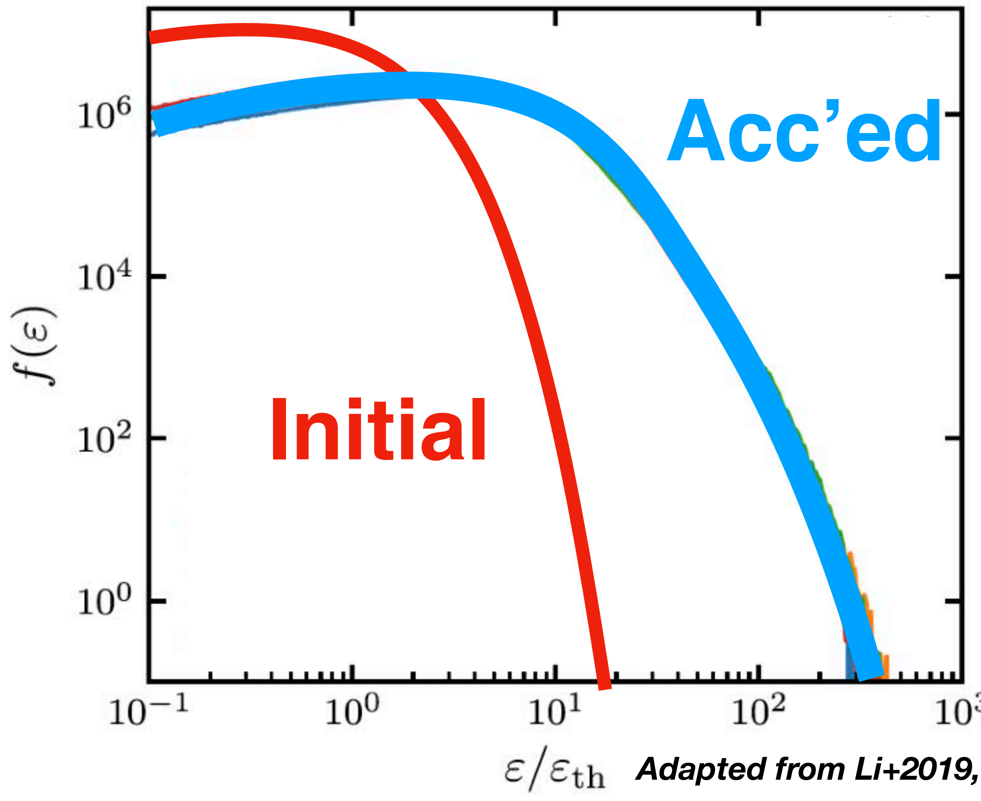
Bulk Electron Energization in the ALT “Magnetic Bottle” Region



- Very low n_{th}/n_{nth} in the“magnetic bottle” region above the looptop
- Bulk electron energization
- Strong particle confinement

Fleishman+2021, in prep

Illustrative e^- spectrum

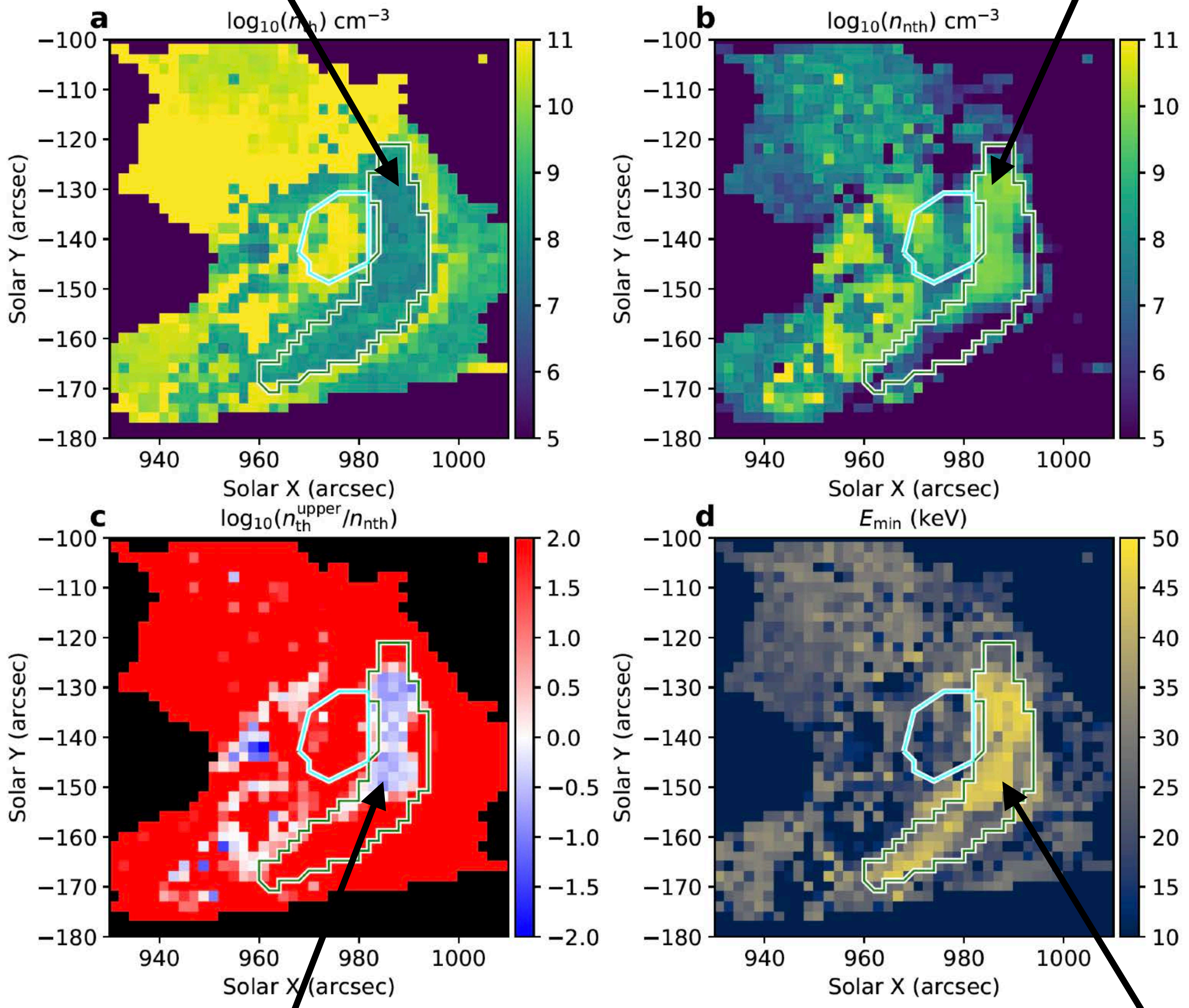


Adapted from Li+2019, ApJ

Low Thermal Density

High Non-thermal Density

Thermal Density



Non-Thermal Density

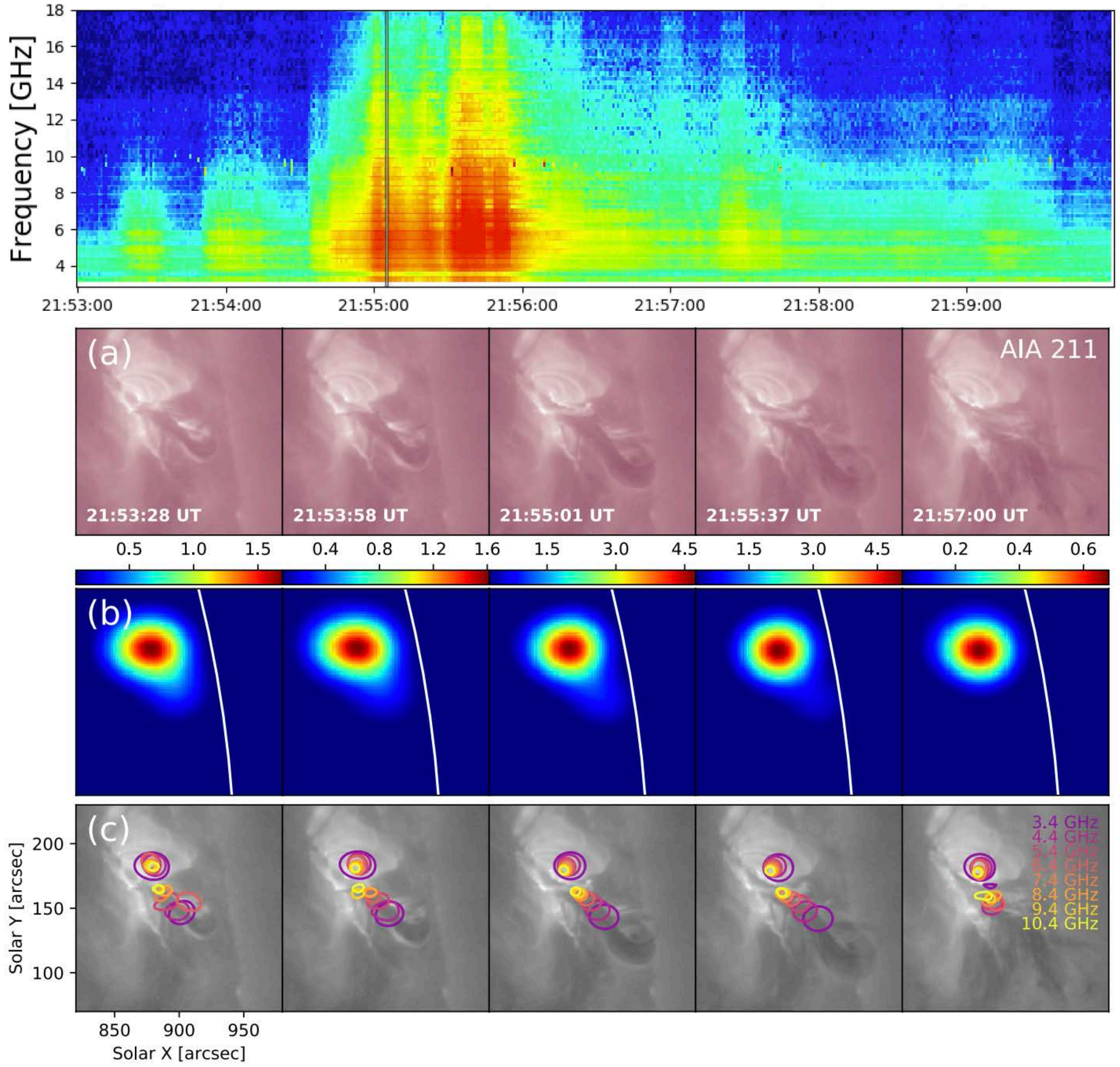
Density Ratio [max(n_{th})/n_{nth}]

