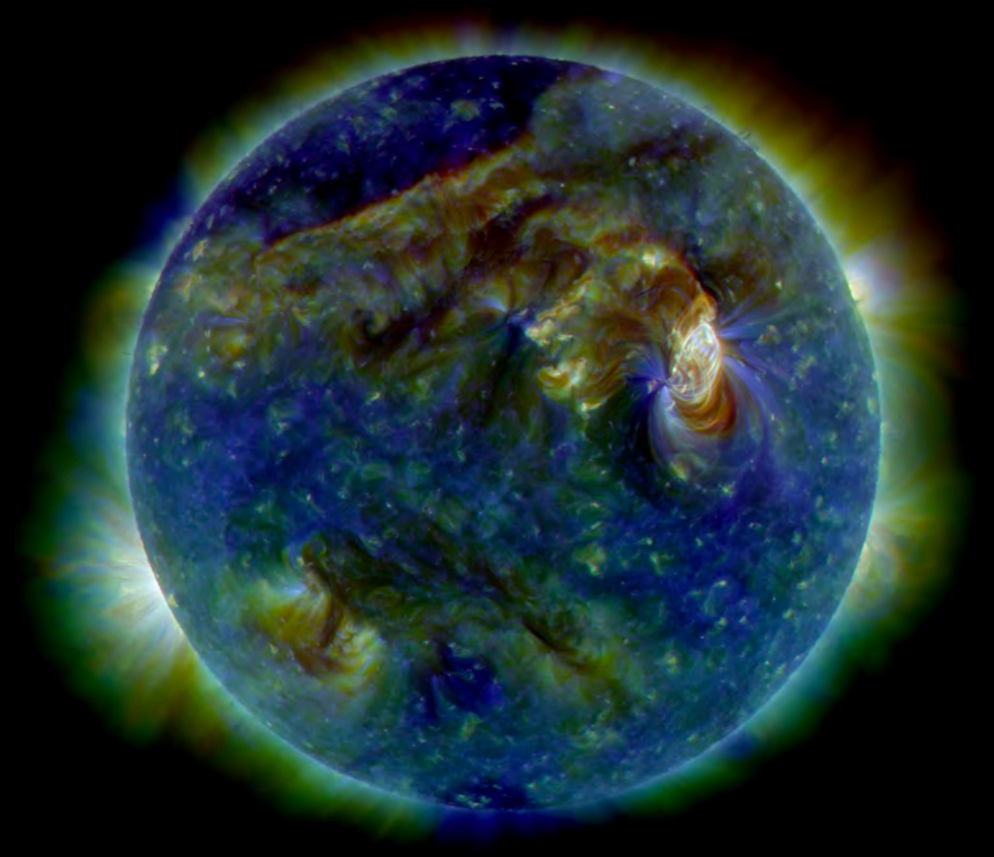
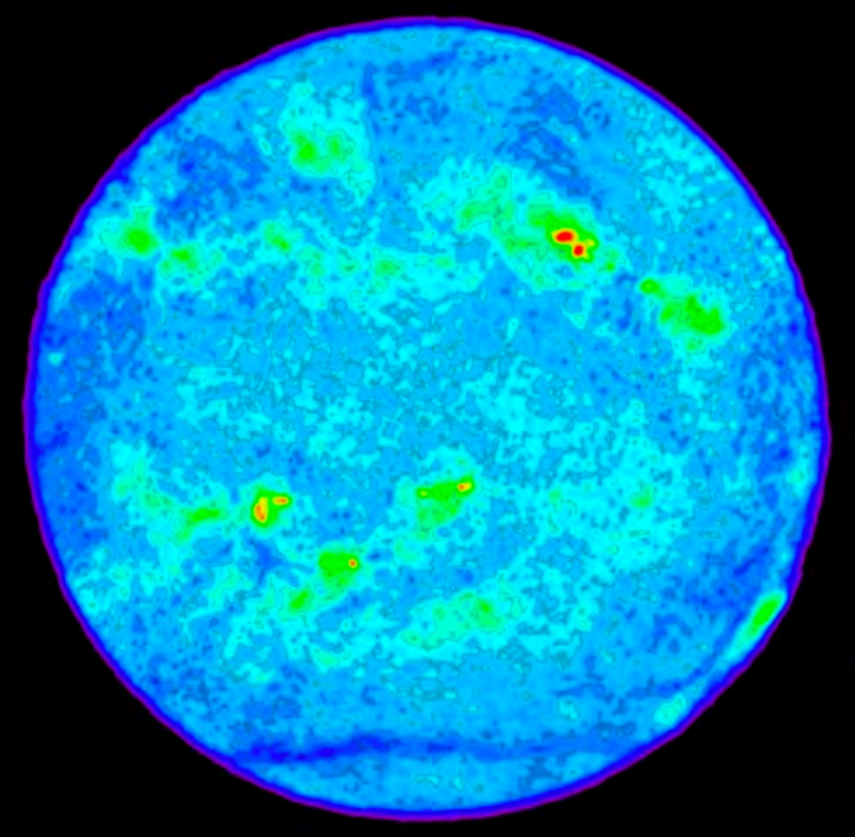
  

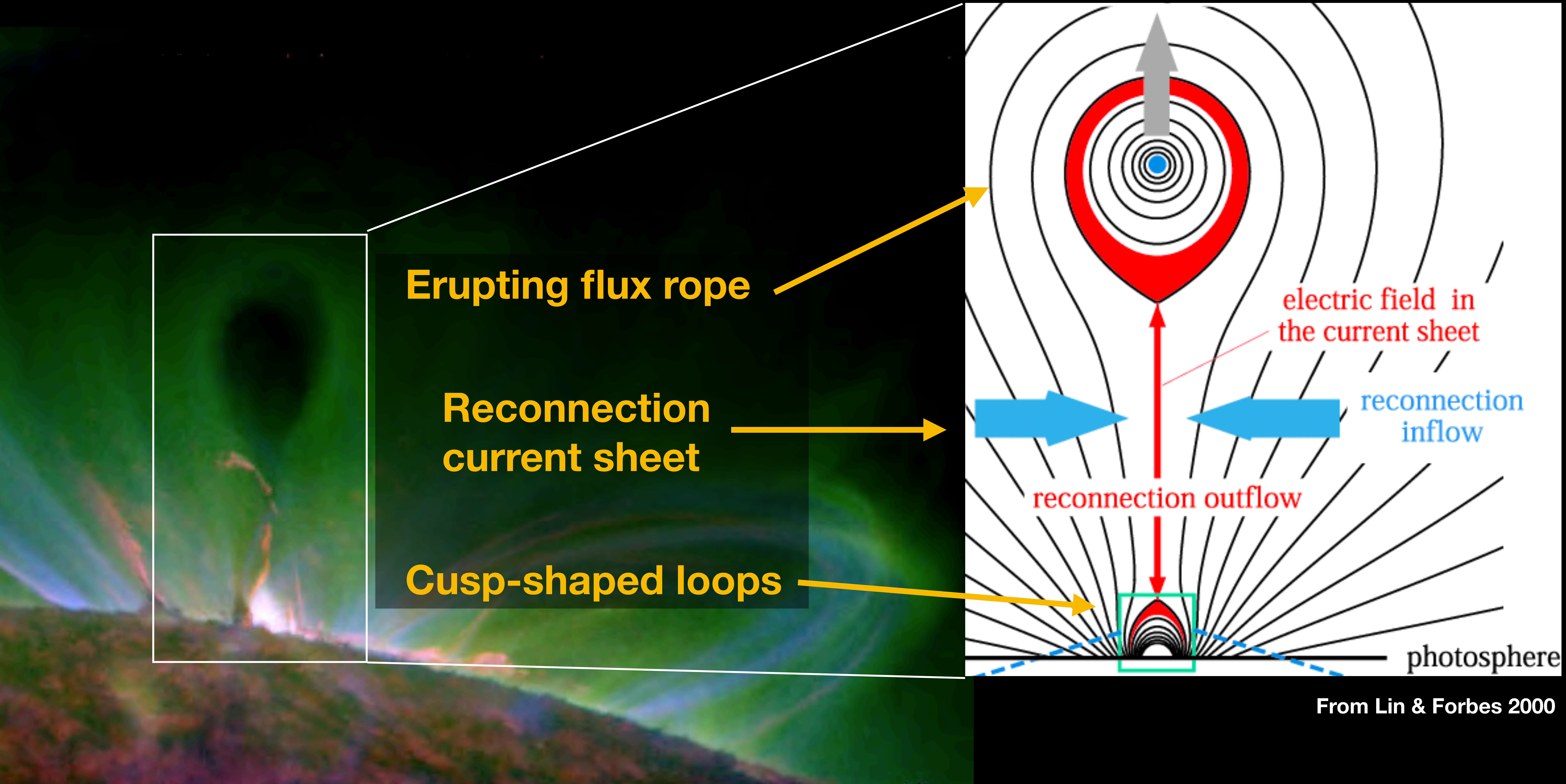
Solar Flare Observations with the Karl G. Jansky Very Large Array

Bin Chen
Center for Solar-Terrestrial Research
New Jersey Institute of Technology

Collaborators:
- NJIT: Dale Gary, Gregory Fleishman, Gelu Nita, Sijie Yu, Yingjie Luo
- NRAO: Tim Bastian, Bryan Butler, Rick Perley, Ken Sowinski, Vivek Dhawan
- CfA: Katharine Reeves, Chengcai Shen, Antonia Savcheva, Samaiyah Farid
- UMN: Lindsay Glesener, Sophie Musset
- FHNW: Marina Battaglia, Rohit Sharma, Säm Krucker
- AFRL: Stephen White
- Nagoya Univ: Kazumasa Iwai

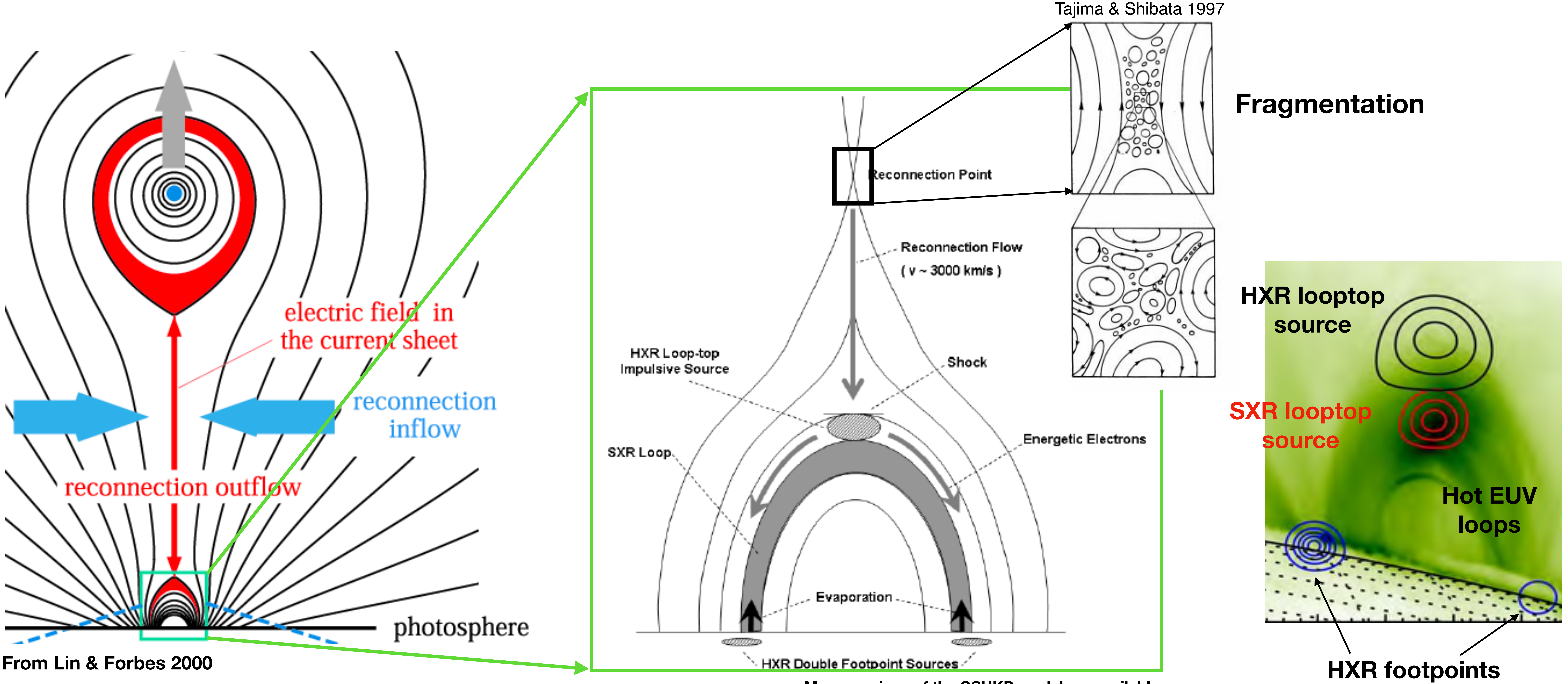
Solar Physics Webinar of Global Reach, 2020 April 01

Standard Flare-CME model



From Lin & Forbes 2000

Standard Flare-CME Model

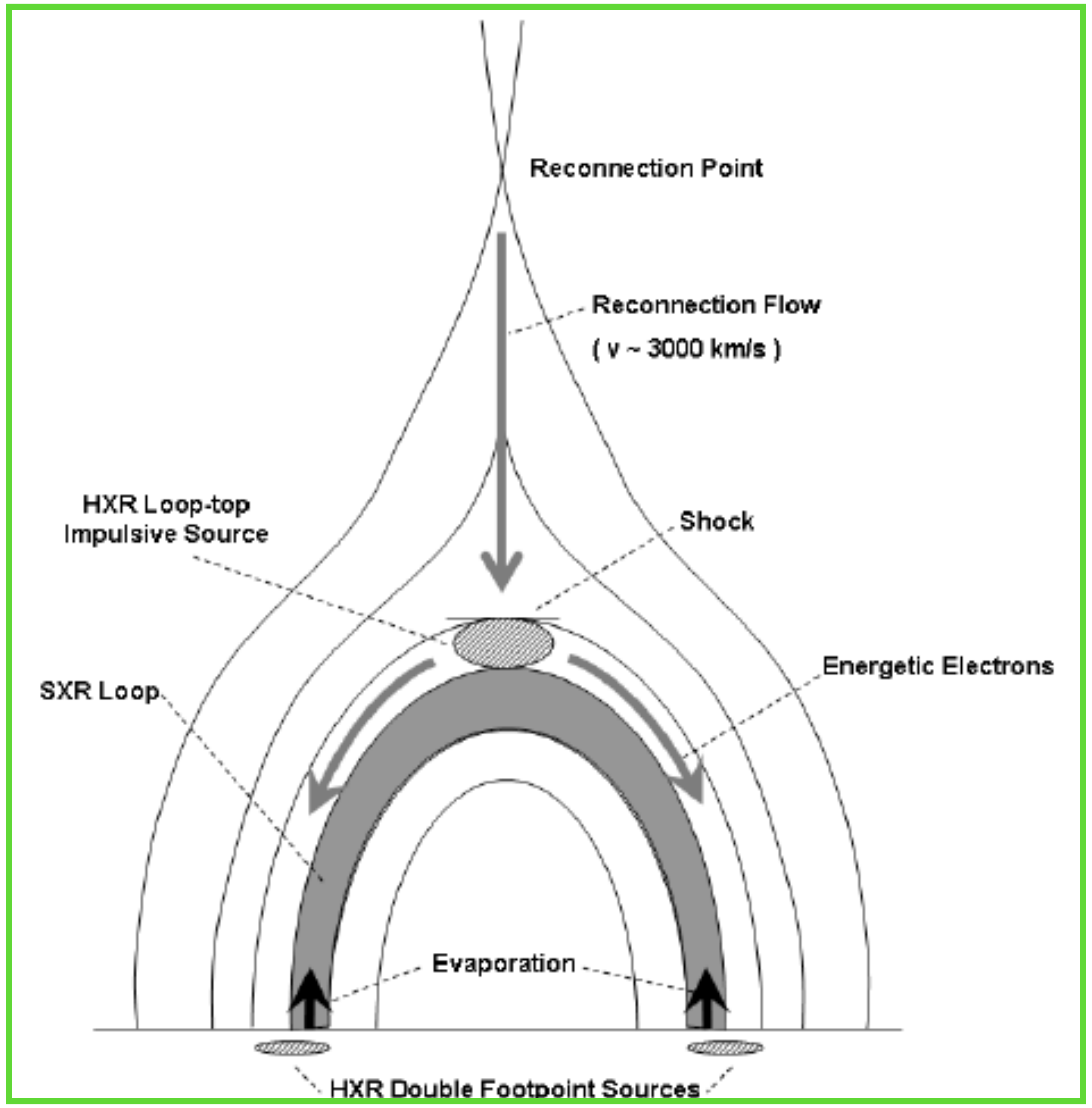


From Lin & Forbes 2000

Many versions of the CSHKP model are available;
This is from Venkatakrishnan & Gosain 2008

From Krucker & Battaglia 2014

Outstanding Questions



Venkatakrishnan & Gosain 2008

Where and how do magnetic reconnection and energy release occur?