Low-Energy Cutoff

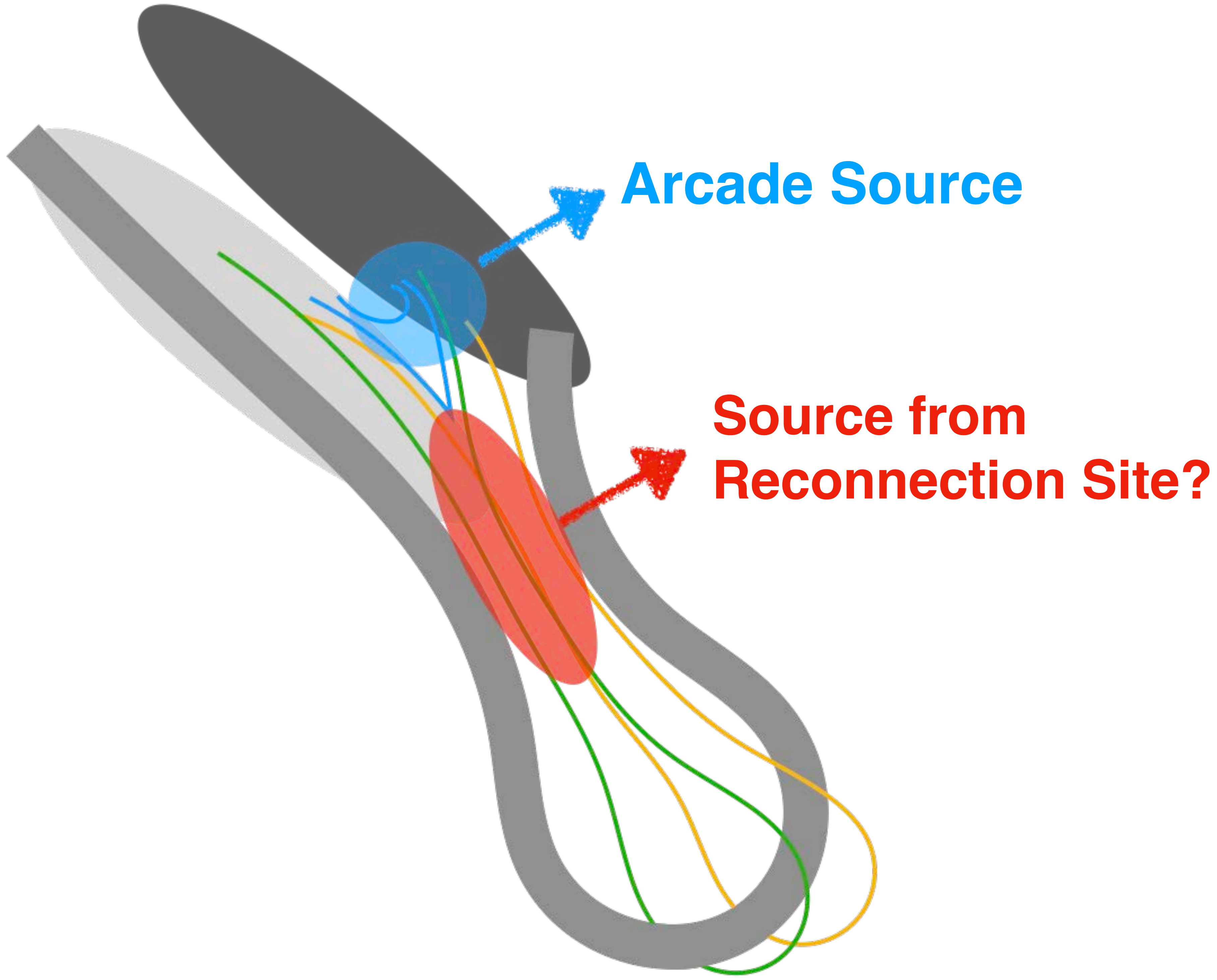
Low Thermal/Non-thermal Ratio

High Low-Energy Cutoff

Microwave Sources from Another Eruptive Event

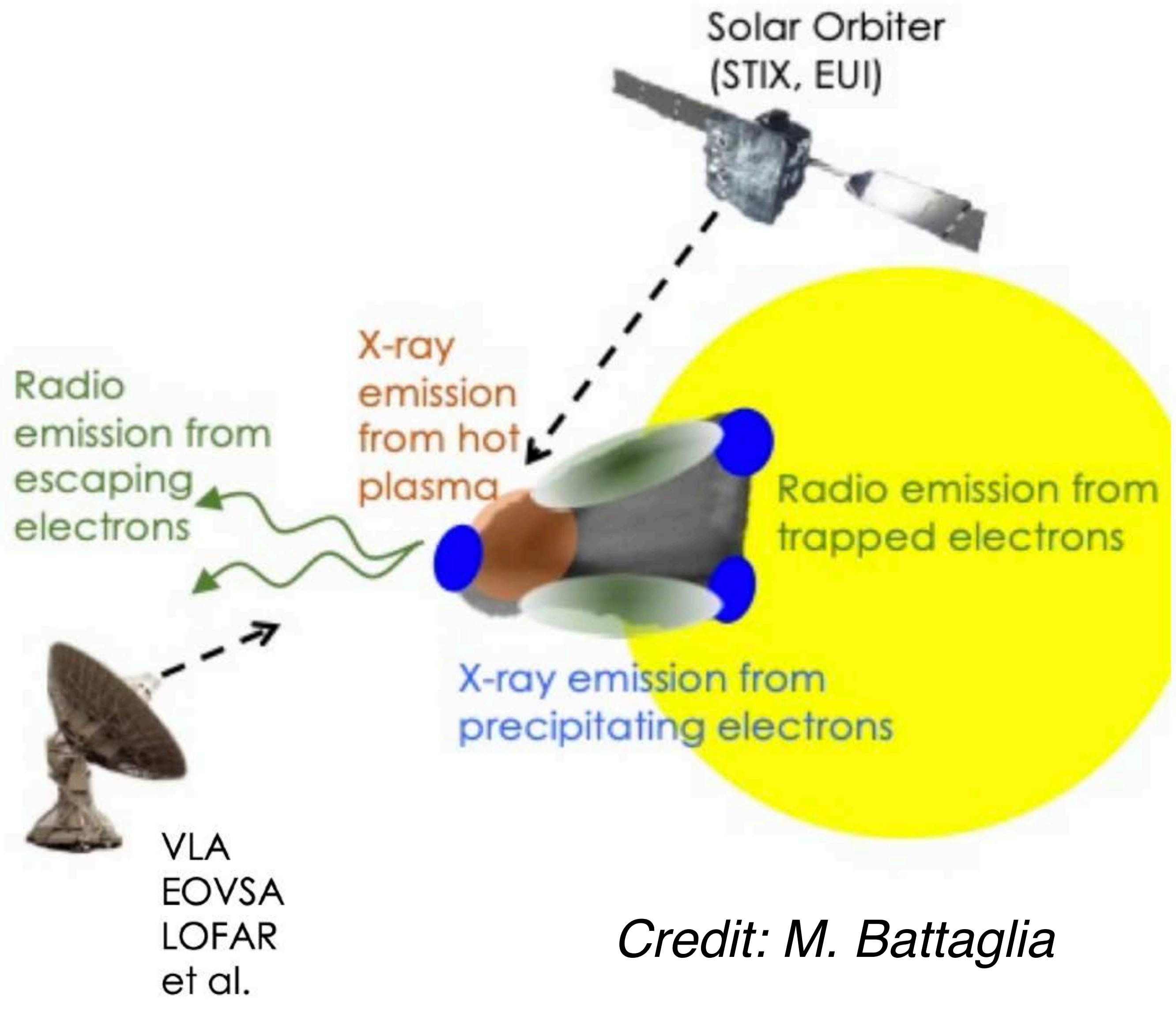


EOVSA observation of a C8.4-class eruptive flare event on 2017 July 13

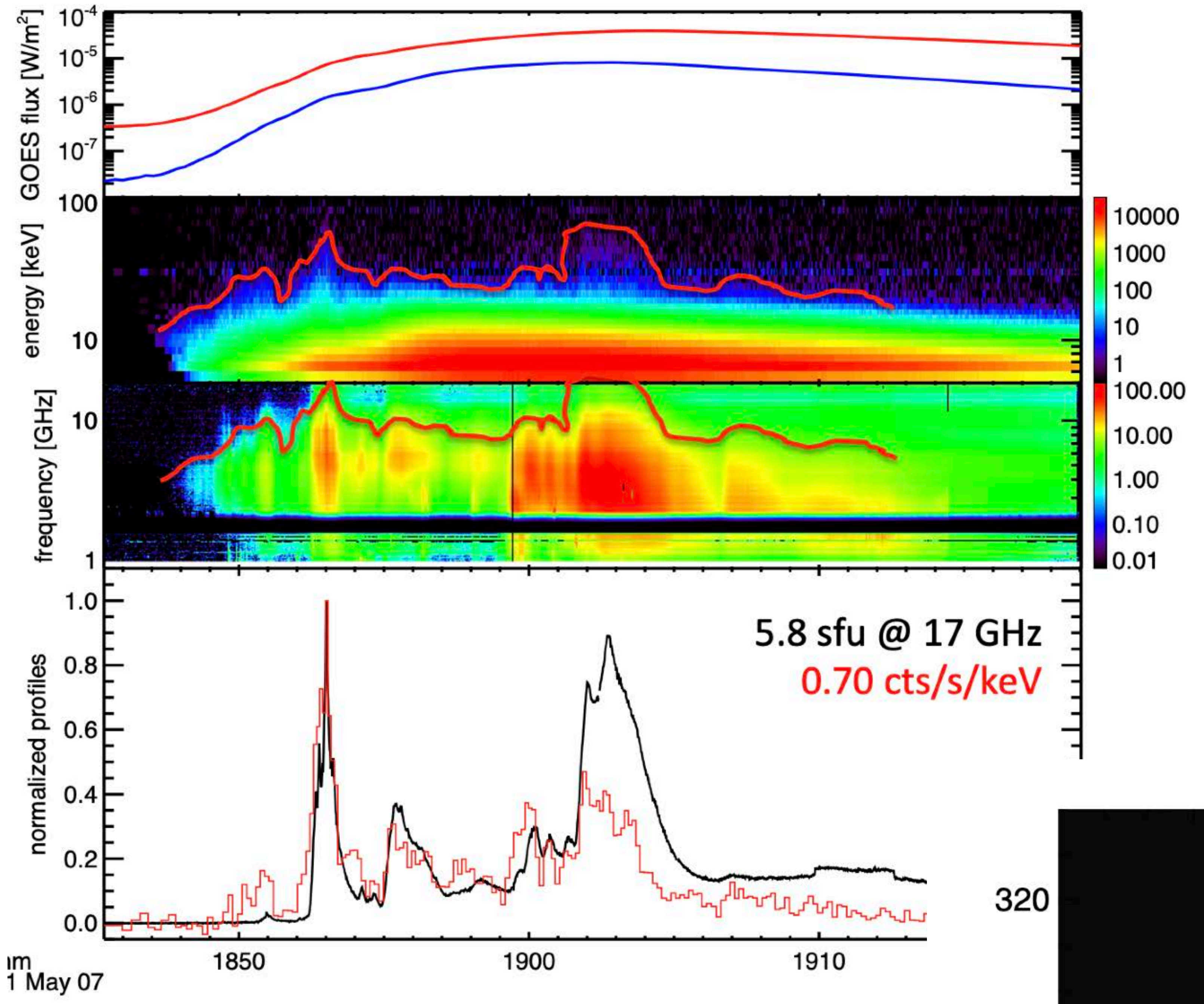


See Yuankun Kou's talk tomorrow

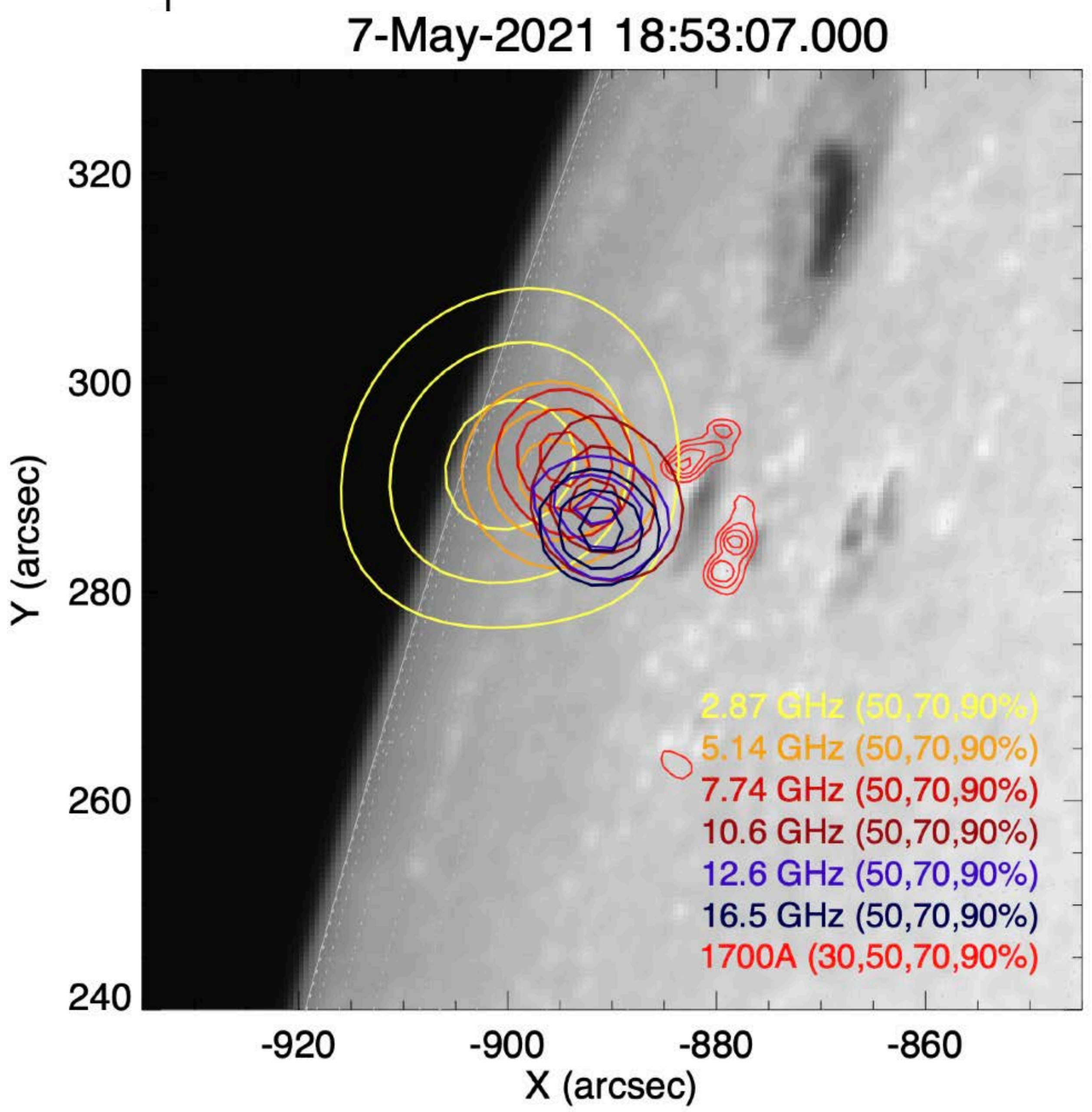
Joint EOVSA and SO/STIX Studies



Credit: M. Battaglia



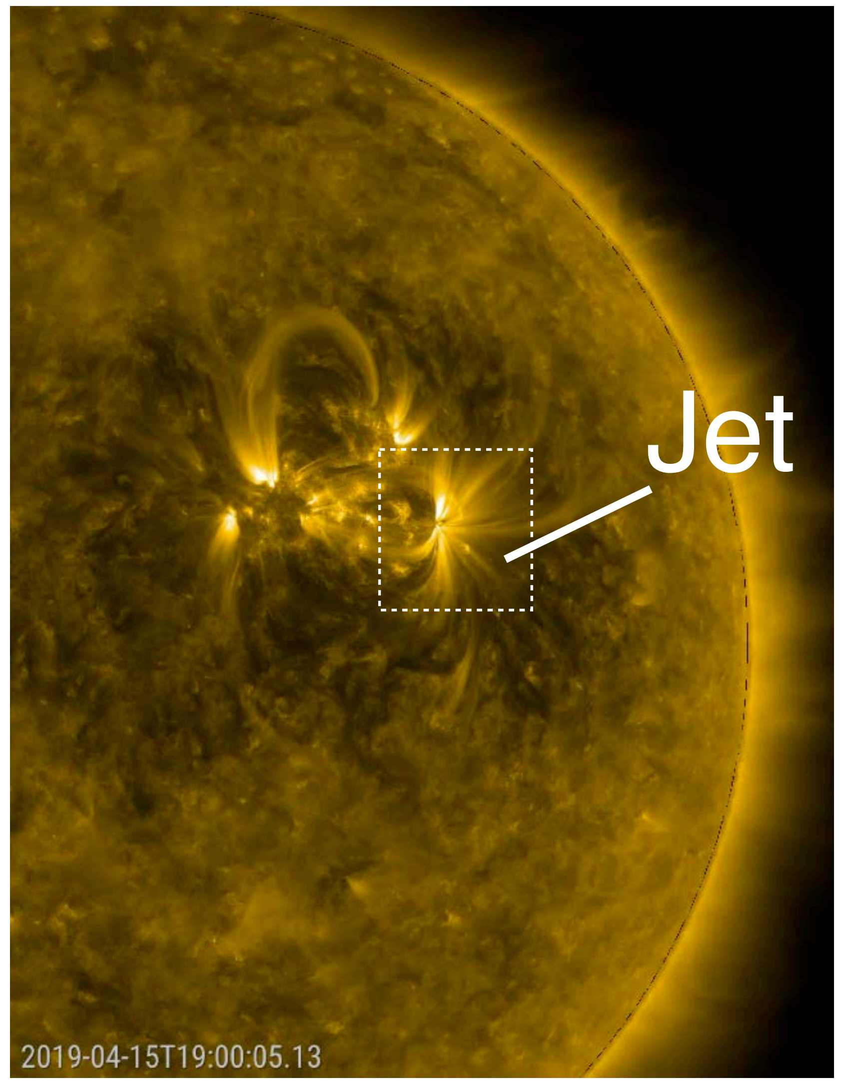
SOL2021-05-07
M4 flare

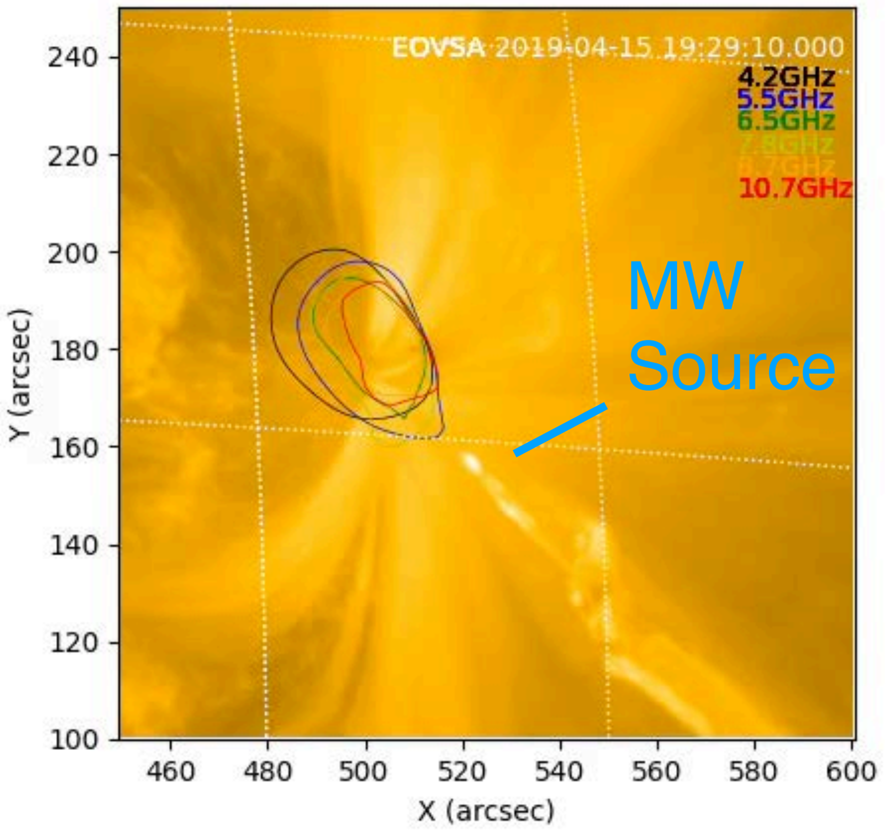


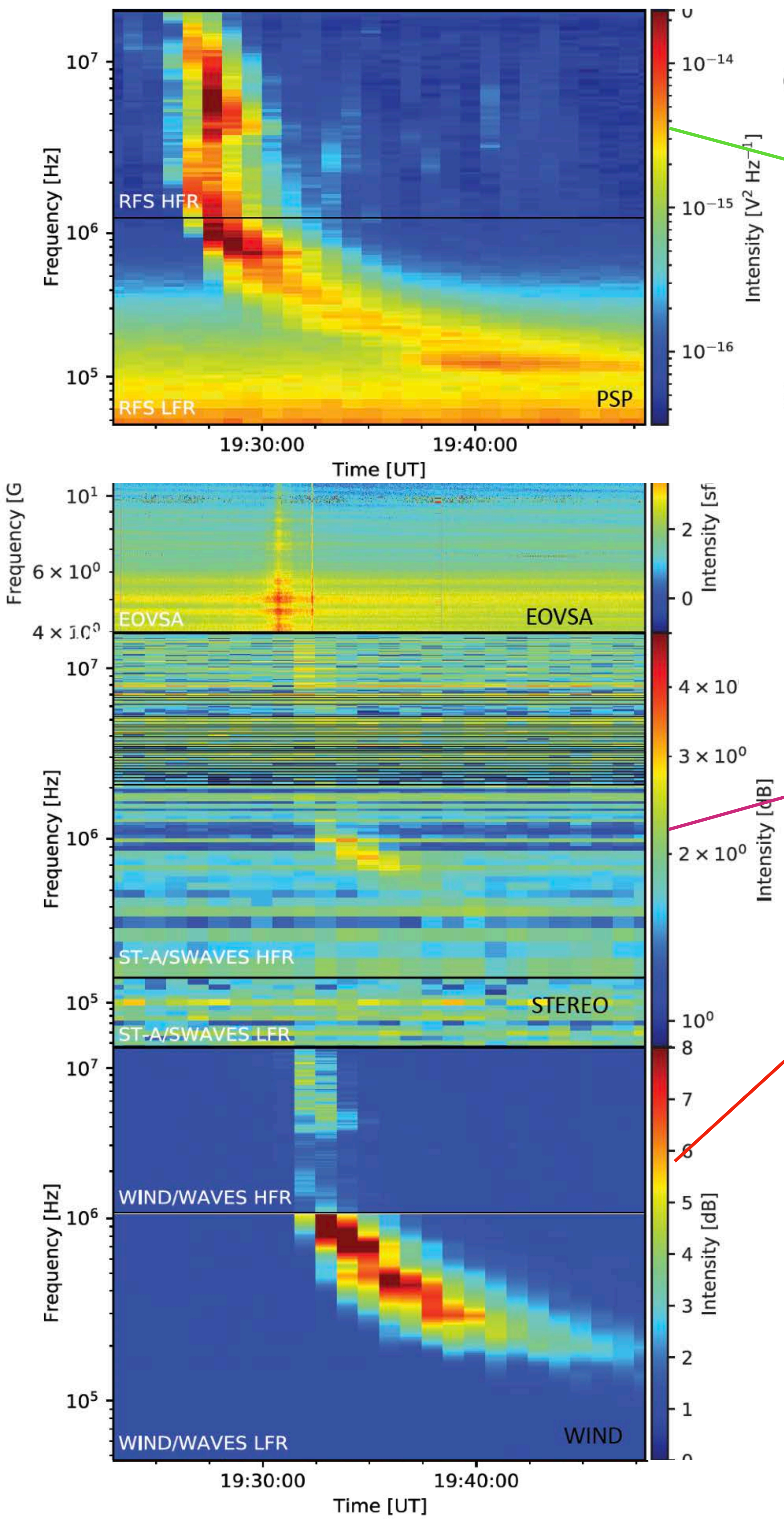
- **EOVSA and SO/STIX jointly observed >10 flare events**
- **Most of them are viewed from different perspectives**
- **Patially occulted flares for STIX are of particular interest**