Where and how does energy conversion occur?

What is the physical nature of the reconnection sites?

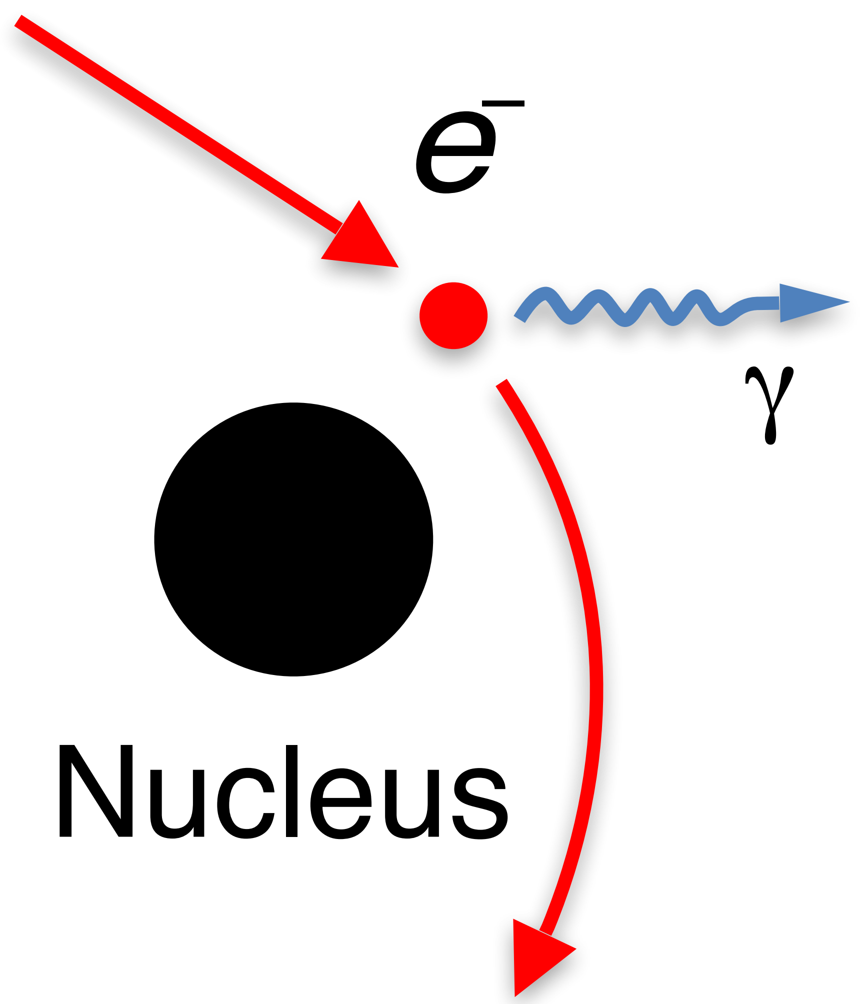
See, e.g., relevant discussions in an Astro2020 White Paper:
https://ui.adsabs.harvard.edu/abs/2019BAAS...51c.507C/abstract

Radio Emission Mechanisms in Flares

- Produced by different sources via a variety of emission processes
- Provides **rich diagnostics** for both thermal plasma and nonthermal energetic electrons