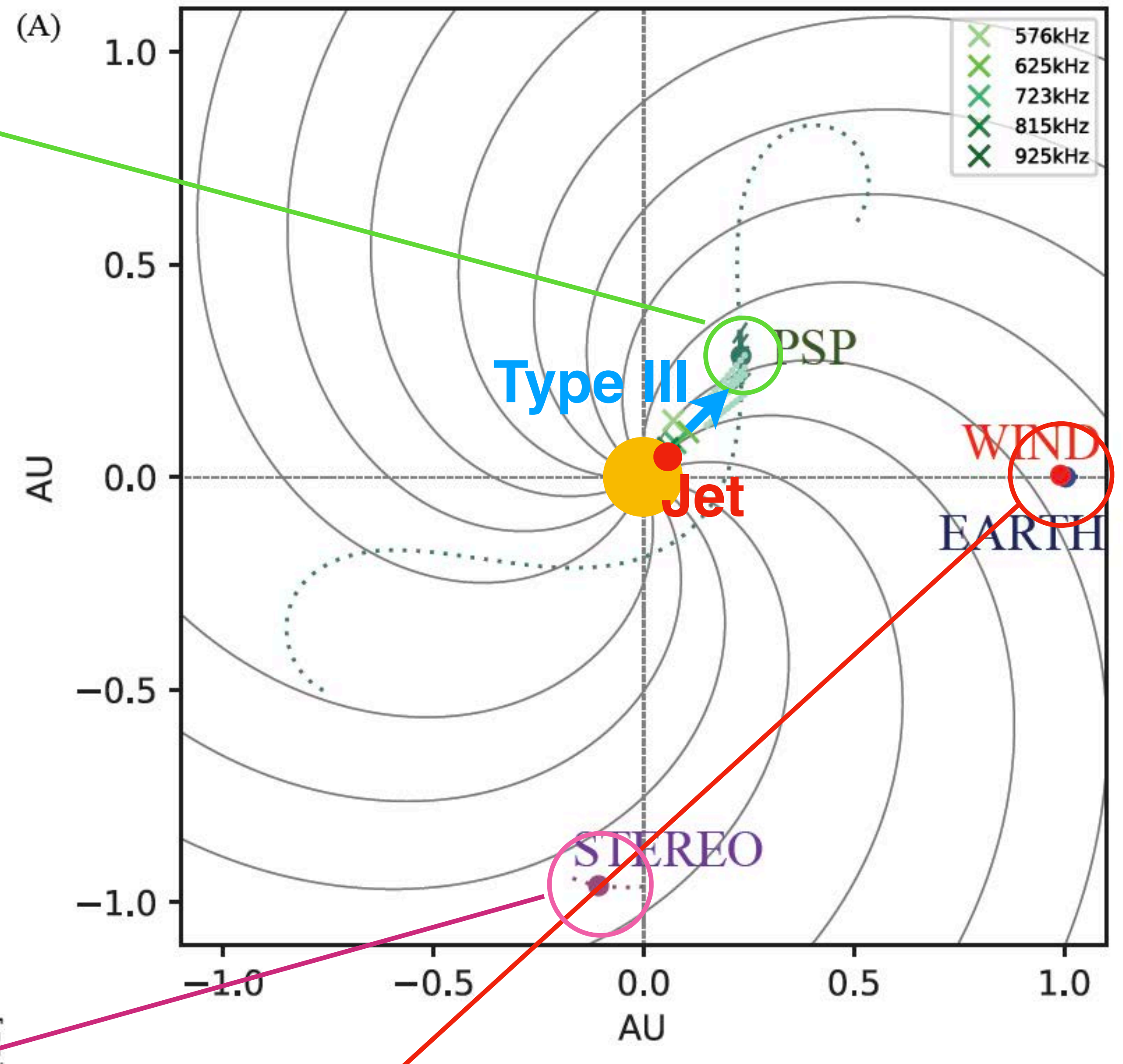
See Säm Krucker's talk tomorrow

Joint EOVSA and PSP Studies

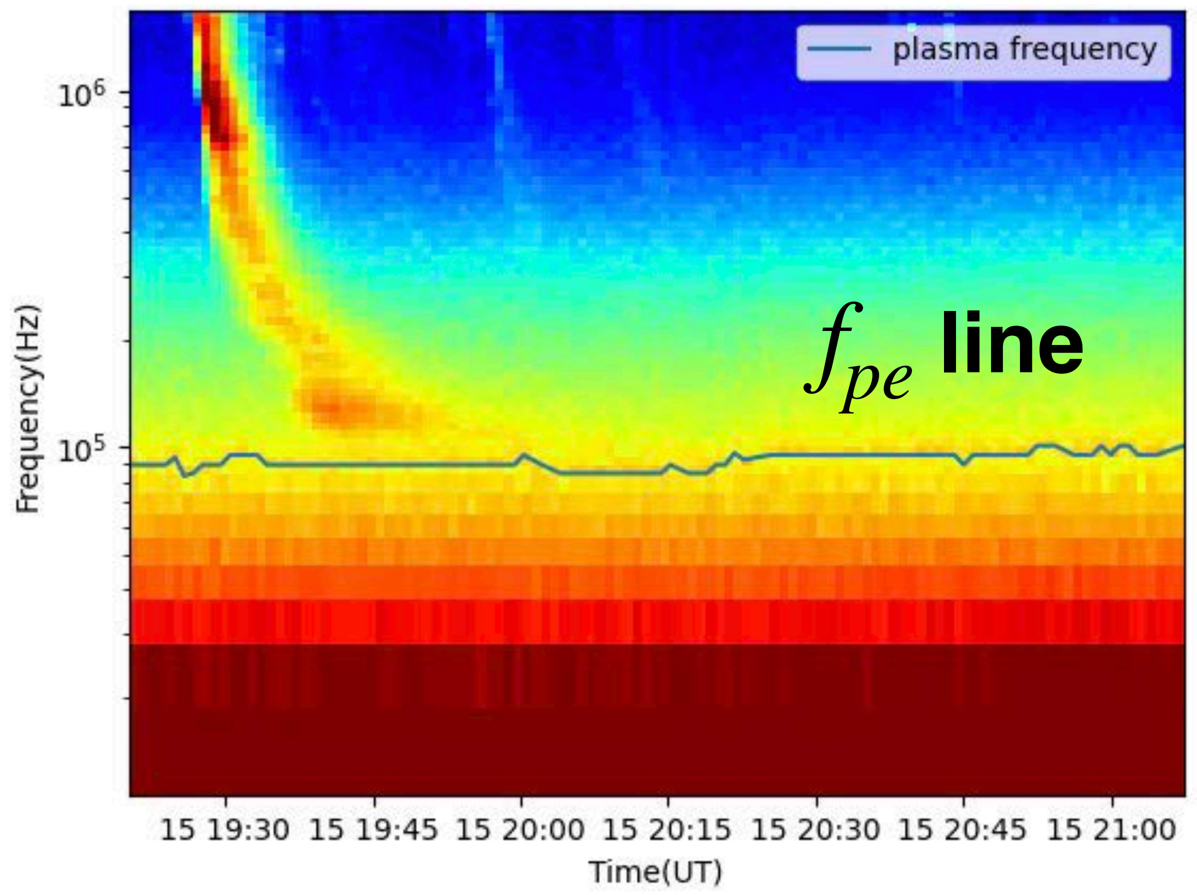




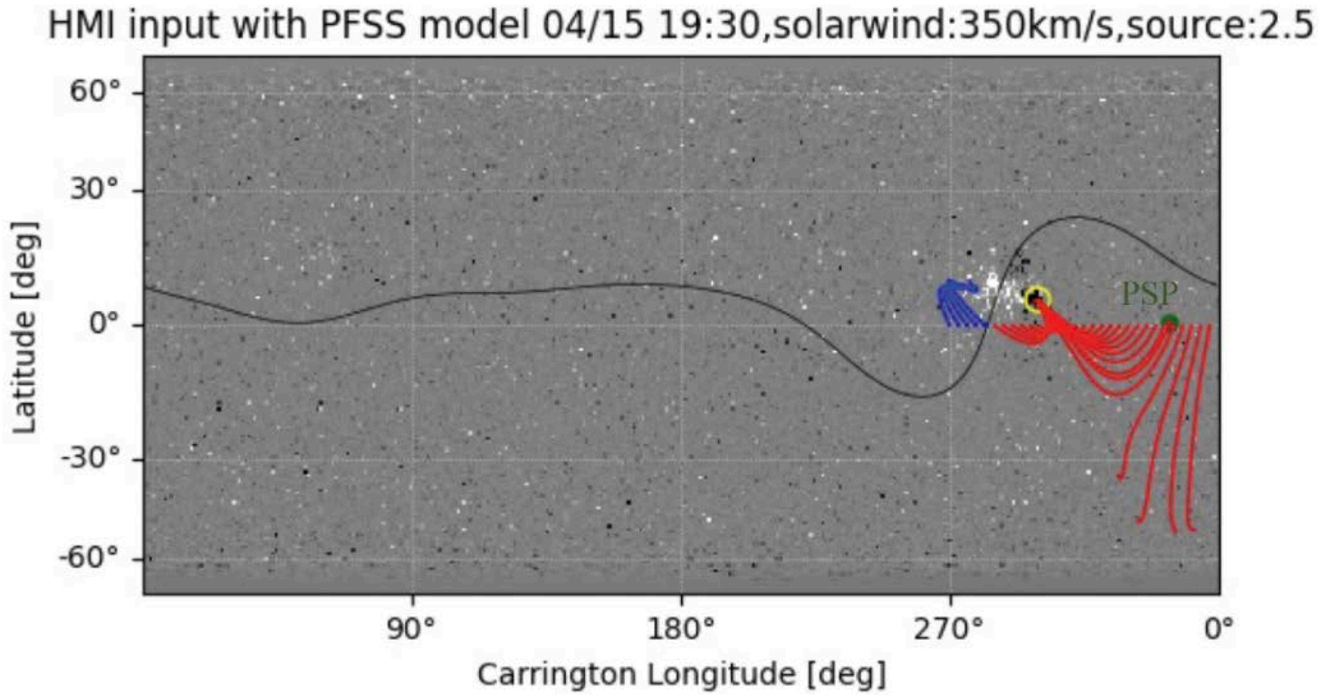




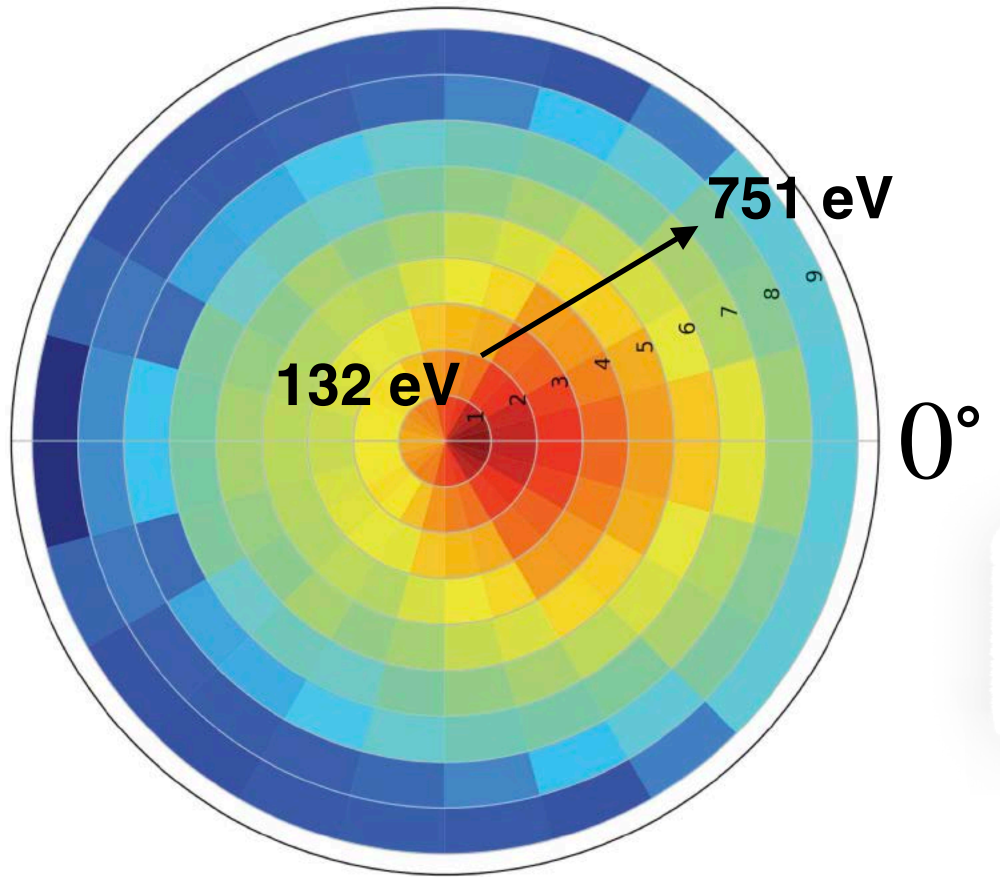
Type III reaches the local plasma line



PSP Connected to Source Region



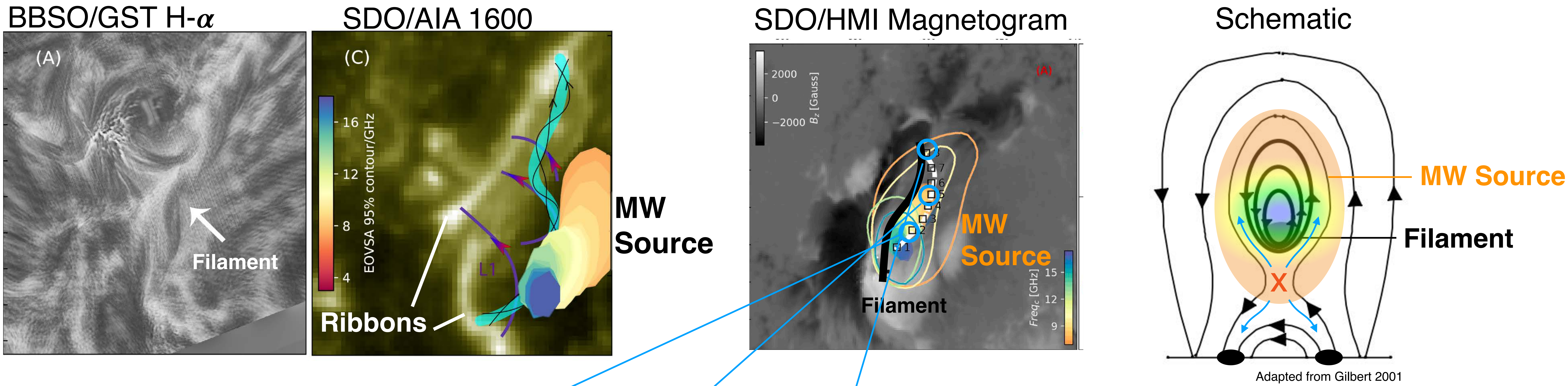
Anti-sunward e^- beams

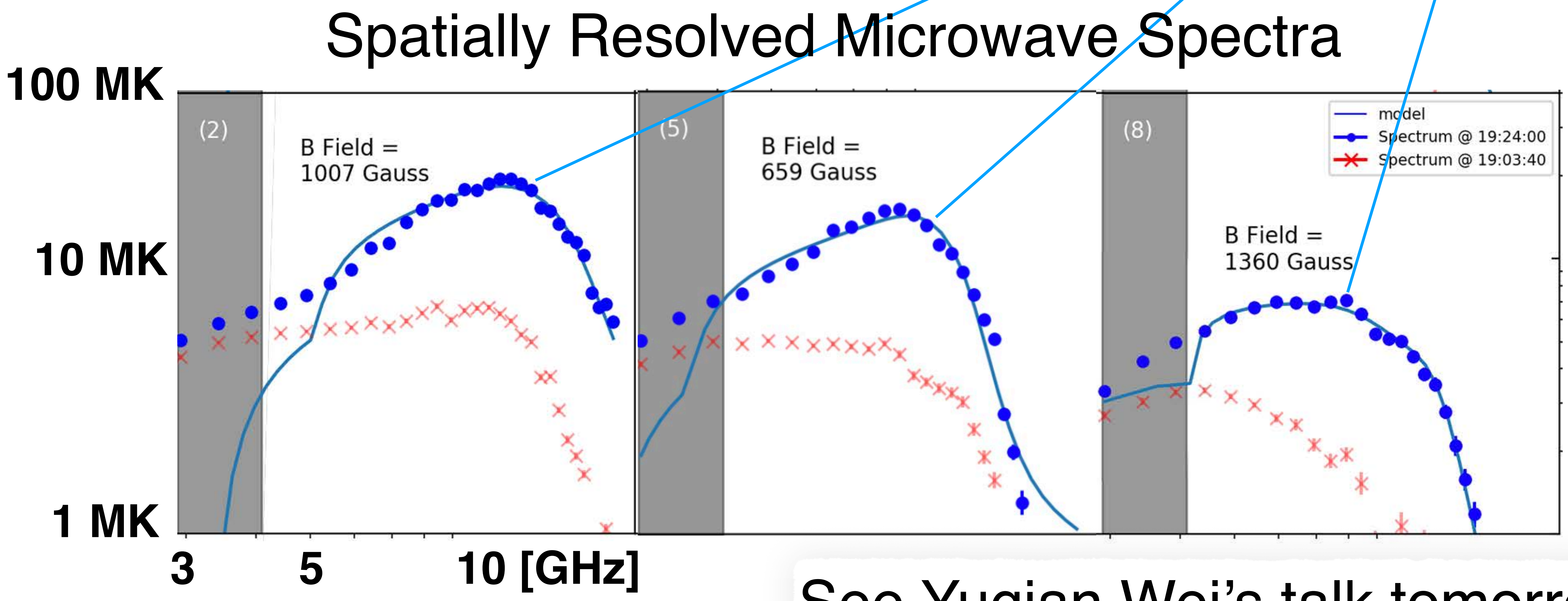


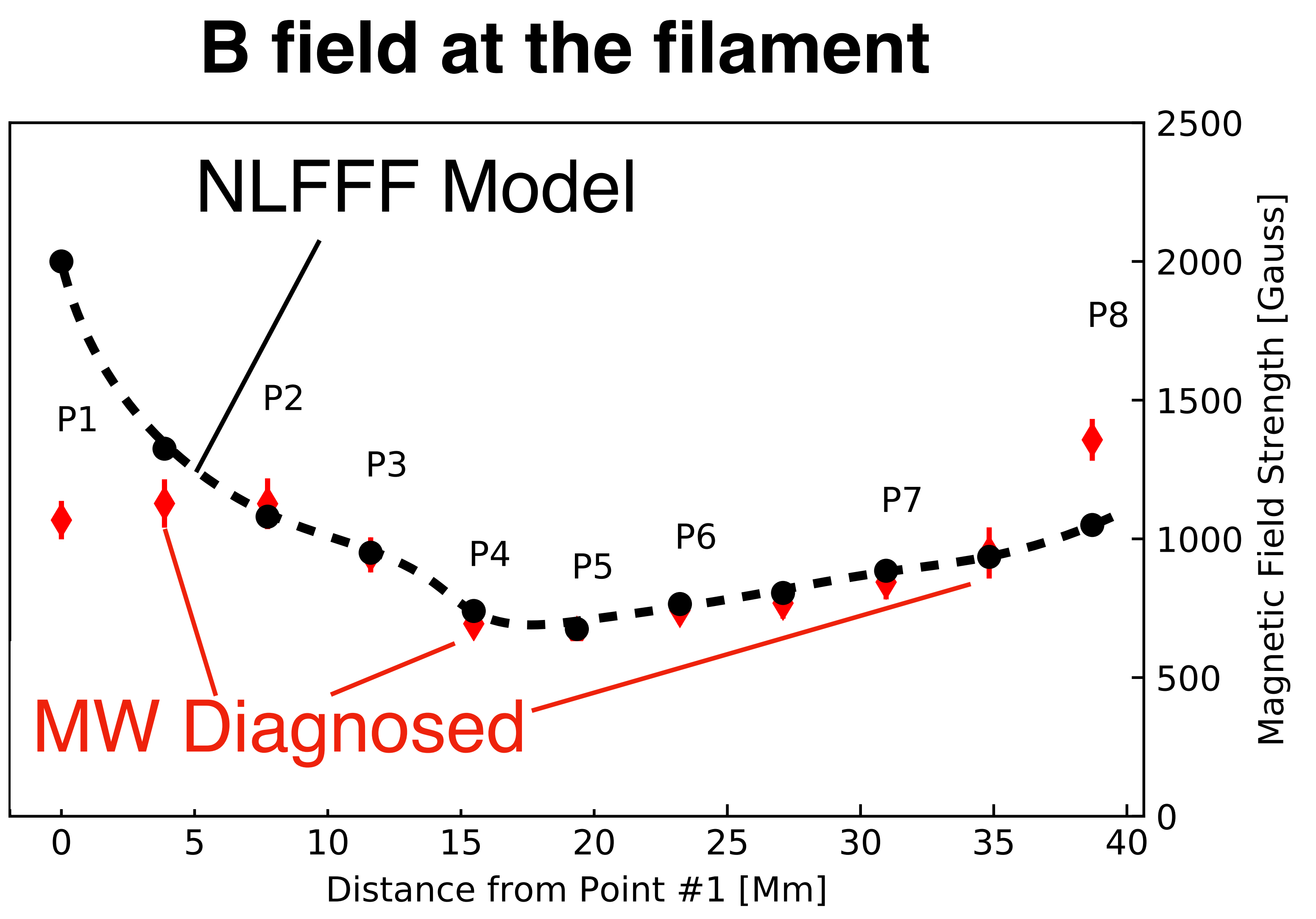
An ***interplanetary*** type III burst event driven by electron beams escaped from a solar jet?