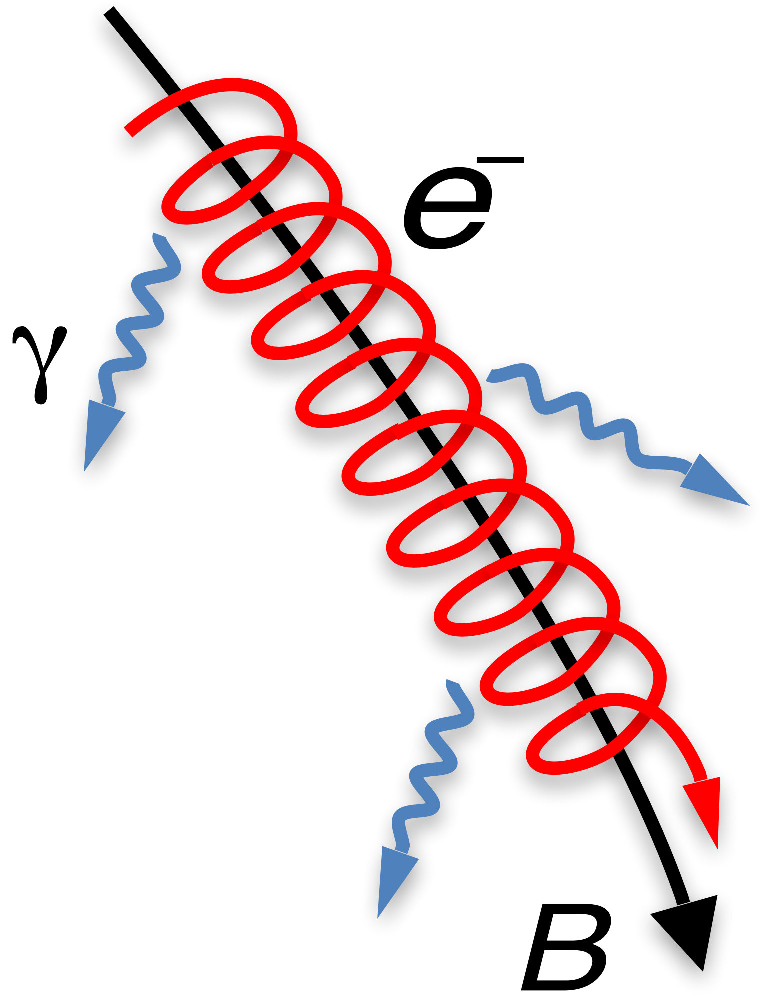
Incoherent Radiation

Bremsstrahlung



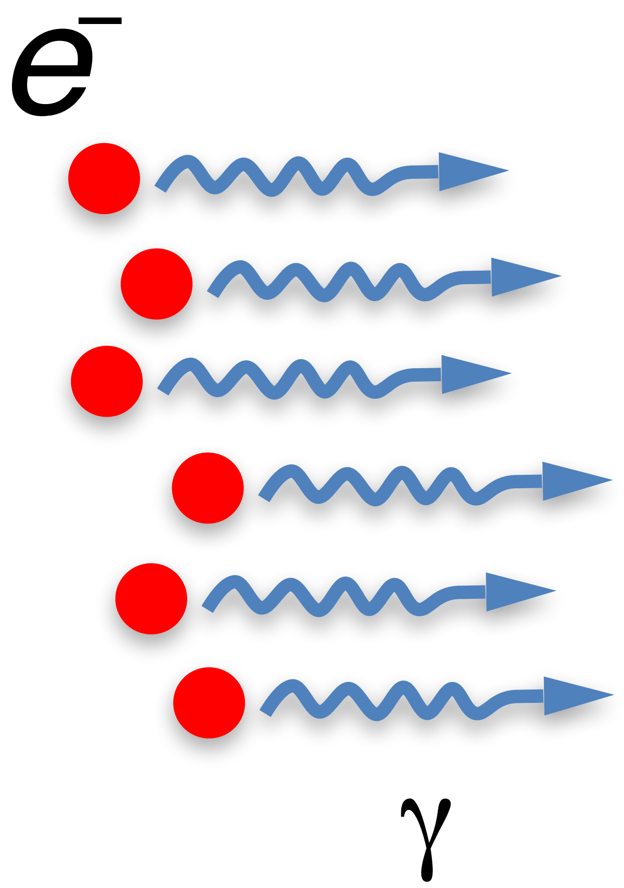
◇ Thermal

Gyromagnetic Radiation

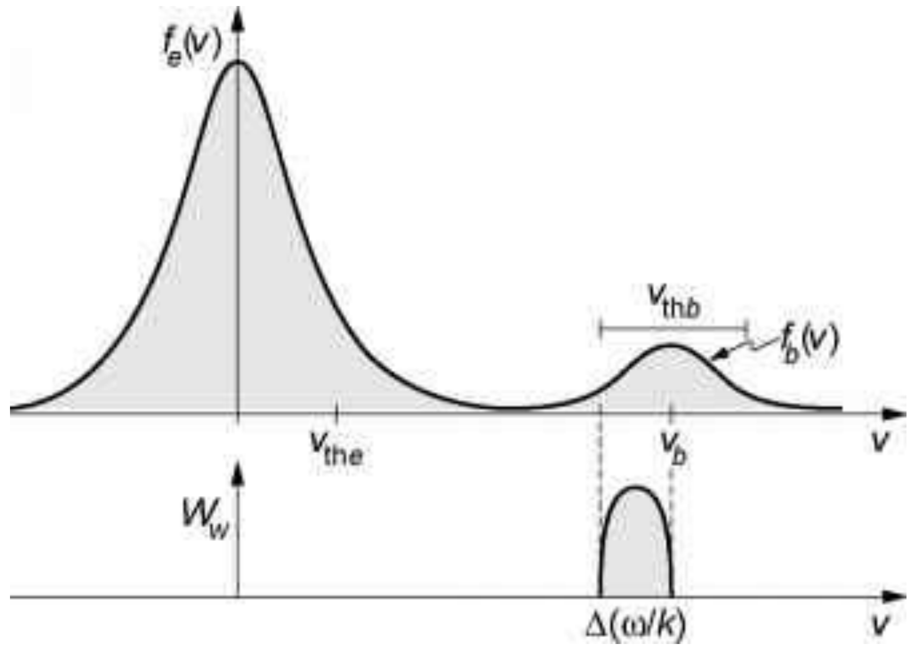


◇ Energetic electrons
◇ Magnetic field
◇ Thermal plasma

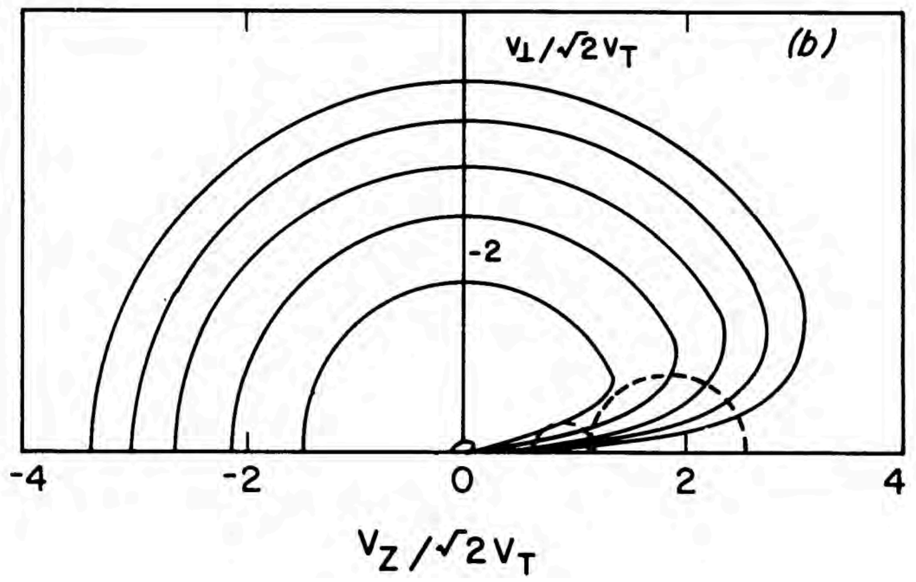
Coherent Radiation



Beam instability

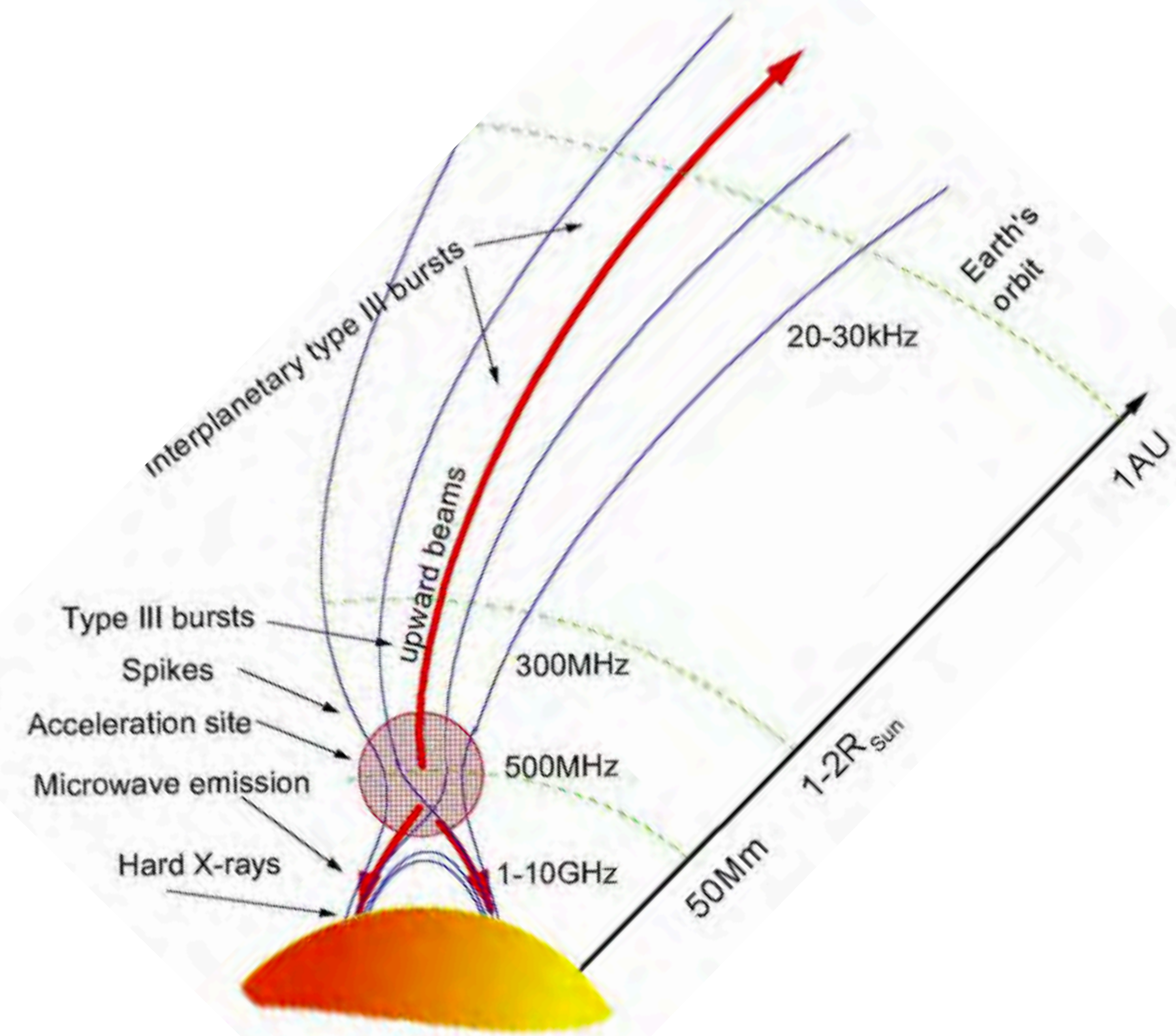


Loss-cone instability

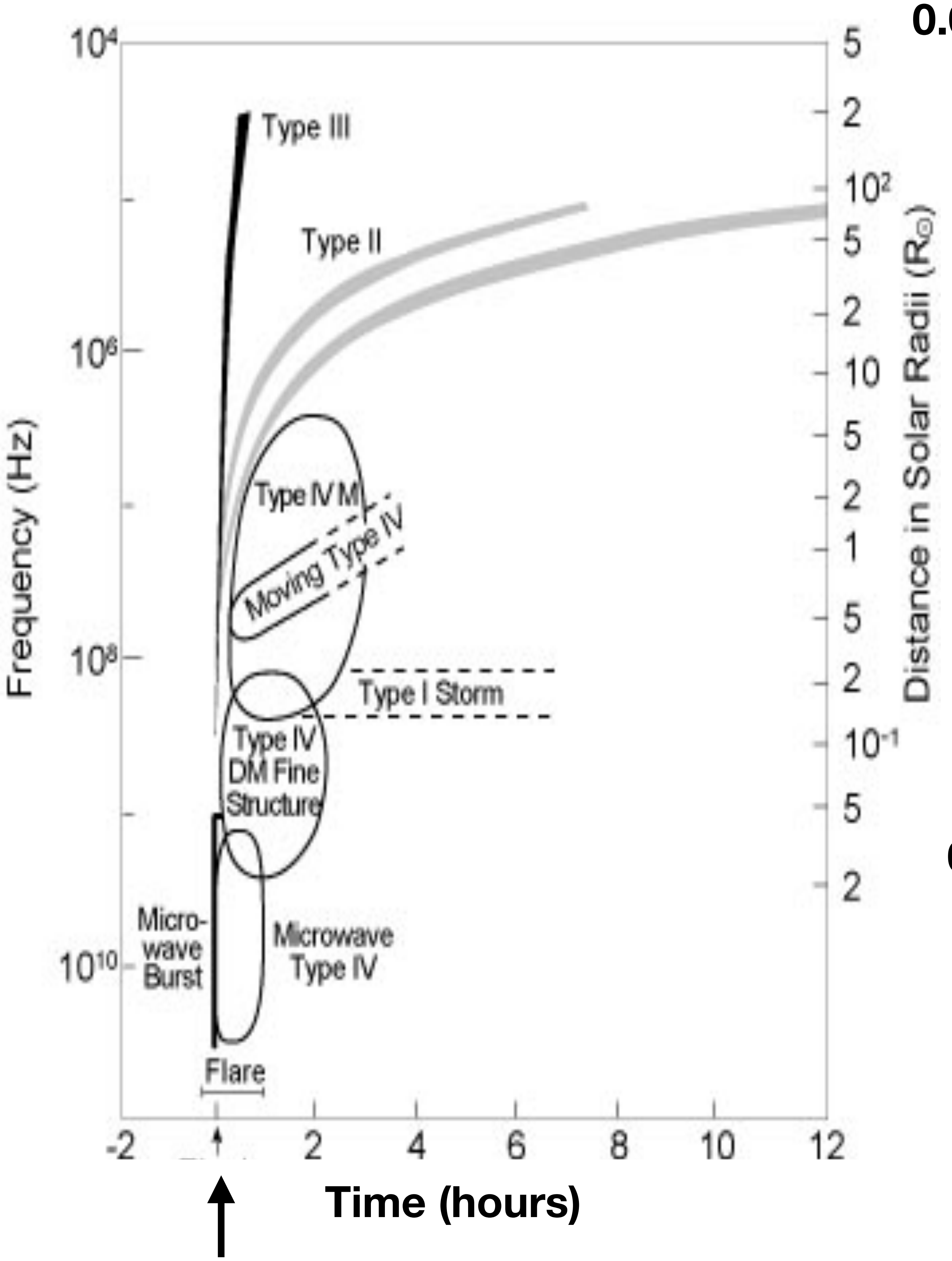


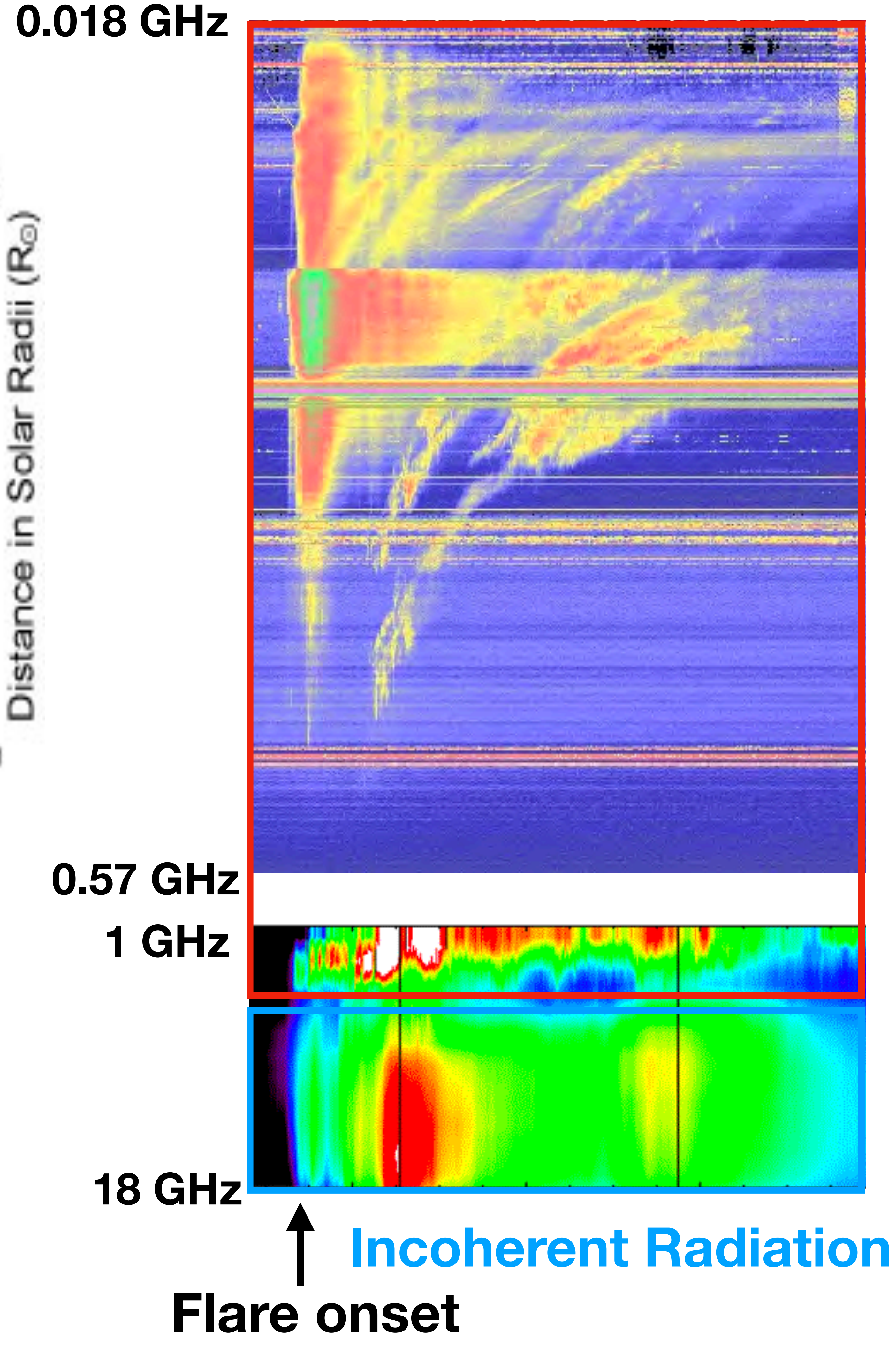
◇ Energetic electrons
◇ Background plasma
◇ Magnetic field

Radio Emission in Solar Flares



From Eduard Kontar





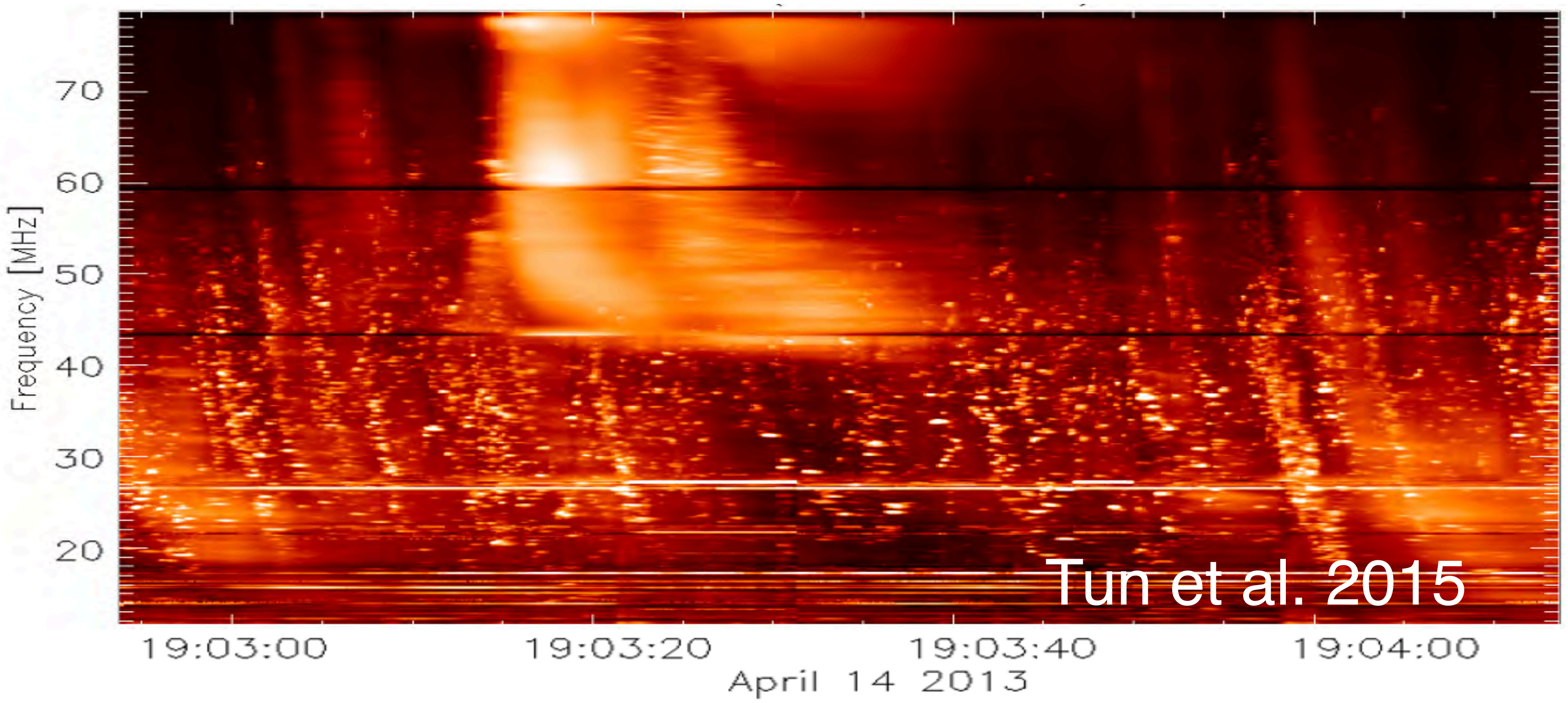
See, e.g., a review by Bastian et al. 1998, ARA&A

Solar Radio Observing: Dynamic Spectroscopy

Antenna

+

FFT Machine

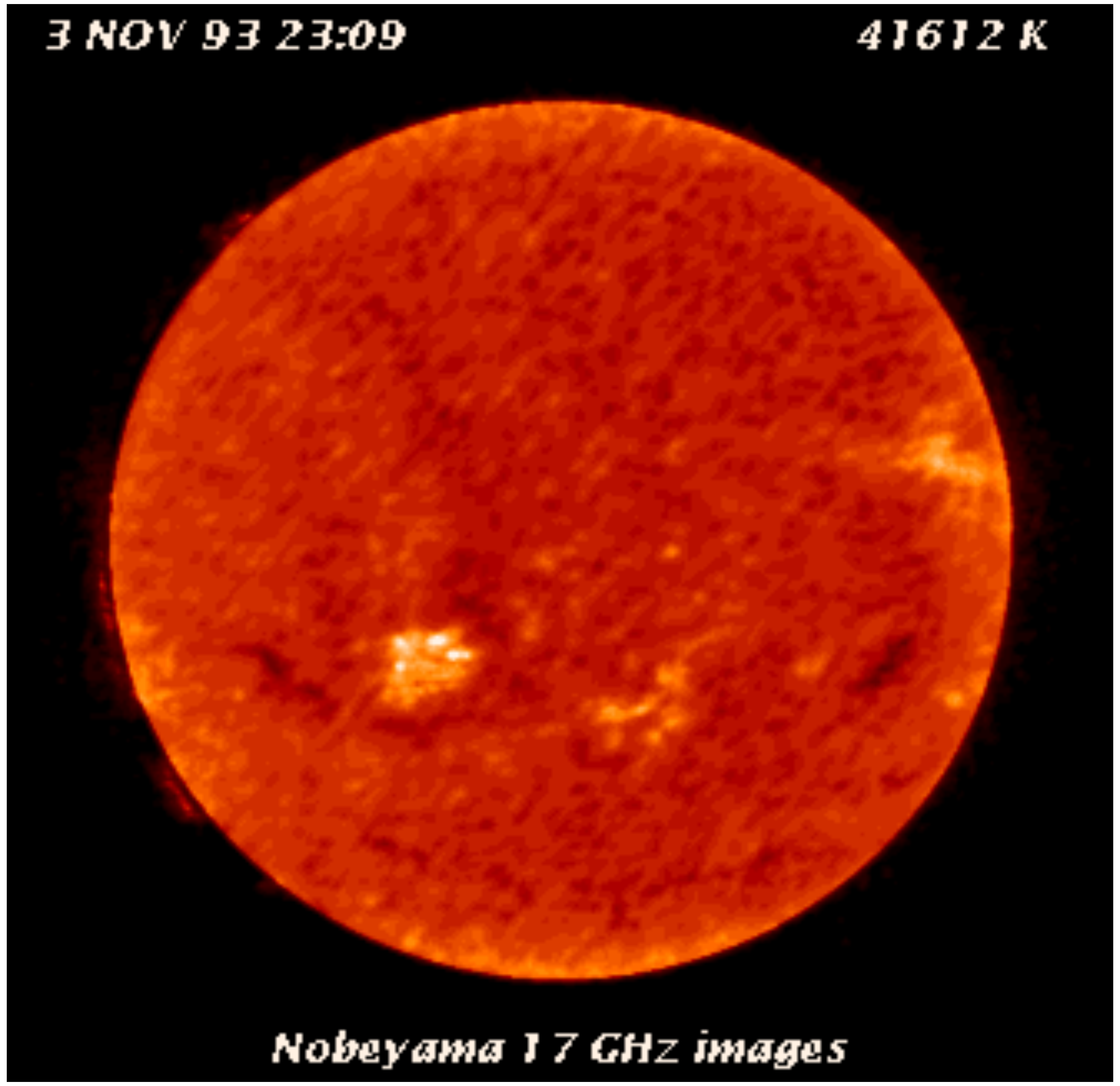


Radio Dynamic Spectrum:

In most cases, spectral resolution and cadence are limited by instrumentation capability