Meiqi Wang+2021, in prep

Joint Study with BBSO & HMI: B Field of a Filament

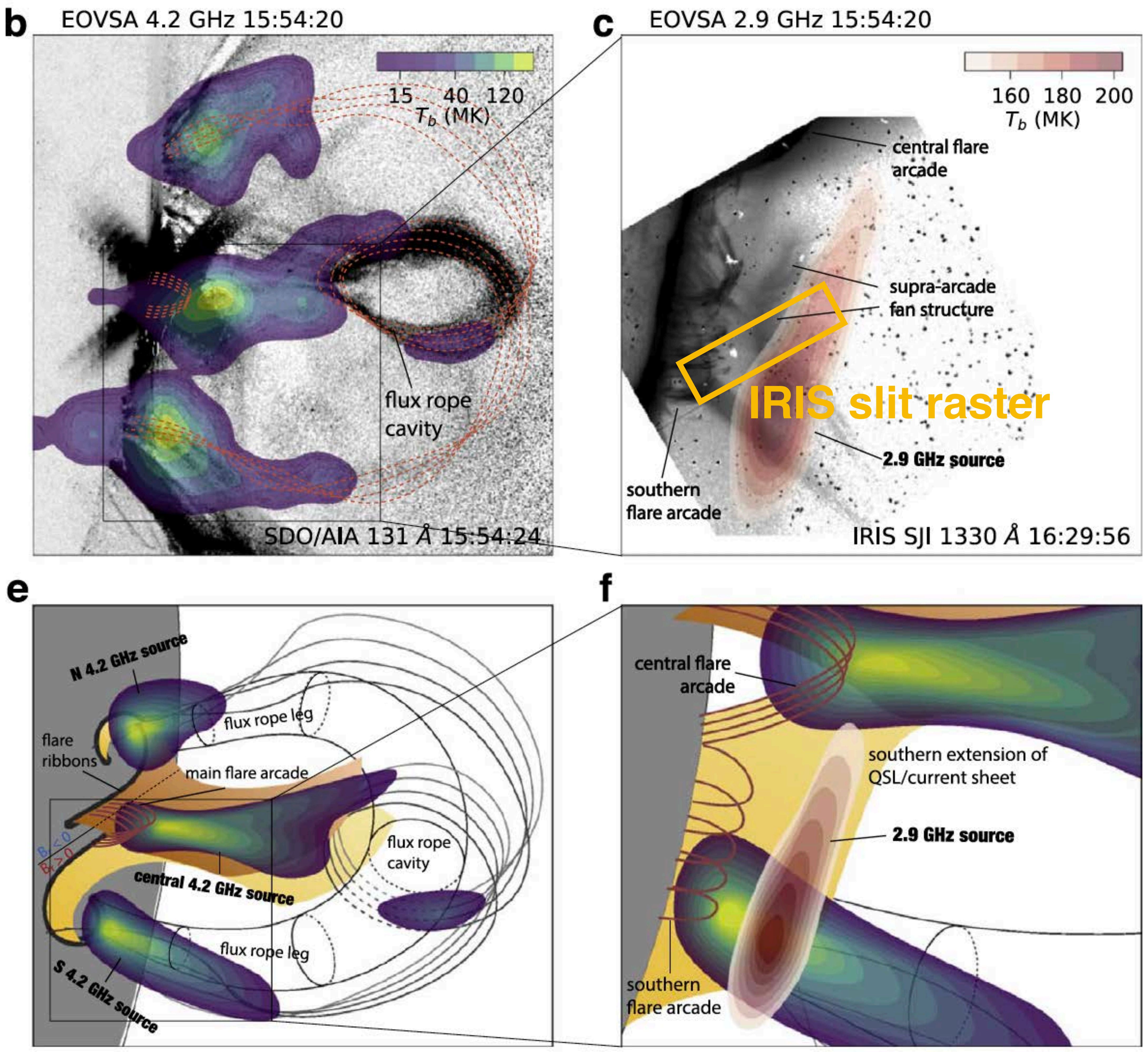




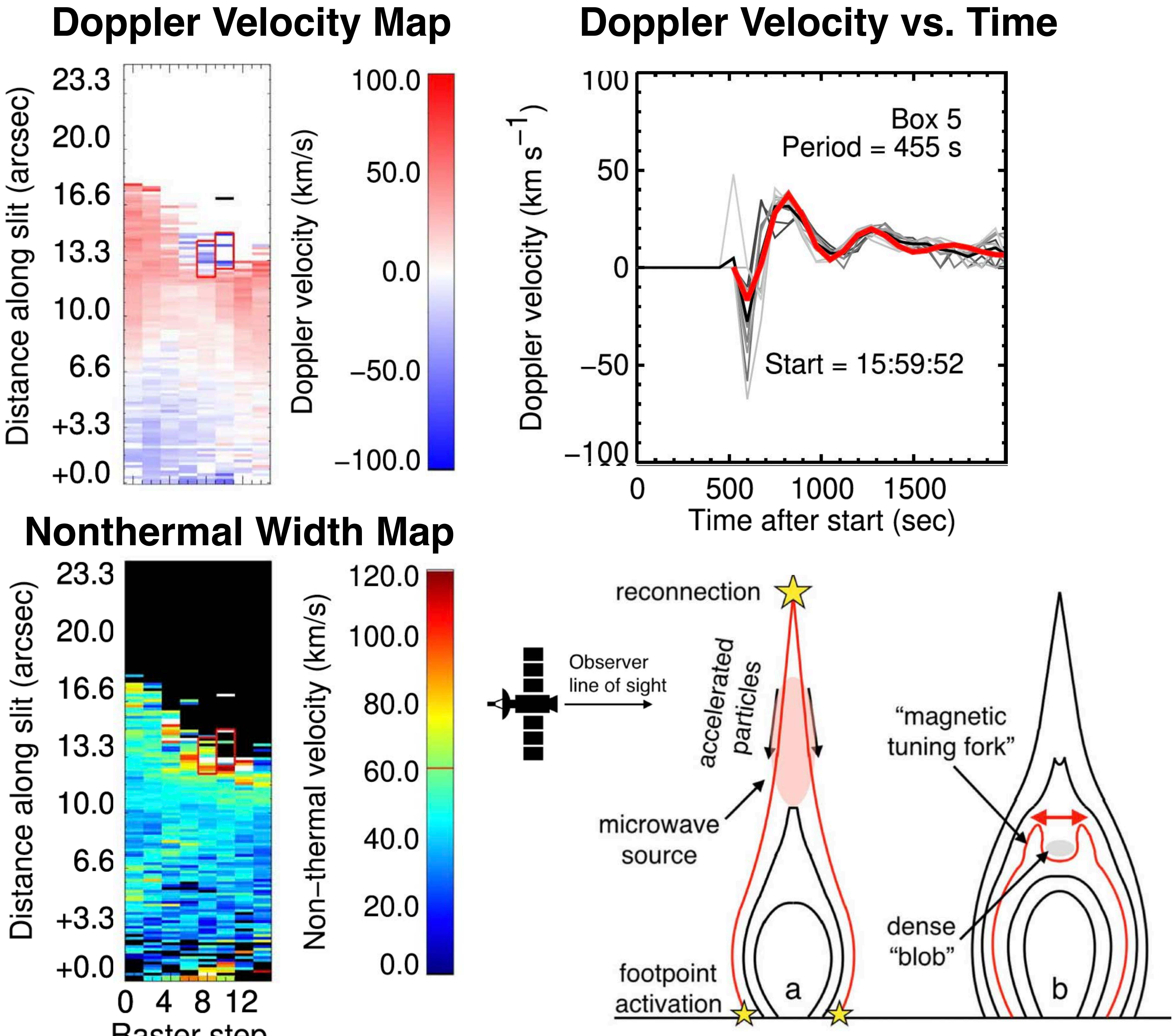


See Yuqian Wei's talk tomorrow

Joint Studies with IRIS and Hinode



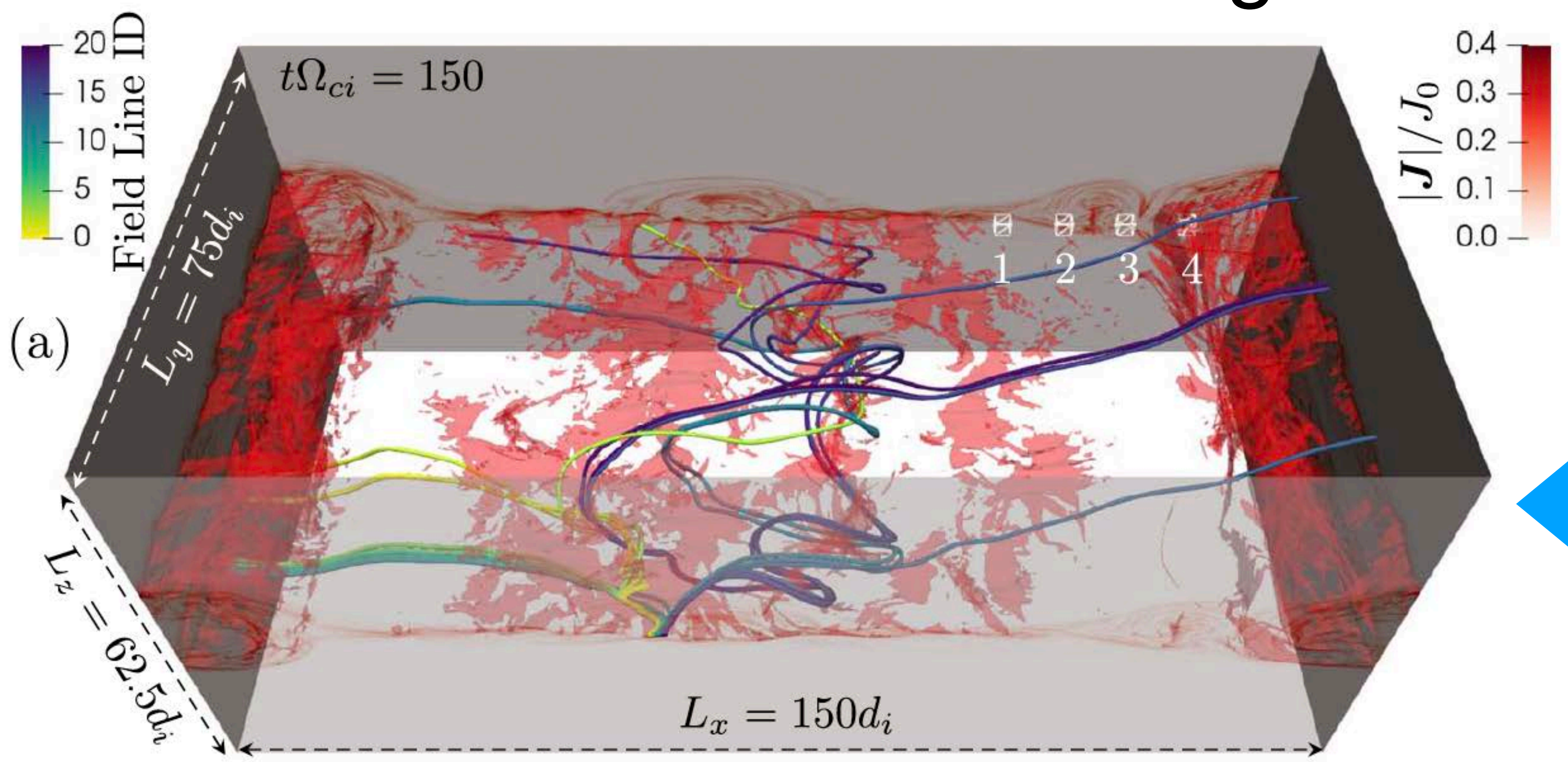
Chen+2020, ApJL



Reeves+2020, ApJ

Interpreting the Observations: Macroscopic Modeling

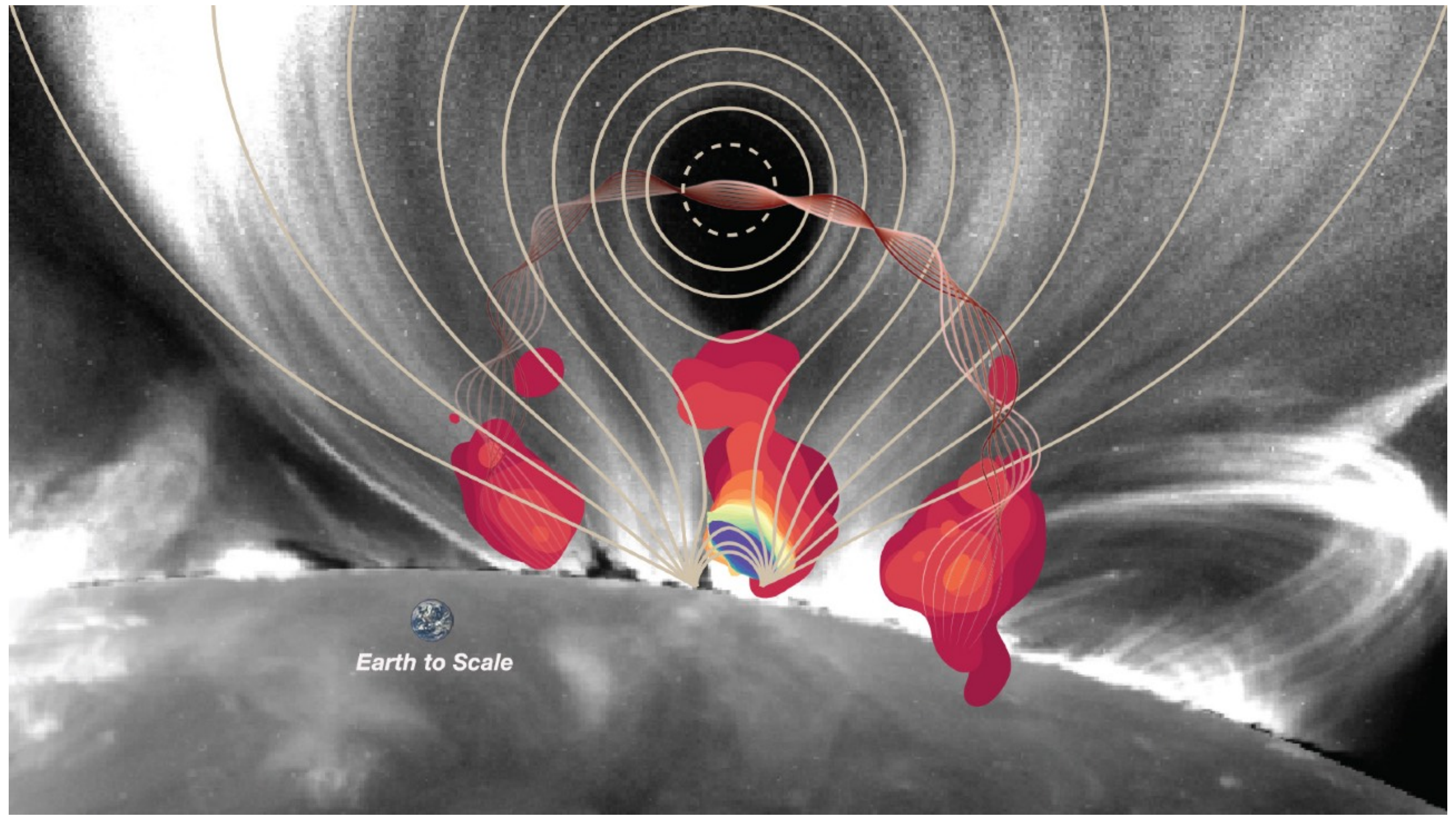
3D PIC Kinetic Modeling



Xiaocan Li+2019, ApJ

>10^5 Scale Separation

Eruptive Flares



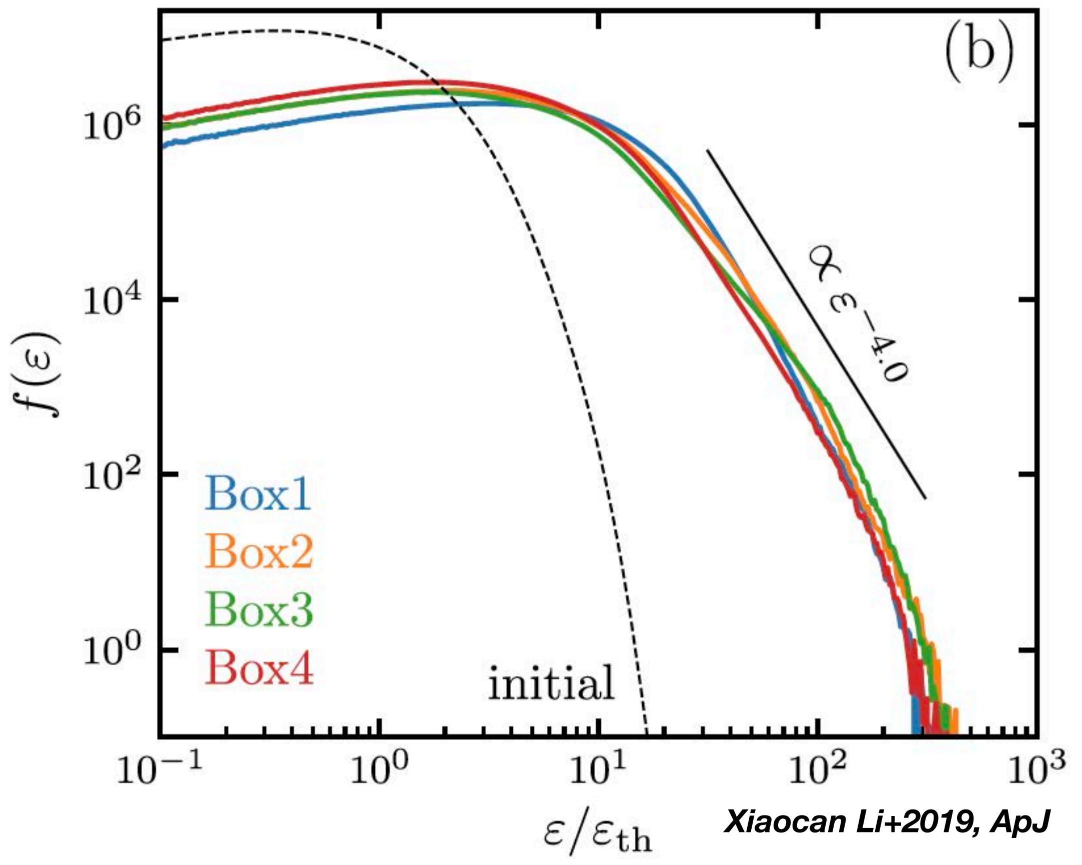
Chen+2020, Nat Astro

ρ_e	1m	ρ_i	10^3m	10^4m	$10^5 - 10^7$m	10^8m