Solar Radio Observing: Synthesis Imaging

Radio Interferometer

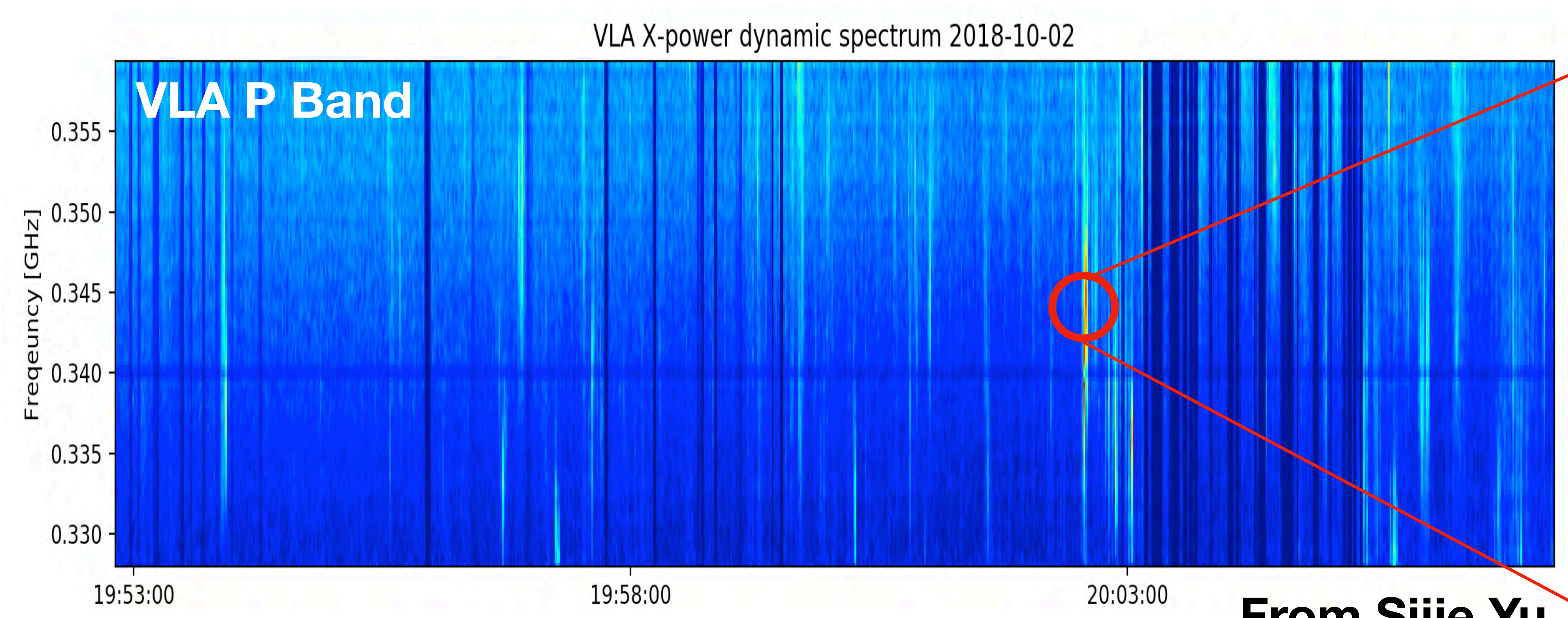


Credit: Stephen White

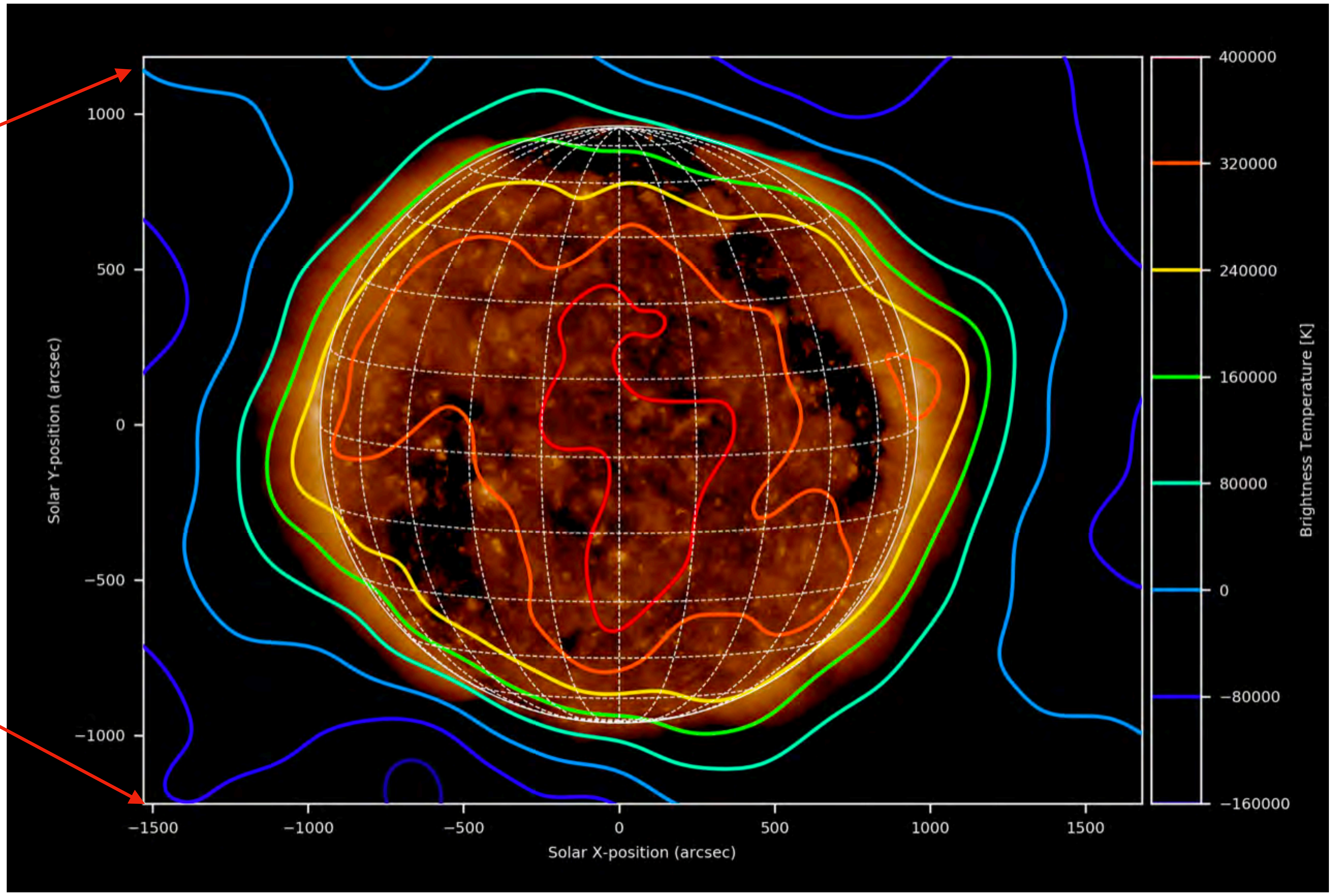
Only since recently, we are able to combine high-resolution dynamic spectroscopy with synthesis imaging

→ **Radio Dynamic Imaging Spectroscopy**

I: Forming an Image from Every Frequency-Time Pixel



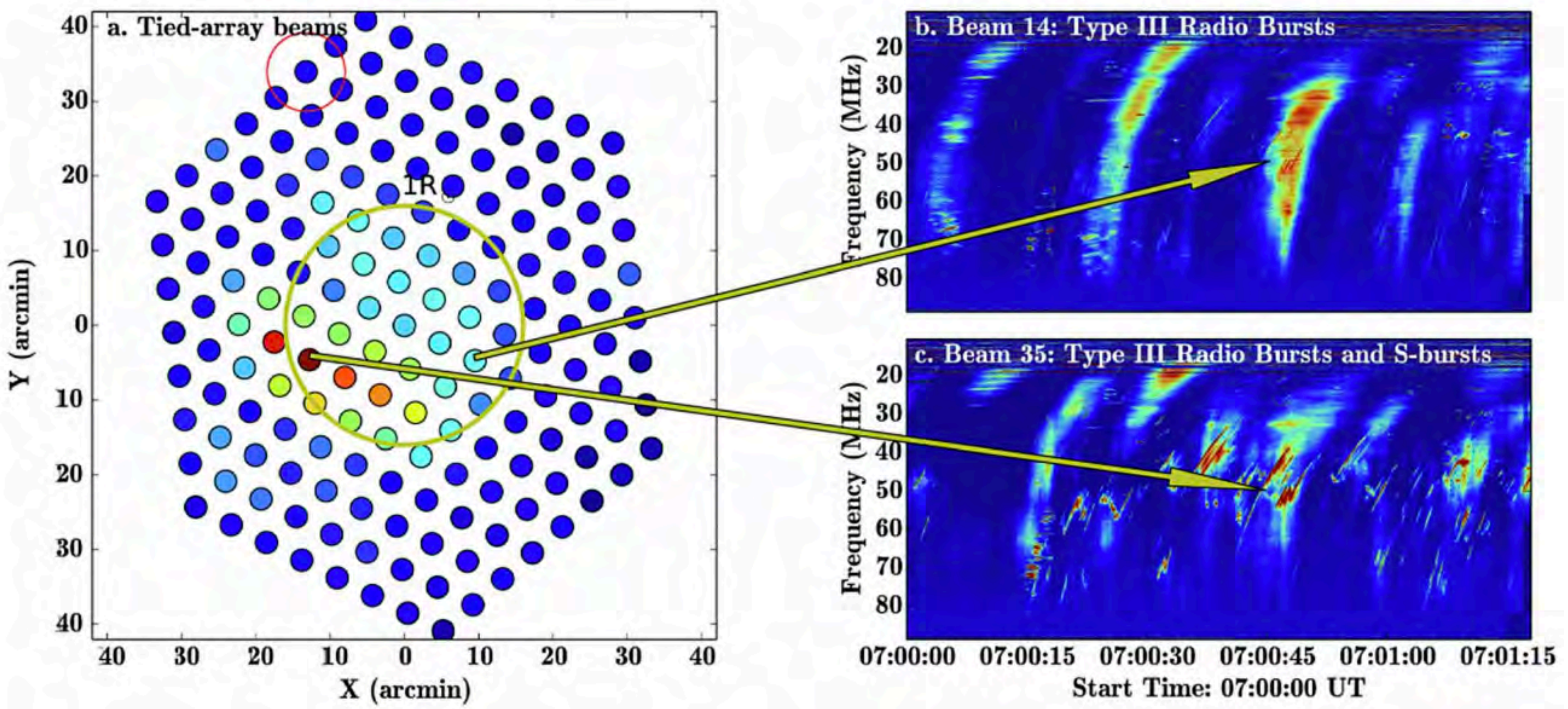
From Sijie Yu



Radio Imaging Spectroscopy

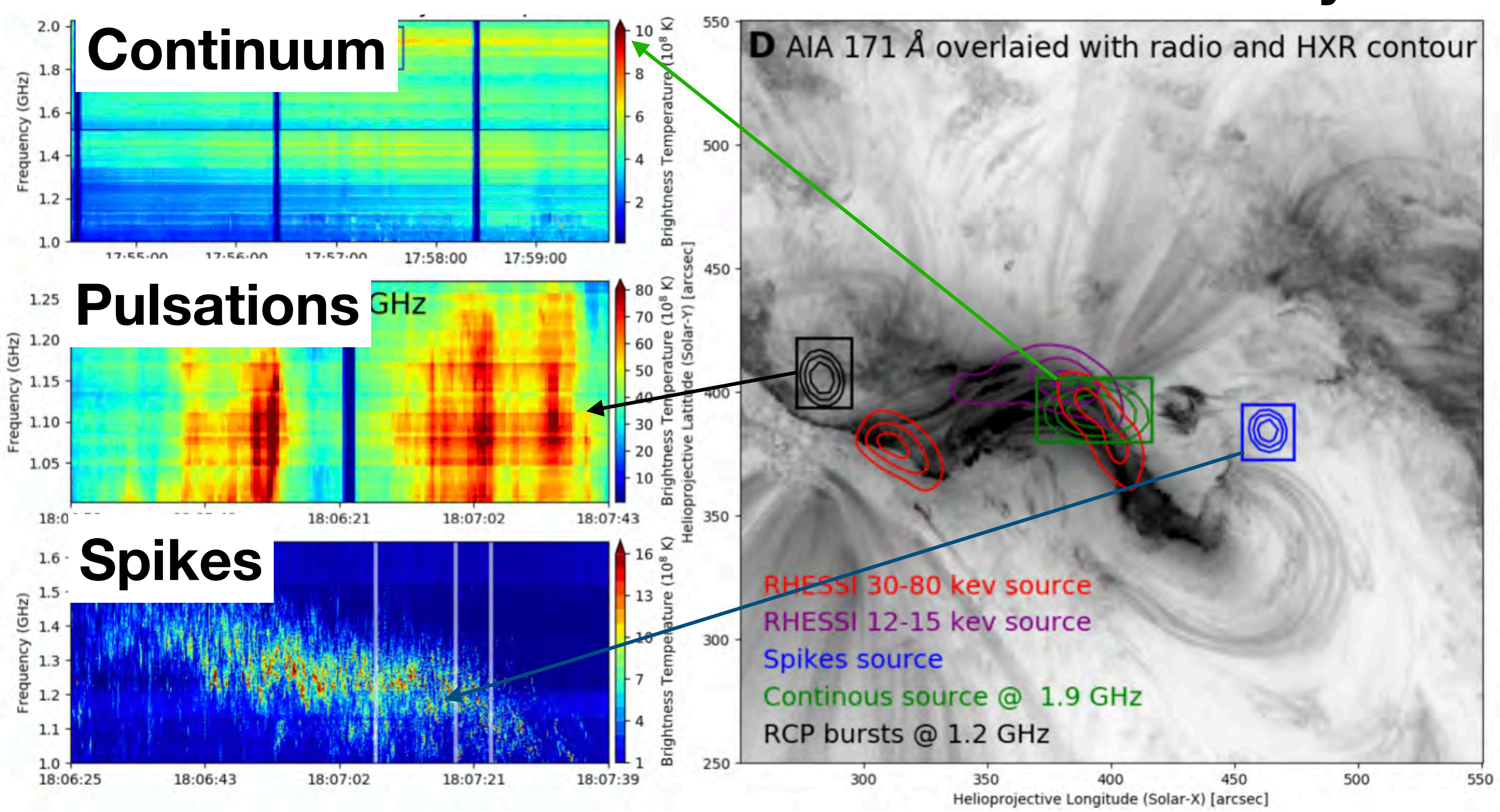
II: Forming Spatially-Resolved Radio Dynamic Spectra

LOFAR



Morosan et al. 2015, A&A, 580, A65

Jansky VLA



Luo et al., in prep

These "vector" dynamic spectra reveal intrinsic properties of very different radio sources that appear at the same time!

Karl G. Jansky Very Large Array

- JVLA is a 27-element (25 m size dishes) reconfigurable interferometric array, located in New Mexico, USA
- High elevation (2100 m), desert climate (76% sunny), good observing conditions
- Four major configurations (A: 36.4 km, B: 11.1 km, **C: 3.4 km, D: 1 km**), offering a wide range of imaging angular resolution.
- Dedicated in 1980, the original VLA was updated in 2011 with hugely improved capabilities

Jansky VLA-VLA capabilities comparison

Parameter	VLA	Jansky VLA	JVLA/VLA factor
Point source cont. sensitivity (1σ, 12 hr of integration)	10 μJy	1 μJy	10
Maximum Bandwidth	0.1 GHz	8 GHz	80
# of frequency channels at max BW	16	16,384	1024
Finest Frequency resolution	381 Hz	0.12 Hz	3180
# of full-pol spectral windows	2	64	32
(Log) Frequency Coverage in 1–50 GHz	22%	100%	5
Highest time resolution	~1 s	0.005 s	200
Maximum data rate for imaging	< 1 MB/s	300 MB/s	>300
Time of scheduling in advance	~1 month	~1-2 days	~15–30

Adapted from Perley et al. 2011, *ApJ,* 739, 1

Jansky VLA Receivers

Band Name	Band (GHz)	λ (cm)
4	0.05–0.08	600–375
P	0.24–0.45	125–67
L	1–2	30–15
S	2–4	15–7.5
C	4–8	7.5–3.2
X	8–12	3.2–2.5
Ku	12–18	2.5–1.7
K	18–26.5	1.7–1.1
Ka	26.5–40	1.1–0.75
Q	40–50	0.75–0.6

25-m paraboloid reflector

Eight feeds around the Cassegrain secondary focus ring

Solar Observing with Jansky VLA

Band Name	Band (GHz)
4	0.05–0.08
P	0.24–0.45
L	1–2
S	2–4
C	4–8
X	8–12
Ku	12–18
K	18–26.5
Ka	26.5–40
Q	40–50

- Solar observing mode was initially commissioned in 2011 as a resident shared risk observing (RSRO) program. Since then multiple efforts were made to expand the capability.

Bin Chen (NJIT)

Tim Bastian (NRAO)

Sijie Yu (NJIT)

Stephen White (AFRL)

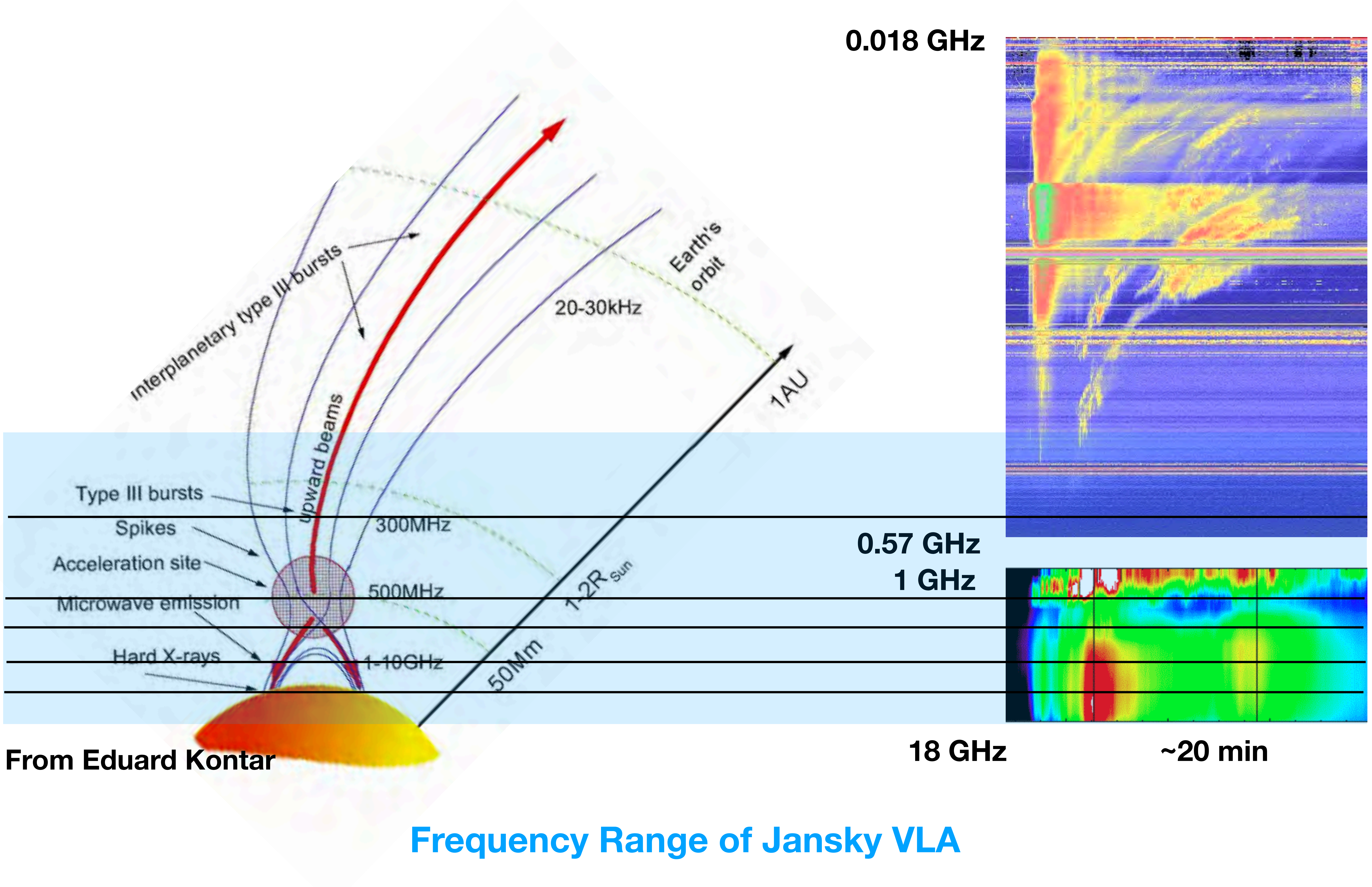
Kuzumasa Iwai (Nagoya Univ)

And many NRAO folks including R. Perkey, B. Butler, M. Rupen, K. Sowenski, V. Dahwan

- Unique capability of **radio dynamic spectroscopic imaging** in **dm-cm wavelengths** with **spectrometer-like temporal and spectral resolution**
  - ❖ Instantaneous bandwidth up to **2 GHz** (8-bit system)
  - ❖ Multiple subarray capability
  - ❖ Simultaneous imaging at **>1000** frequency channels per subarray
  - ❖ Cadence: **50 ms** (previous), **10 ms** newly commissioned
  - ❖ **1,400,000,000** radio images **per hour** of observation at maximum time/frequency resolution with two subarrays

    ➡ data processing/analysis is a real challenge!

Why Jansky VLA?



Frequency Range of Jansky VLA

- Jansky VLA probes the **"heart" of flare energy release** and the subsequent energy transport in the low solar corona
- Jansky VLA's **ultrahigh temporal and spectral resolution** with **high sensitivity** are ideal for studying rapidly varying **coherent radio bursts**
- Not the ideal instrument for studying broadband **gyrosynchrotron radiation**, as band-switching is required -> **Expanded Owens Valley Solar Array**

Jansky VLA Flare observations

Partial list of Jansky VLA flare observations

Flare Start Time	Class	Instruments
SOL2011-11-05T20:31	M1.8	VLA, SDO, Hinode, RHESSI, Fermi
SOL2011-11-18T17:07	C2.7	VLA, SDO, RHESSI
SOL2012-03-03T18:13	C1.9	VLA, SDO, Hinode, RHESSI, Fermi
SOL2012-03-10T17:15	M8.4	VLA, SDO, RHESSI, Fermi
SOL2013-04-23T19:29	C1.8	VLA, SDO, Hinode, Fermi
SOL2013-04-25T17:09	C3.9	VLA, SDO, Hinode, RHESSI, Fermi
SOL2013-04-25T17:24	C5.6	VLA, SDO, Hinode, Fermi
SOL2013-05-14T16:00	C1.4	VLA, SDO, Hinode, RHESSI, Fermi
SOL2014-11-01T16:37	C7.2	VLA, SDO, RHESSI, Fermi
SOL2016-02-18T19:59	C1.2	VLA, SDO, IRIS, Fermi
SOL2016-04-09T18:40	C1.5	VLA, SDO, Hinode, IRIS, Fermi
SOL2016-04-09T22:50	C1.8	VLA, SDO, Hinode, IRIS, Fermi
SOL2016-04-16T19:42	C5.8	VLA, SDO, Hinode, Fermi

- Observing time obtained via competed proposals. Proposal call usually occurs twice a year.
- Within **~140 hrs** of JVLA time obtained since Fall 2011, captured more than **20** major (>C-class) flares and numerous microflares (thanks to dynamic scheduling!)
- Successful observing campaigns with spacecraft including RHESSI, SDO, Hinode, IRIS, and NuSTAR

- Full list available at: http://www.ovsa.njit.edu/wiki/index.php/VLA_Data_Survey
- Details on proposing for VLA time at: https://science.nrao.edu/facilities/vla/docs/manuals/propvla

Examples of recent solar flare studies with Jansky VLA

◉ Tracing fast electron beams

- Chen et al. 2018, ApJ, 866, 62
- Chen et al. 2013, ApJL, 763, 21

◉ Mapping solar flare termination shocks

- Luo et al., in prep
- Chen et al. 2019, ApJ, 884, 63
- Chen et al. 2015, Science, 350, 1238

◉ Imaging waves and oscillations

- Yu & Chen, 2019, ApJ, 872, 71
- Wang, Chen & Gary 2017, ApJ, 848, 77

◉ Microflares

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- Sharma et al., in prep

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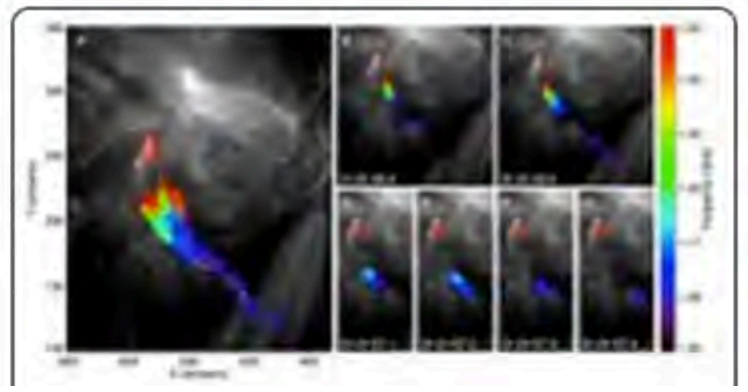
BY BIN CHEN, TIMOTHY S. BASTIAN, CHENGCAI SHEN, DALE E. GARY, SÄM KRUCKER, LINDSAY GLESENER

SCIENCE | 04 DEC 2015 : 1238-1242

NRAO 2013 Science Highlights

Imaging Magnetic Reconnection on the Sun



Type III radio bursts from the Sun
VLA has imaged these bursts on ti
located in the low corona and propa
diameter of these loops is less than
of the Sun's corona. The localized e
reconnection model that involves s

Electron Beams and type III radio bursts

Accelerated Electron Beams

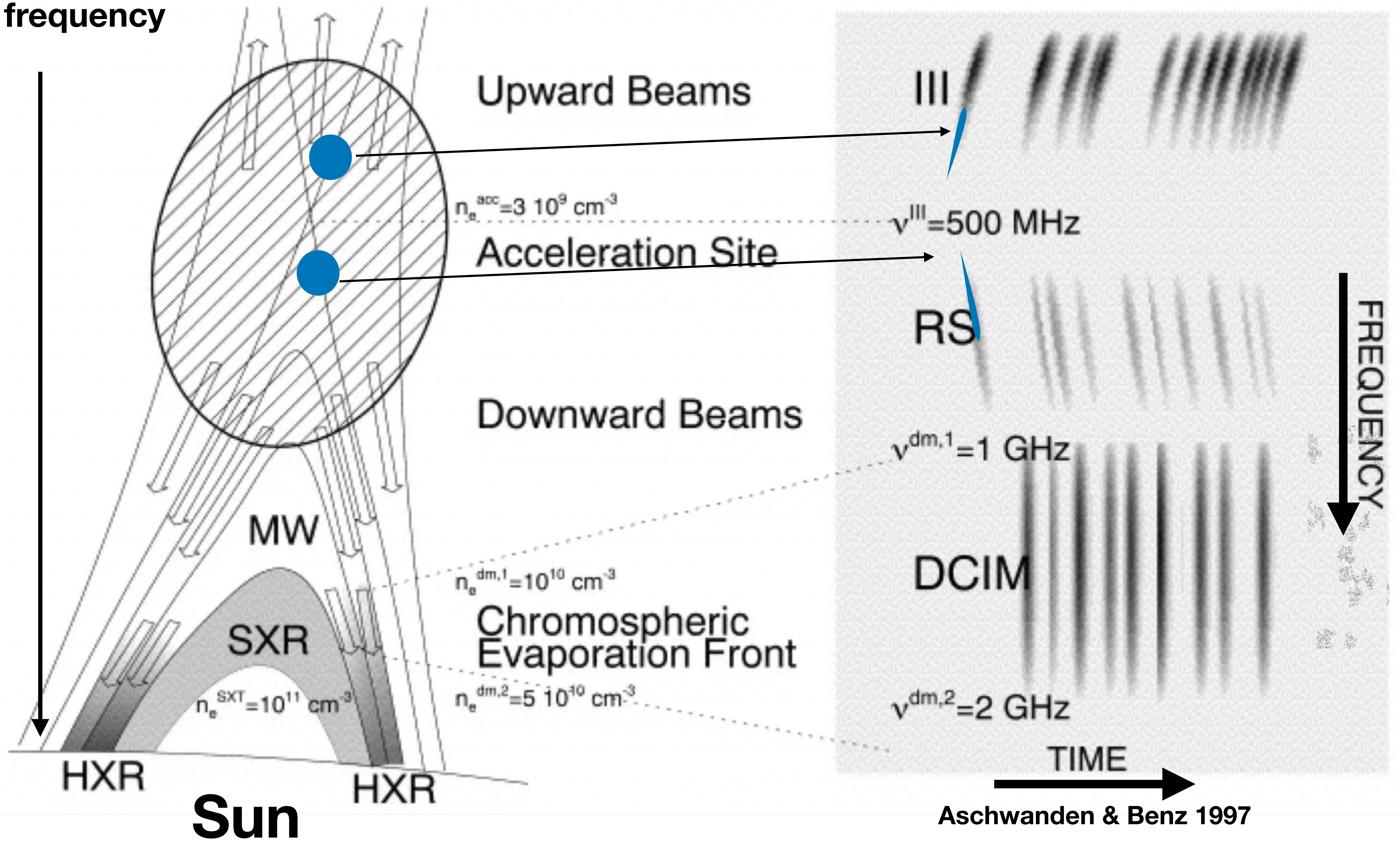
Bump-on-tail Instability ↓

Langmuir waves:
$f_L \sim n^{1/2}$

Nonlinear conversion ↓

Radio waves:
$f \sim sf_L \sim sn^{1/2}$

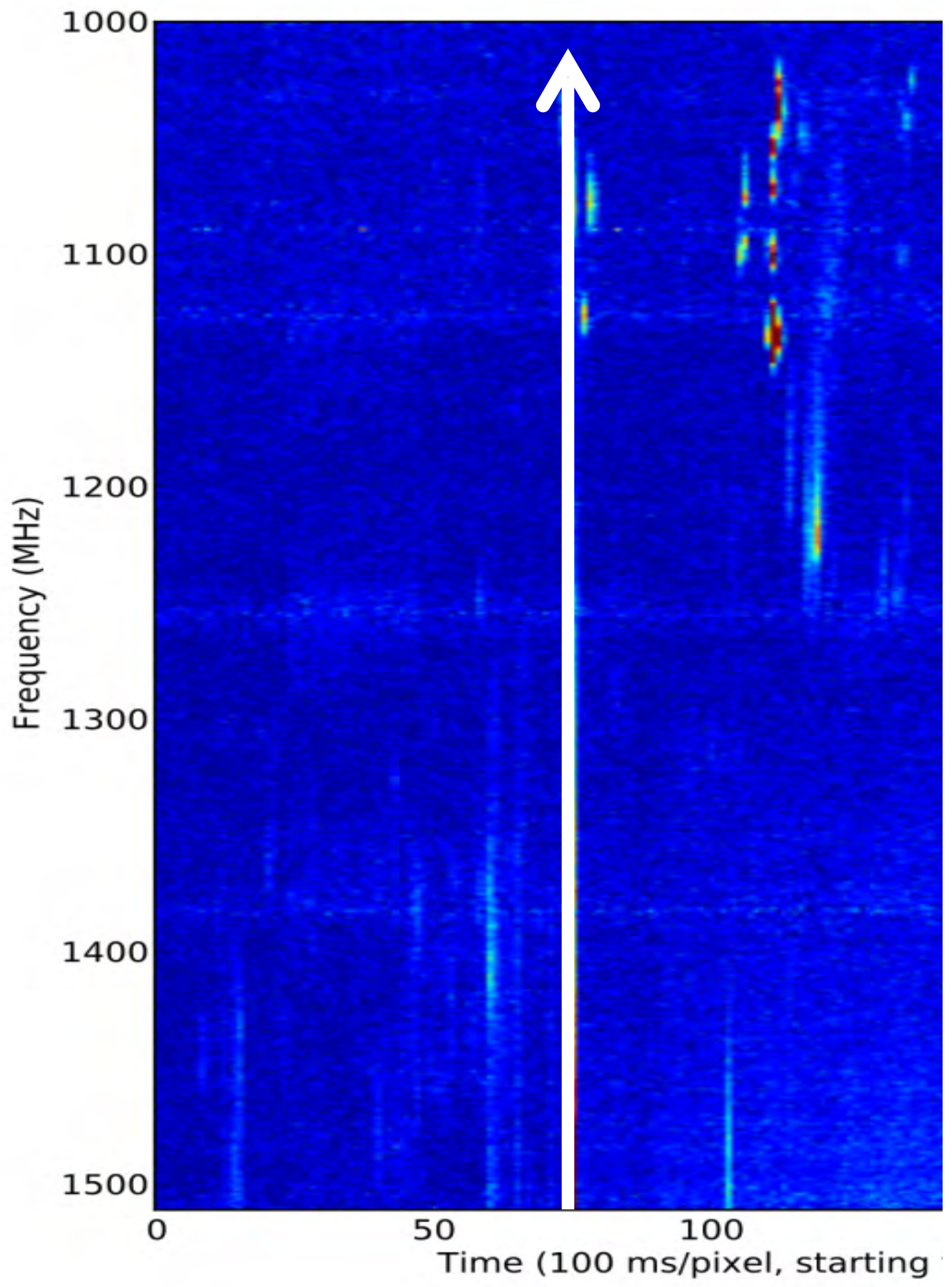
Density increase downward, so does frequency