Energetic Electrons	d_i	Energetic Ions	Largest PIC	MHD Grid	Observation Resolution	Flare

Interpreting the Observations: Macroscopic Modeling

Self-Consistent Macroscopic Modeling

$\overrightarrow{B}, \overrightarrow{v}, j, \boxed{f(\varepsilon, \theta)}$



Xiaocan Li+2019, ApJ

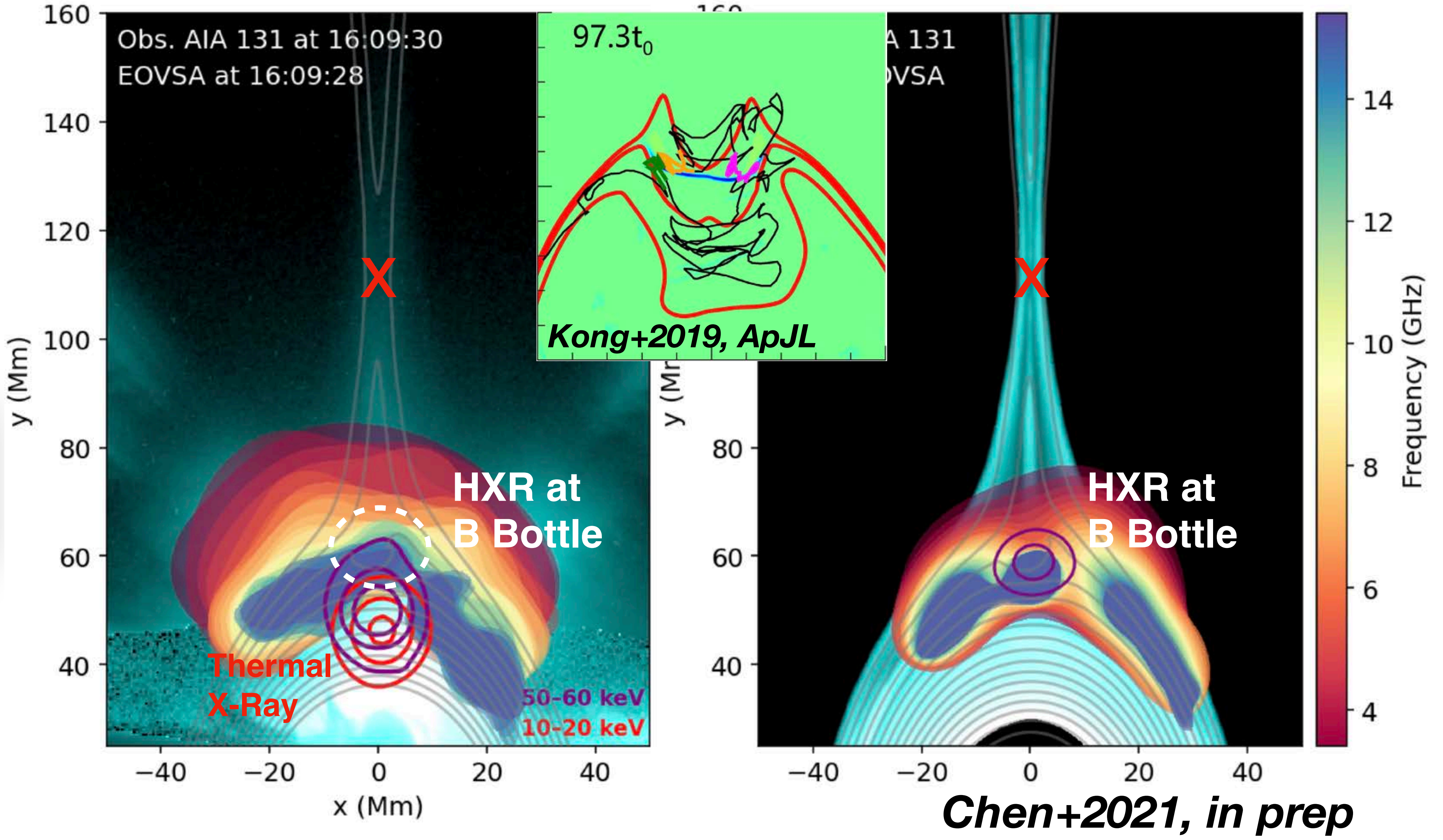
Synthetic Emission Calculation

GX_Simulator, GSFIT…

Flare Signatures

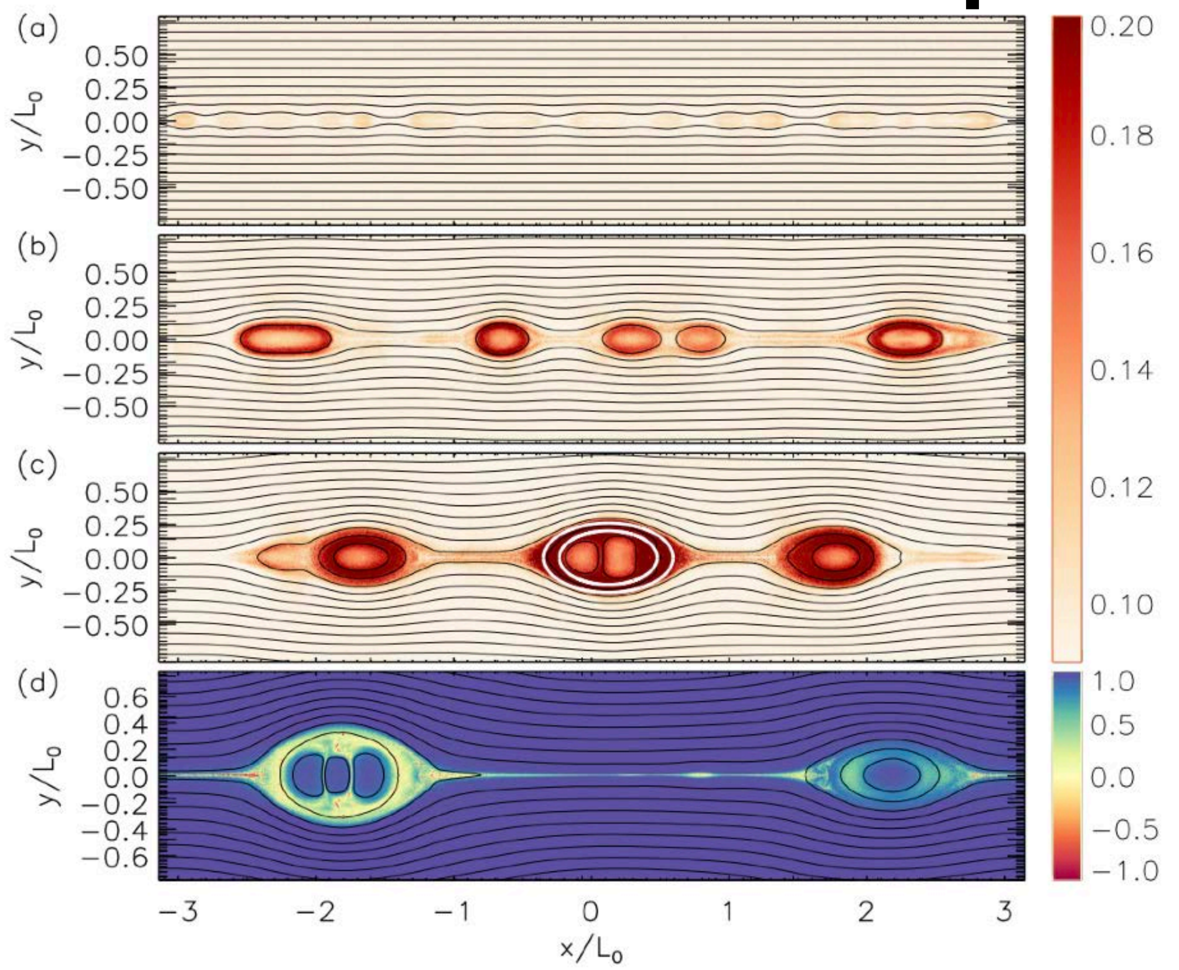
Microwave, X-ray, EUV Images and Spectra

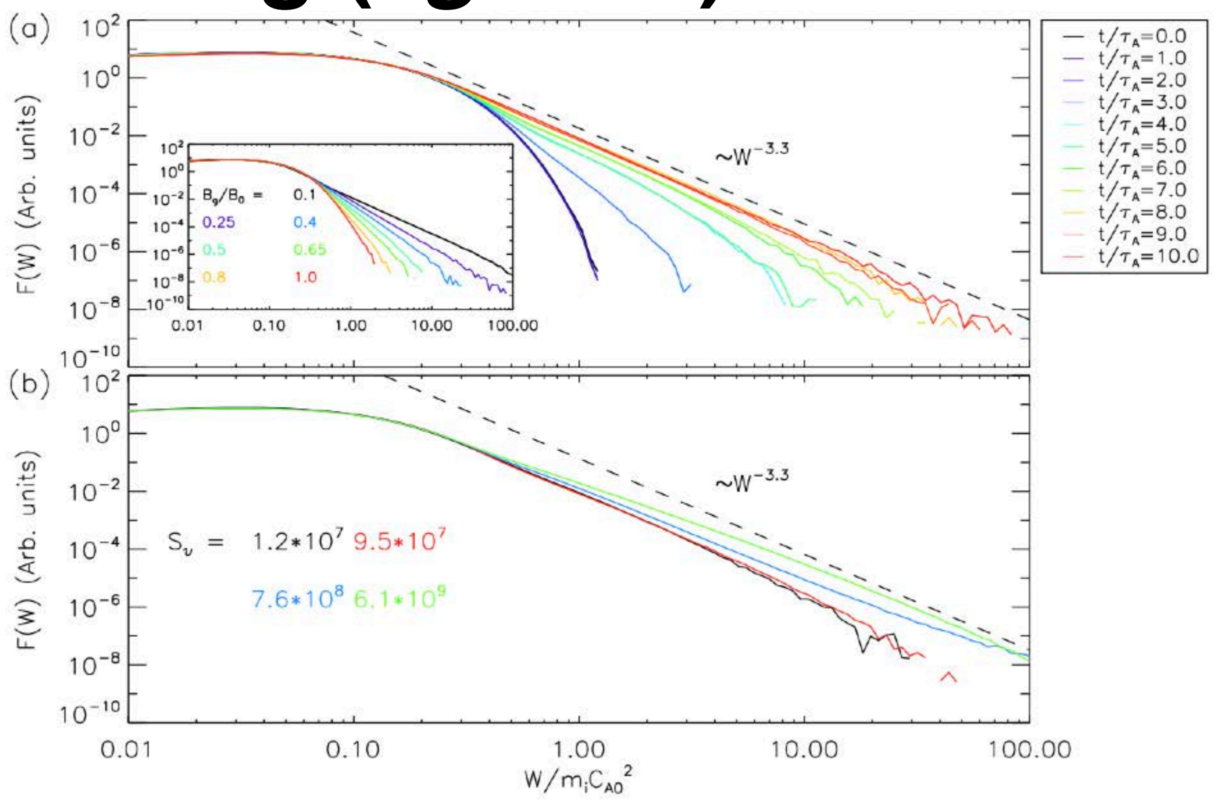
MHD Framework + Particle Modeling



Chen+2021, in prep

Macroscopic Modeling (*kglobal*)