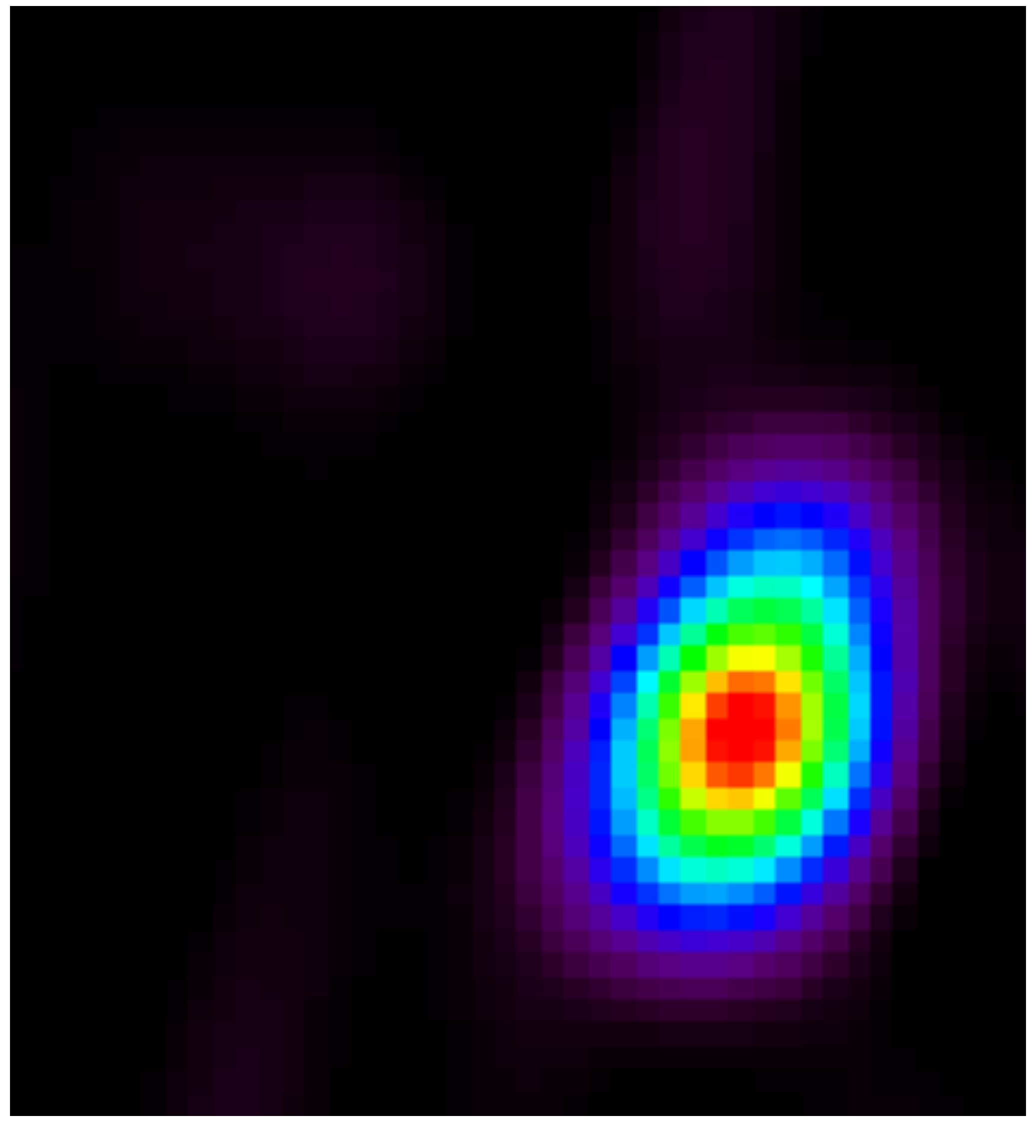
Aschwanden & Benz 1997

Snapshot of an upward-going electron beam

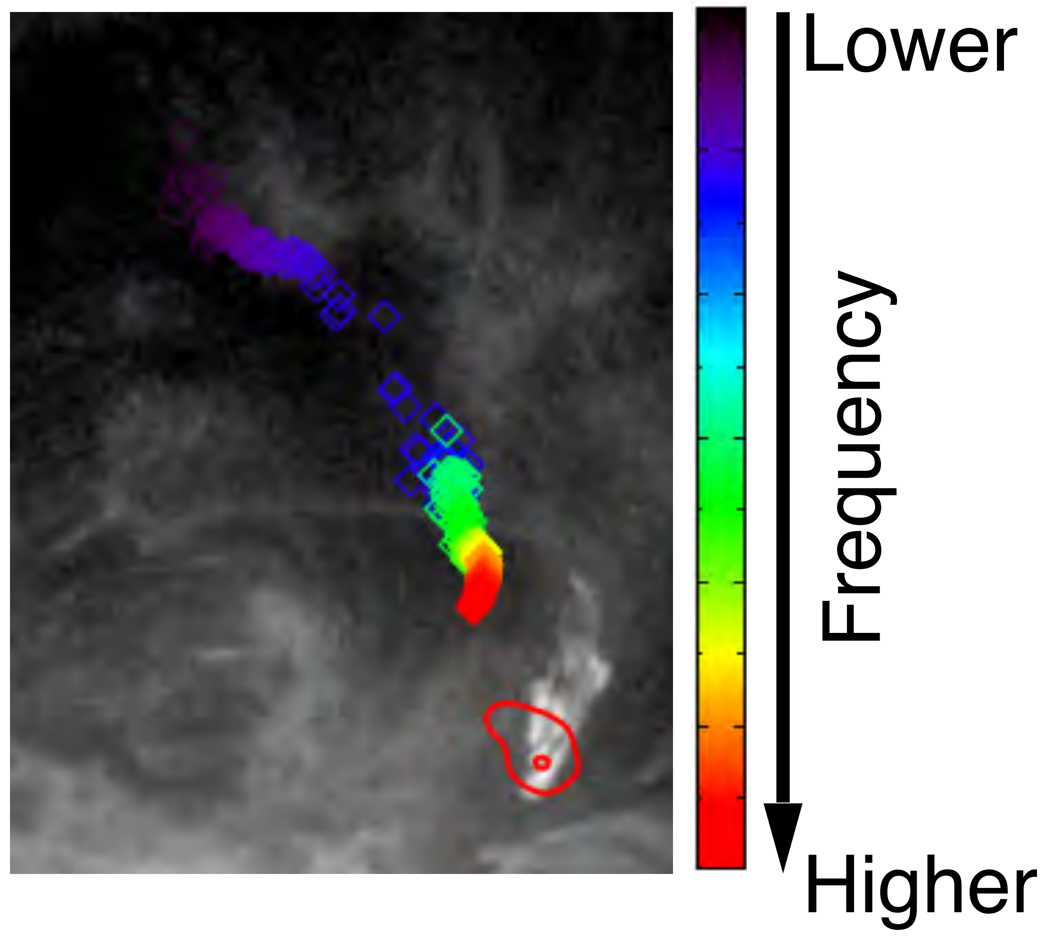
High-resolution Dynamic spectrum



Channel-by-channel spectral imaging

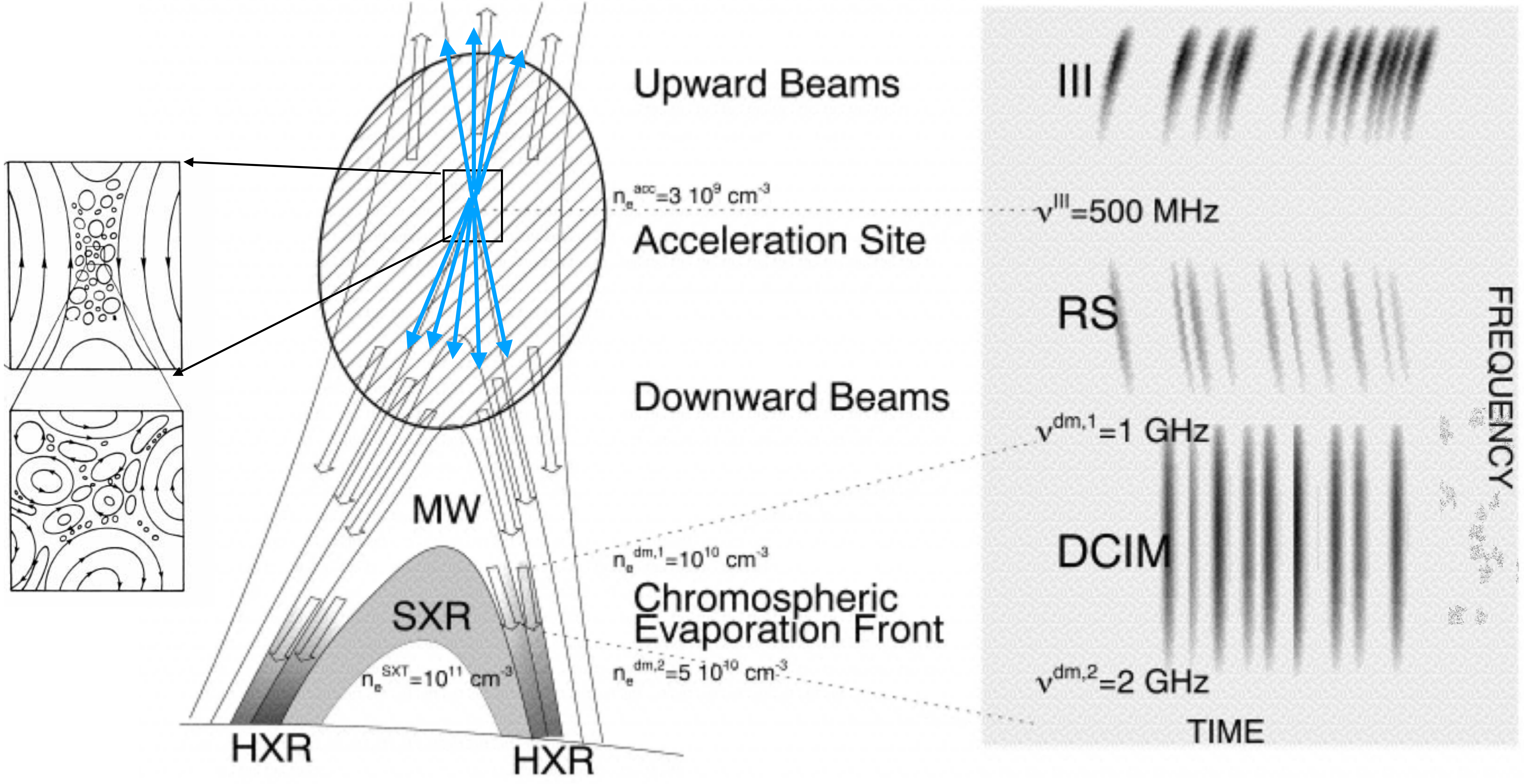


Electron beam trajectory



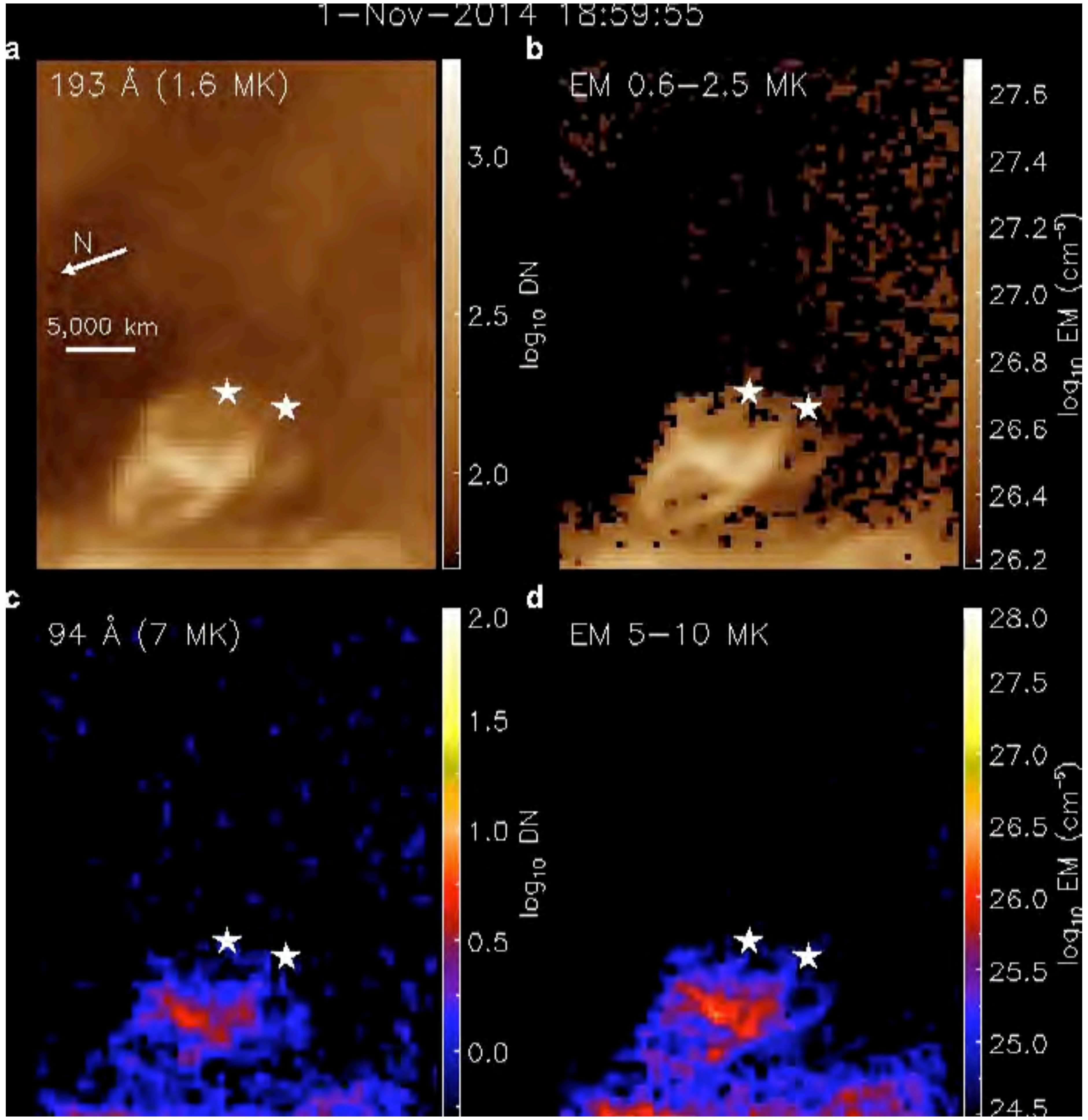
Chen et al. 2013, *ApJL*, 763, 21

Fragmentation in Reconnection

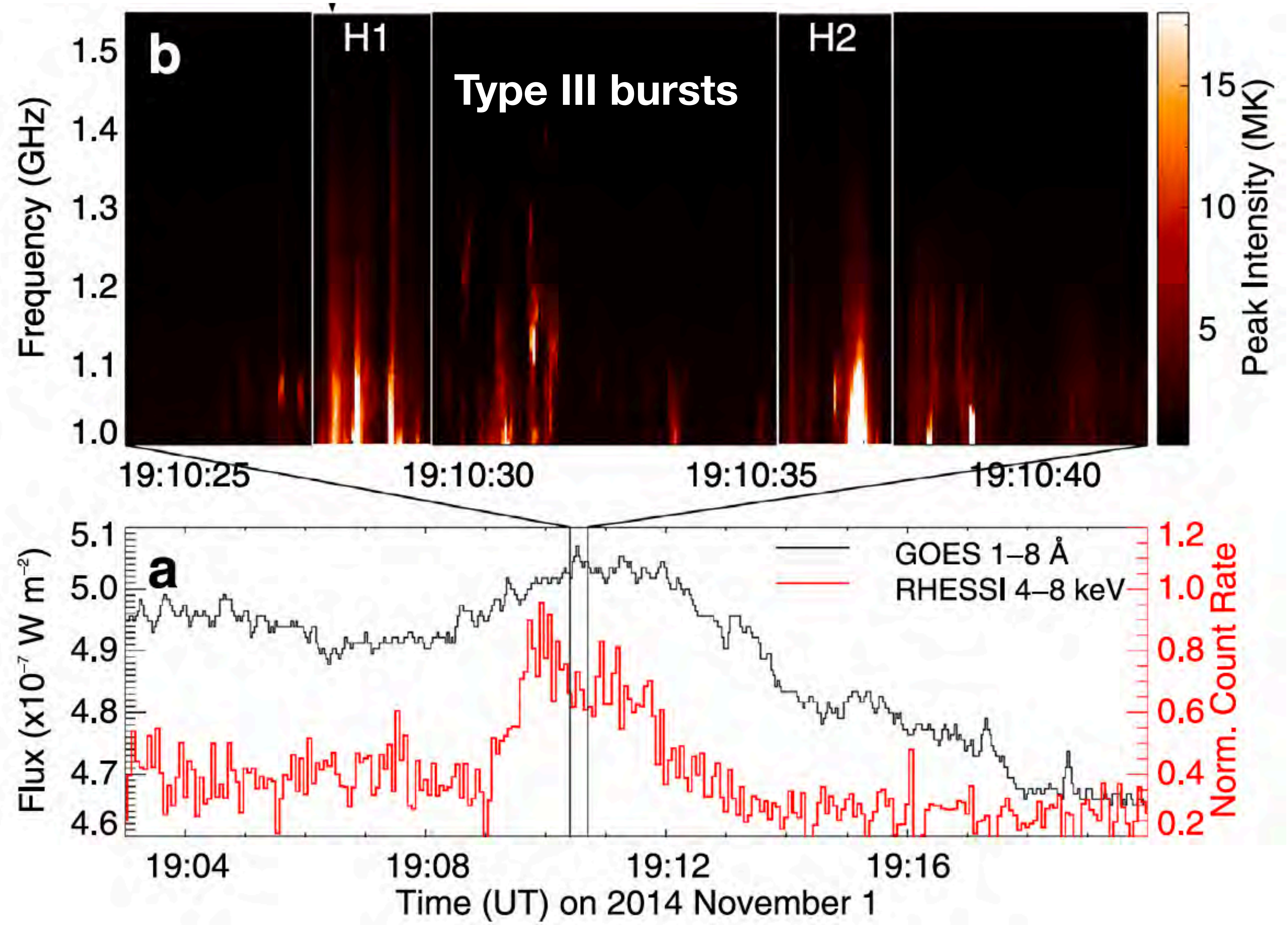


Imaging Type IIIs with High Spatial, Spectral and Temporal

Solar Jet in EUV



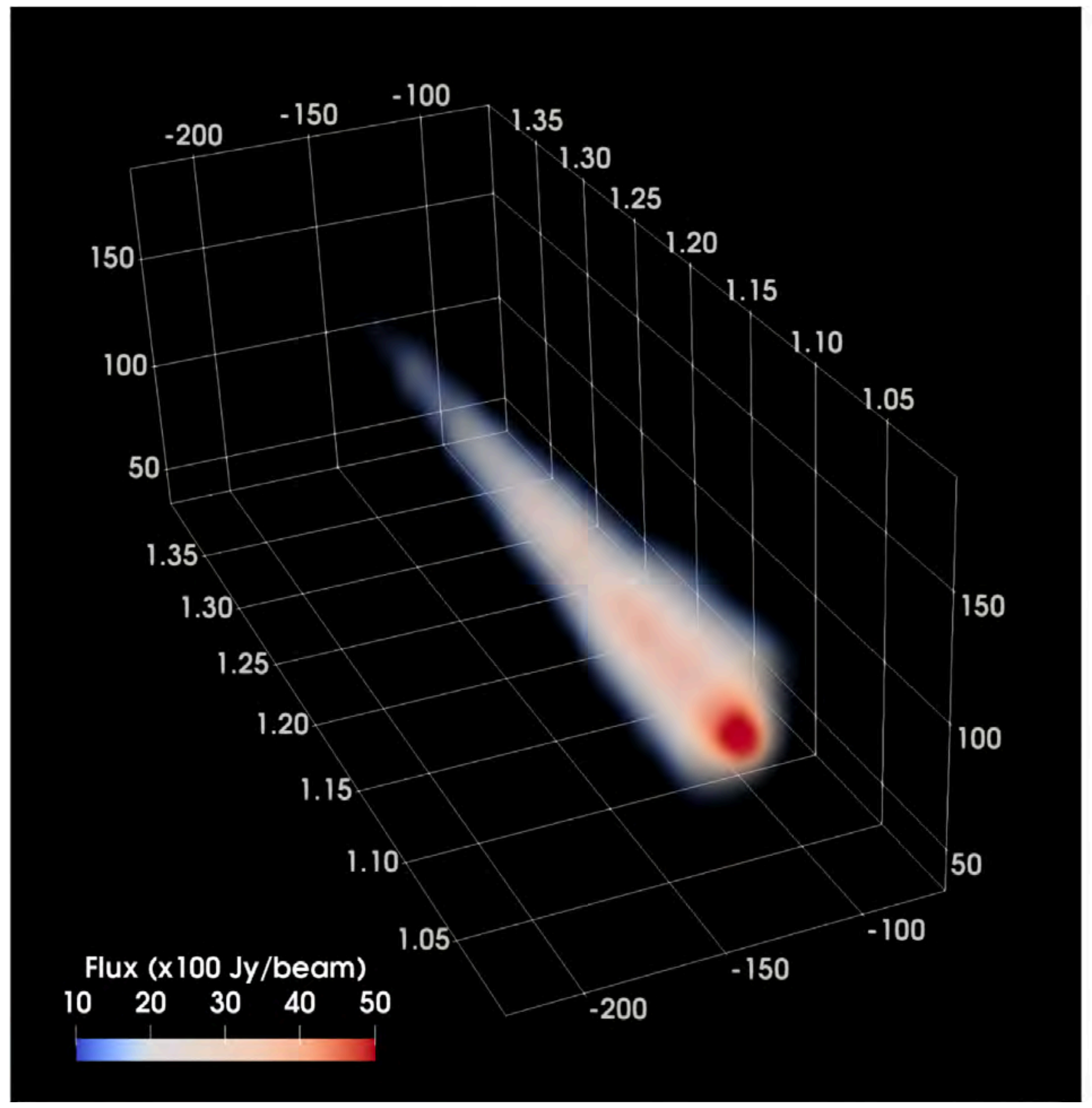
VLA 1.0-1.6 GHz dynamic spectrum



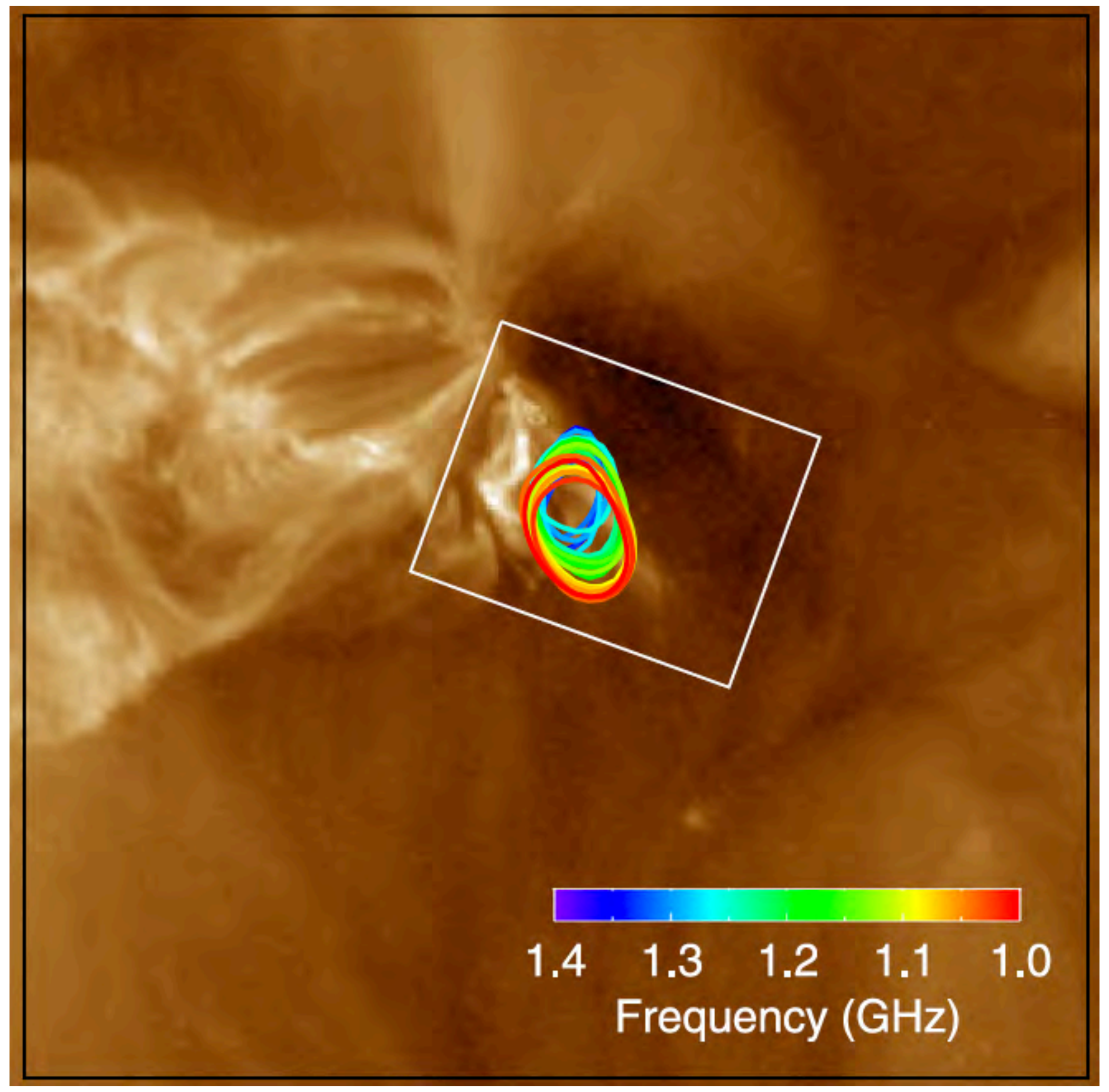
X-ray light curve (hot plasma)