Arnold+2021, PRL

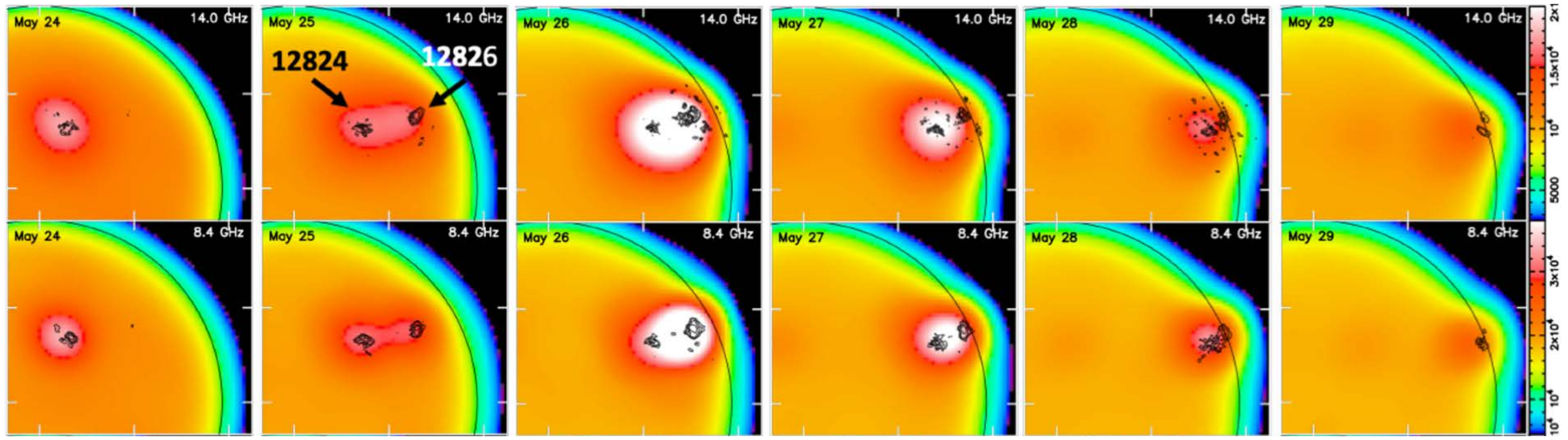
One of the main objectives of the [SolFER DRIVE Science Center](#)

See Jim Drake’s talk later today

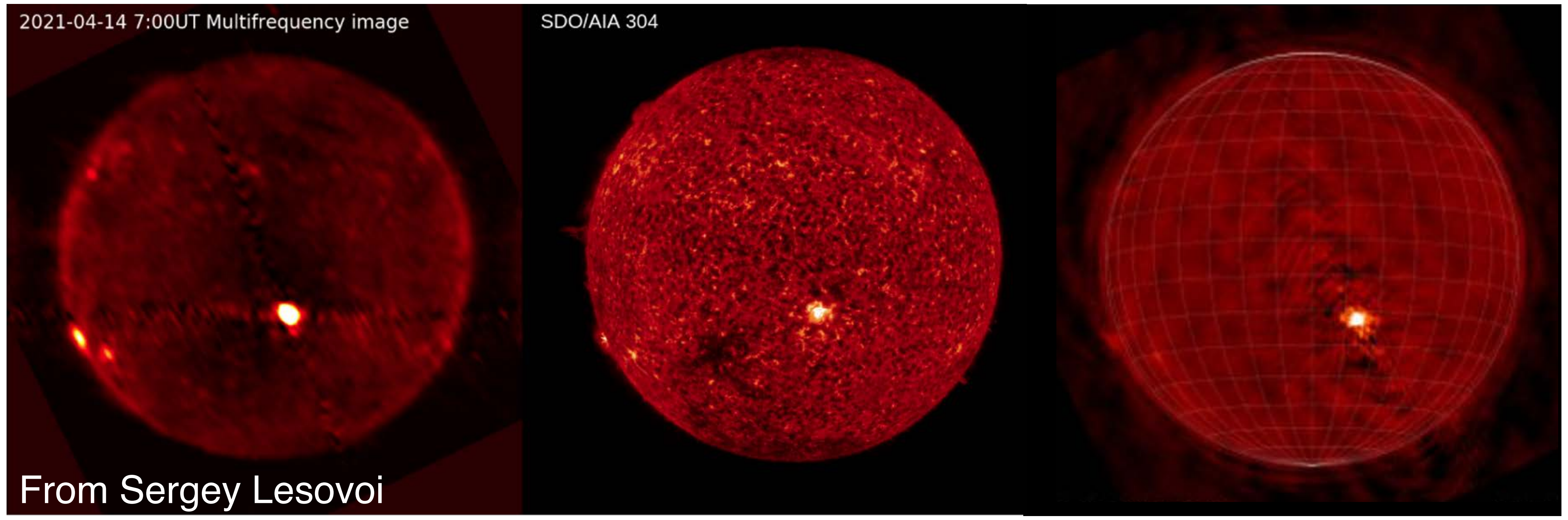
Full Disk Studies

- With 13 antennas and sparse uv coverage, EOVSA is not optimized for full-disk imaging.
- However, taking advantage of **Earth-rotational synthesis** to (greatly) improve the uv coverage (by sacrificing time resolution), we have a working pipeline to produce daily full-disk images at 7 frequency bands – see EOVSA Data Browser
- We have plans to further improve these images by taking account of solar rotation (a complex problem —see Dale's talk yesterday) and combining our data with other observations.
- The latter includes GAVRT single-dish images and SRH interferometeric images.

GAVRT 34-m single dish images + EOVSA (contours)

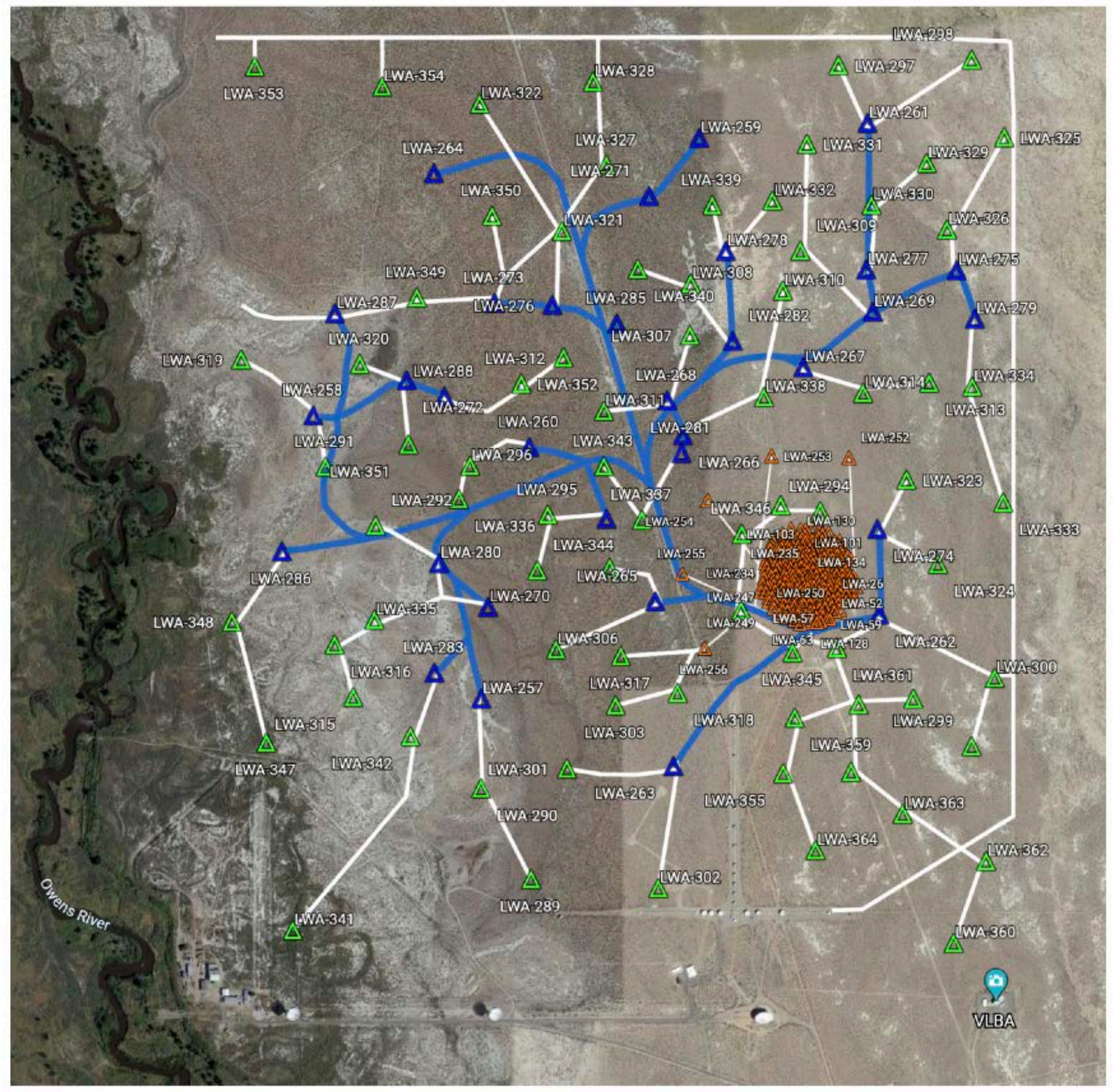


Siberian Radioheliograph 4.2 GHz **SDO/AIA 304** **EOVSA 4.5 GHz**



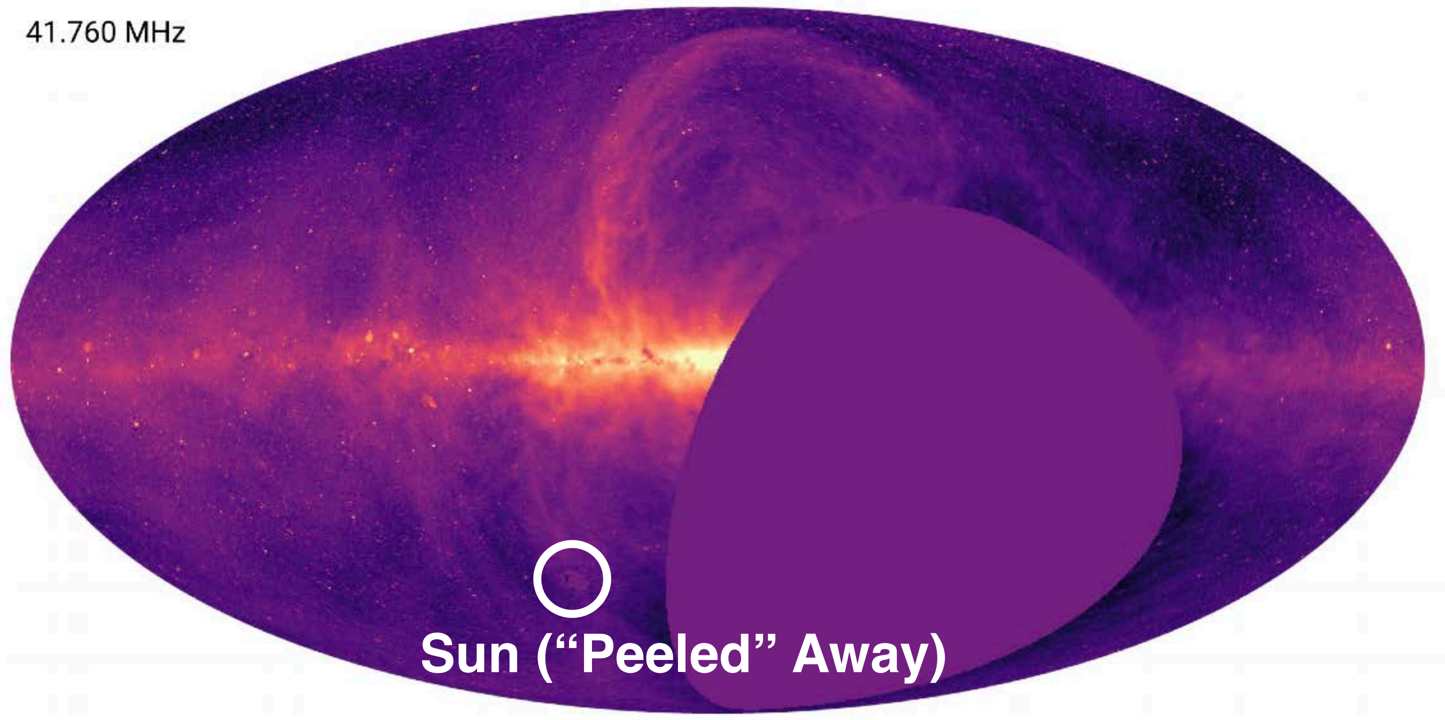
Future Outlook: OVRO–LWA

The Owens Valley Long Wavelength Array (led by Caltech)

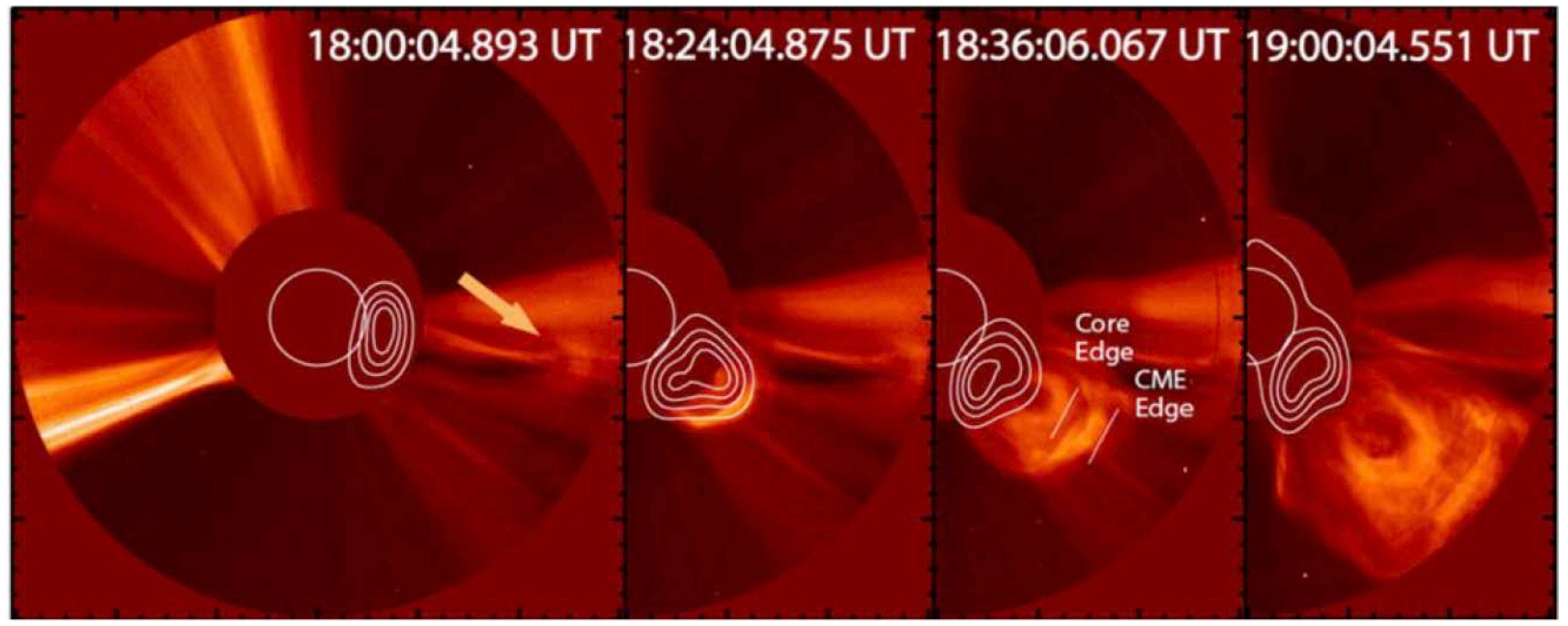


Credit: Gregg Hallinan

- An **all-sky spectral imager** operating in **20–88 MHz** (meter waves)
- 352 antennas spread in a 2.6-km region
- **Sun is in its FOV** during the day. NJIT is the lead institution for its solar science.
- Ideal for studying **coherent radio bursts** (type II, type III, type IV…) **in the middle corona** out to ~2 $R_\odot$
  - Escaping electron beams
  - CME-driven shocks
  - Radio CMEs
- **Dedicated solar backend** with 48 antennas, providing 5’–20’ resolution
- **Data expected later this year**



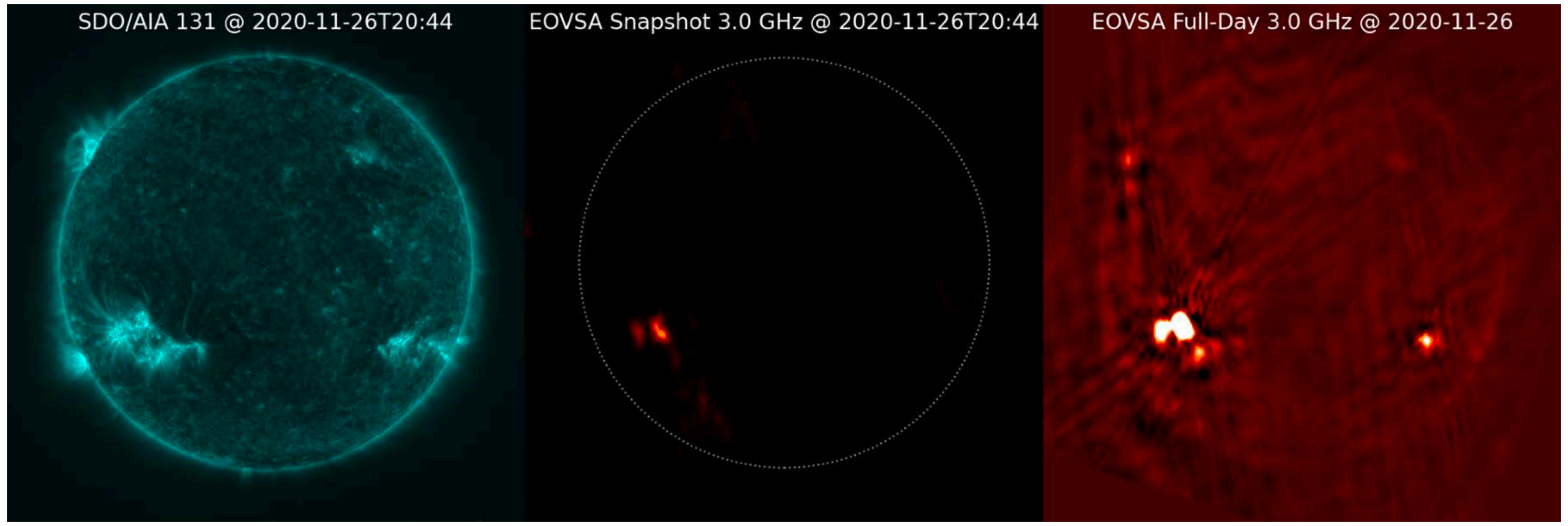
Eastwood+2018, ApJ

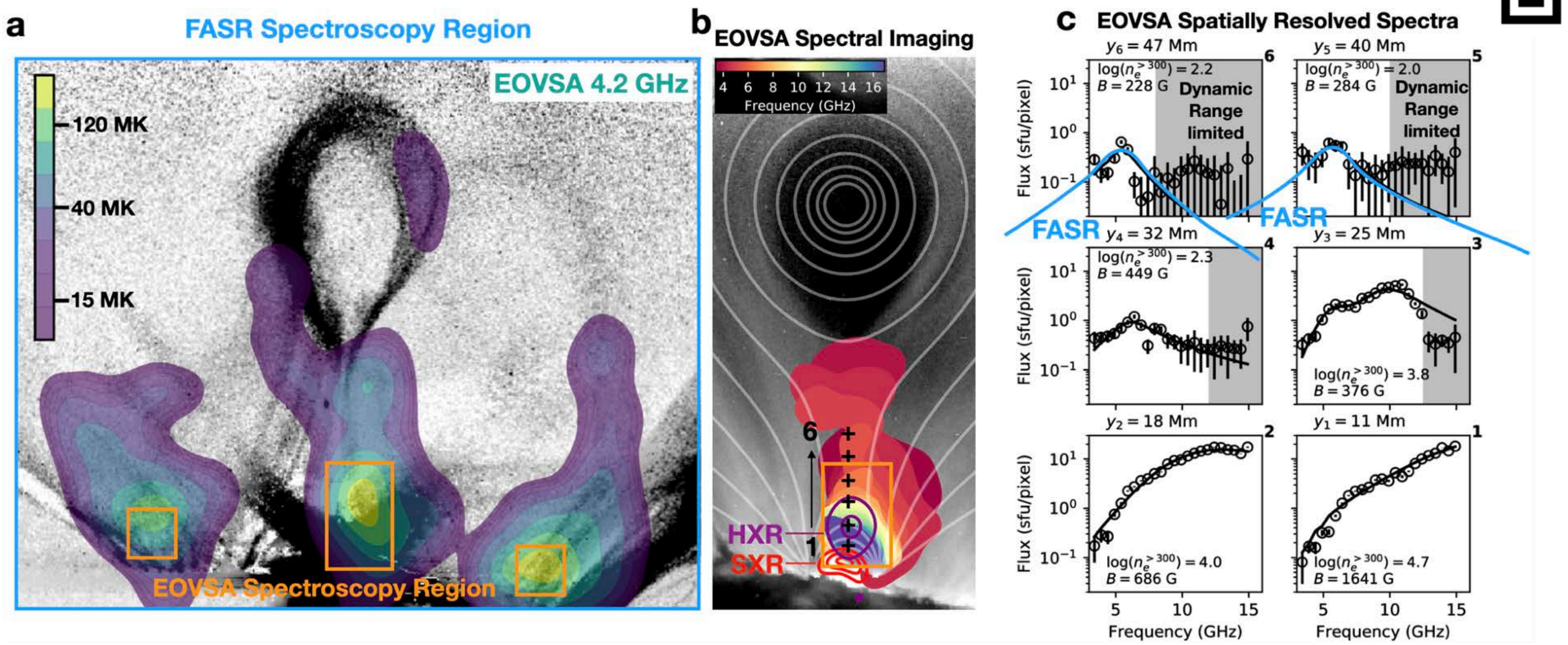


Chhabra+2021, ApJ

Future Outlook: Frequency Agile Solar Radiotelescope

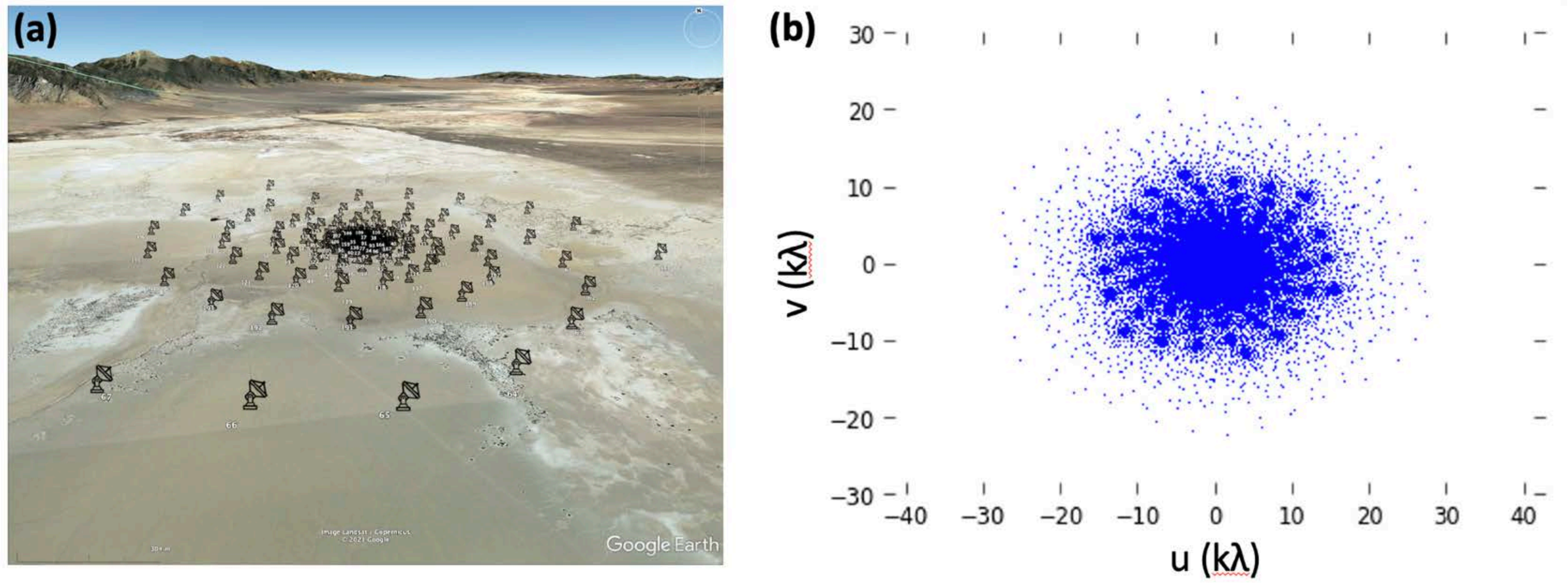
- With only 13 antennas and a longest baseline of 1 km, EOVSA is limited in its **dynamic range (<100:1)**, **image fedelity**, and **angular resolution** $(60''/\nu_{GHz})$
- With >100 antennas, FASR will improve upon EOVSA's spectral imaging capabilities by many orders of magnitude
- FASR will be a true **thousand channel, HDR radio video camera**.
- White paper submitted to Astro2020; Proposing to NSF MSIP or Mid-RI Program.



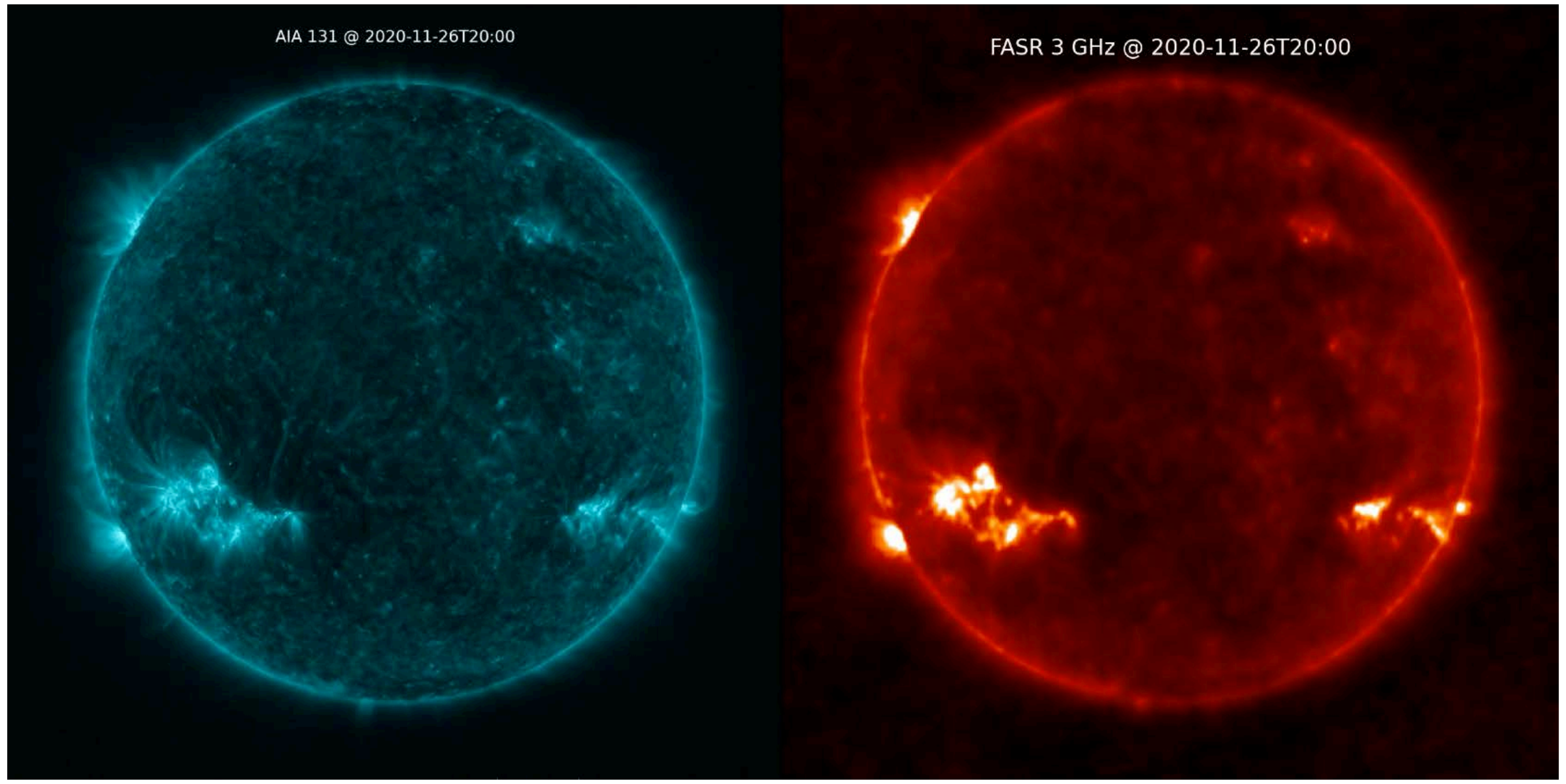


See [my Helio2050 iPoster]() for more details

Example FASR Array Configuration and UV Coverage



Synthesized FASR Full-Disk Movie at 3 GHz



Questions/Comments?