Type III radio bursts in a solar jet

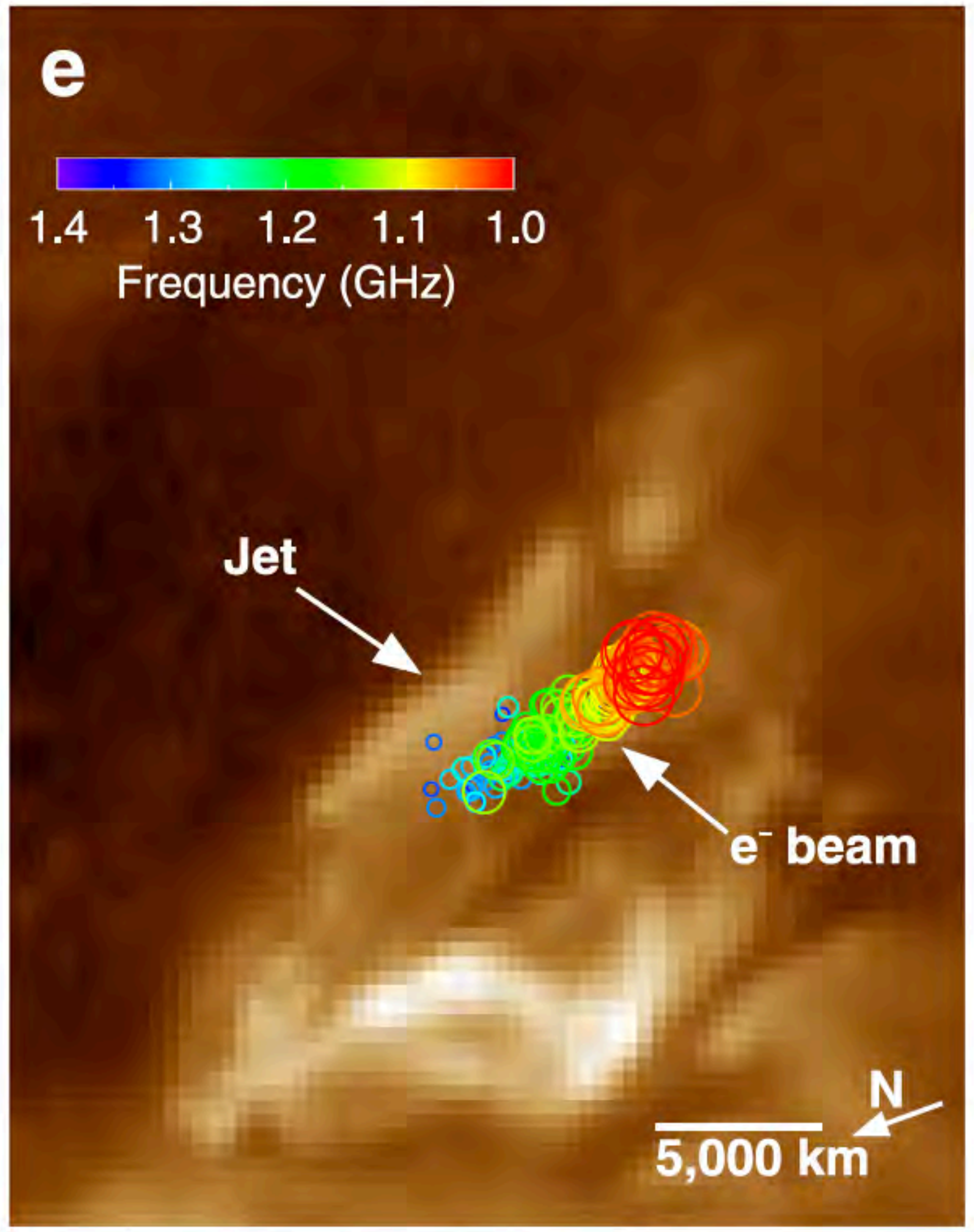
Radio Spectral Image Cube

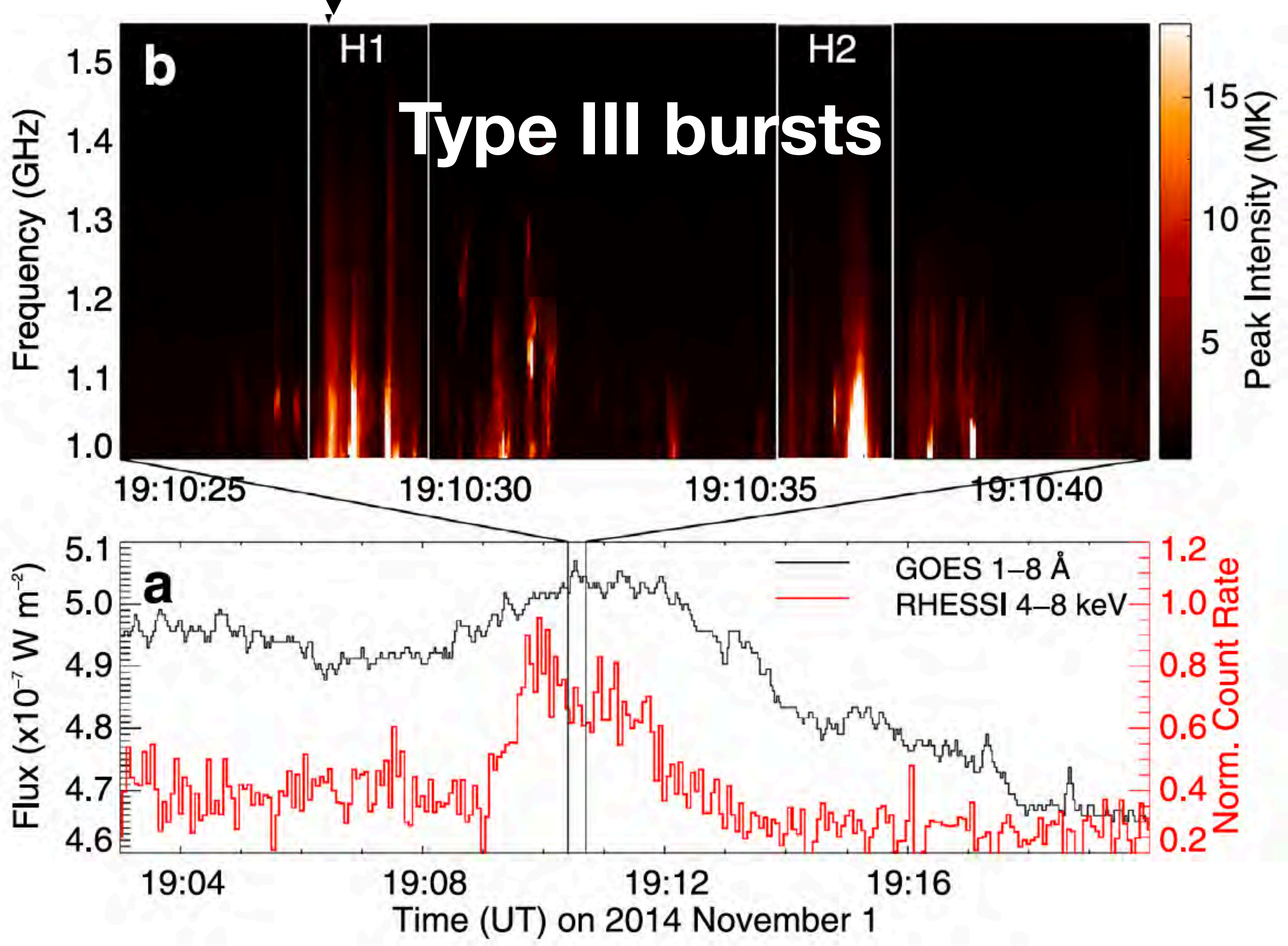


Overlaid on EUV Image



A 50-ms "snapshot" of the electron beam trajectory





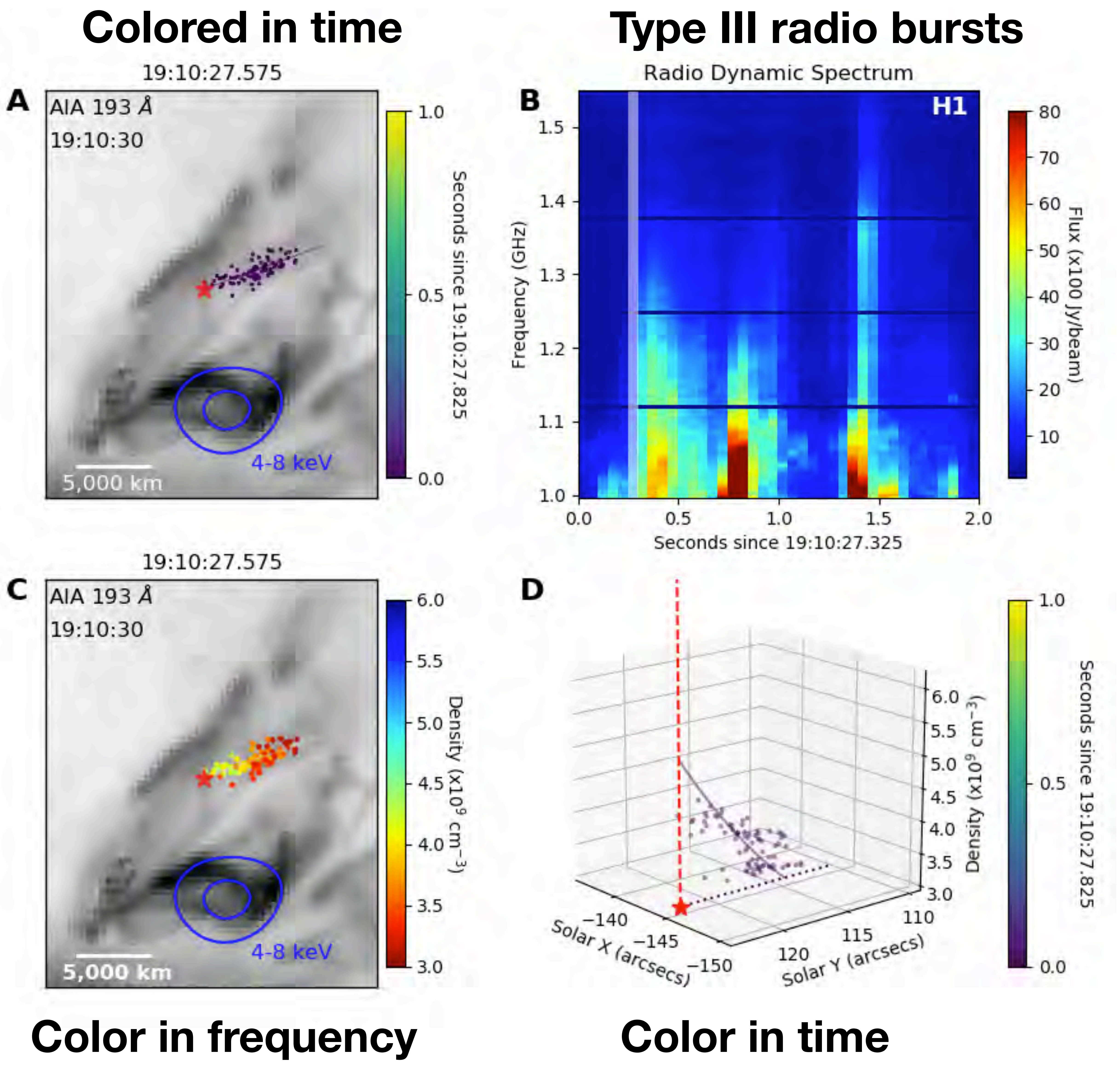
VLA 1.0-1.6 GHz dynamic spectrum

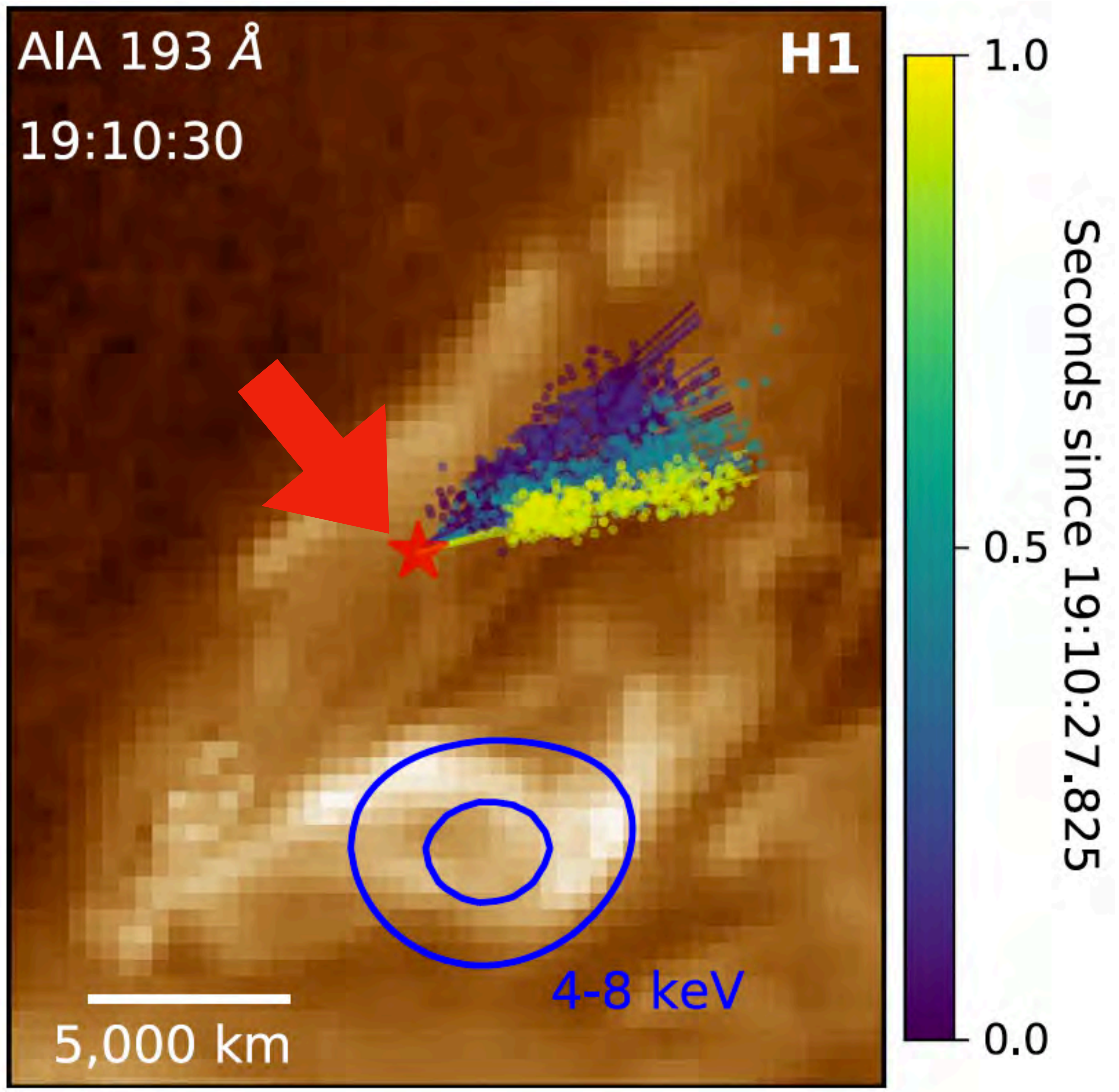
Beam speed >0.5 c

X-ray light curve (hot plasma)

Each colored dot is the emission centroid of a radio image at a given frequency

A common origin of electron beams

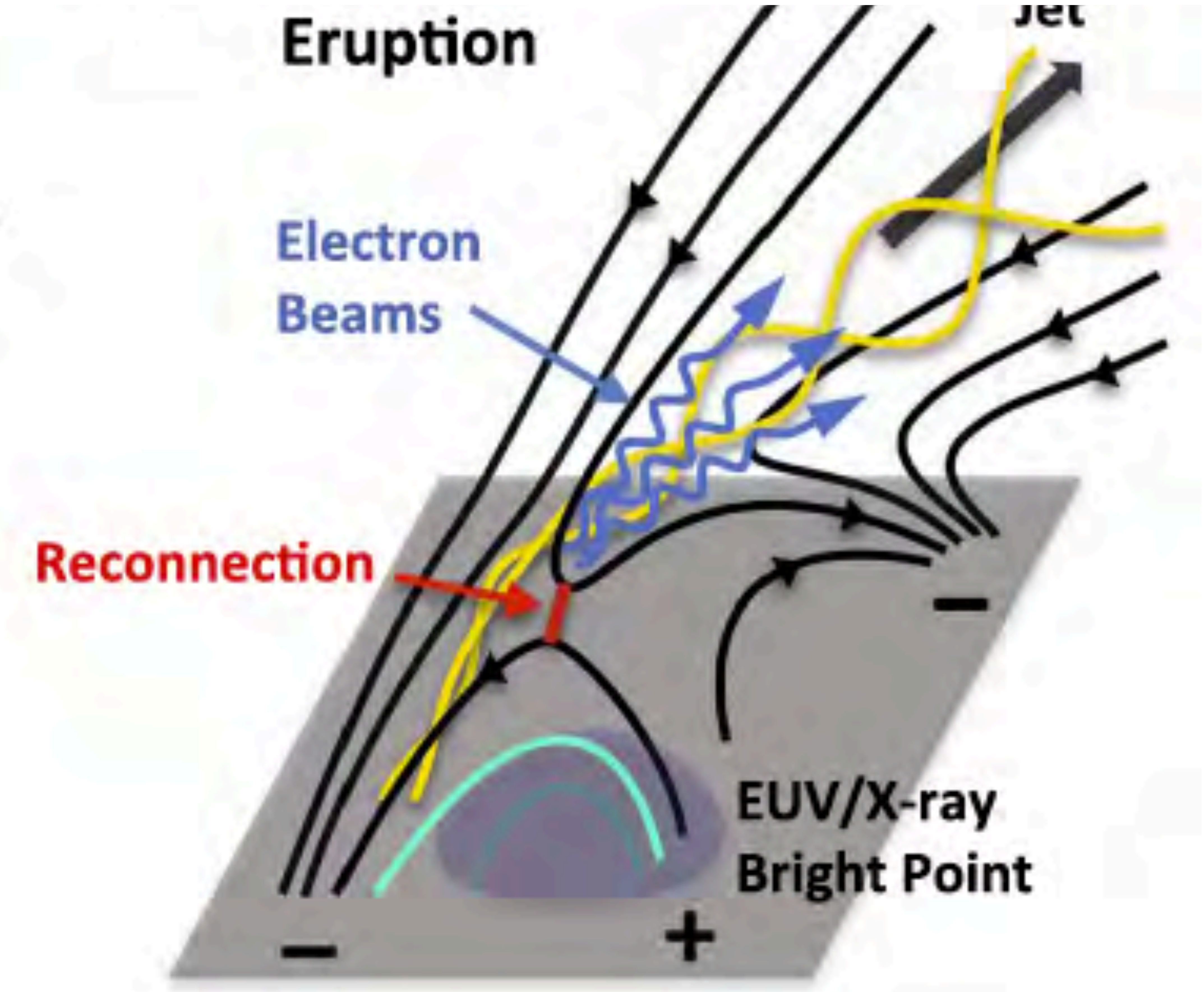




All the electron beams originate from a single, extremely compact region of <1,000 km²

Electron beams from reconnection null points

- All electron beams produced within ~1 second originate from **a single, compact site (<600 km)** → size **comparable or smaller than** the width of a coronal loop
- They propagate out along trajectories with different position angles and different density profiles → **many field lines "packed" into a compact region**
- **Fragmentation in the reconnection region**



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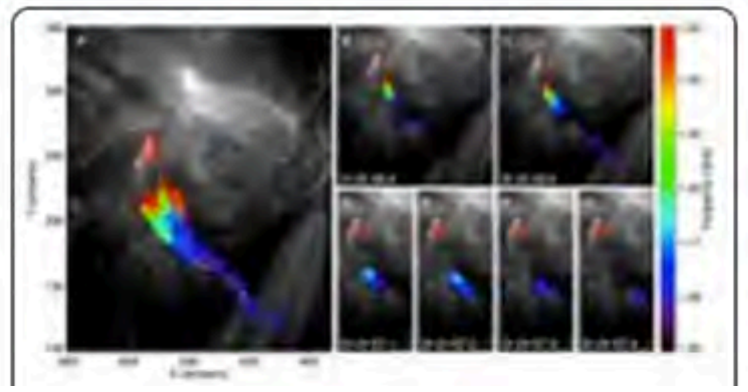

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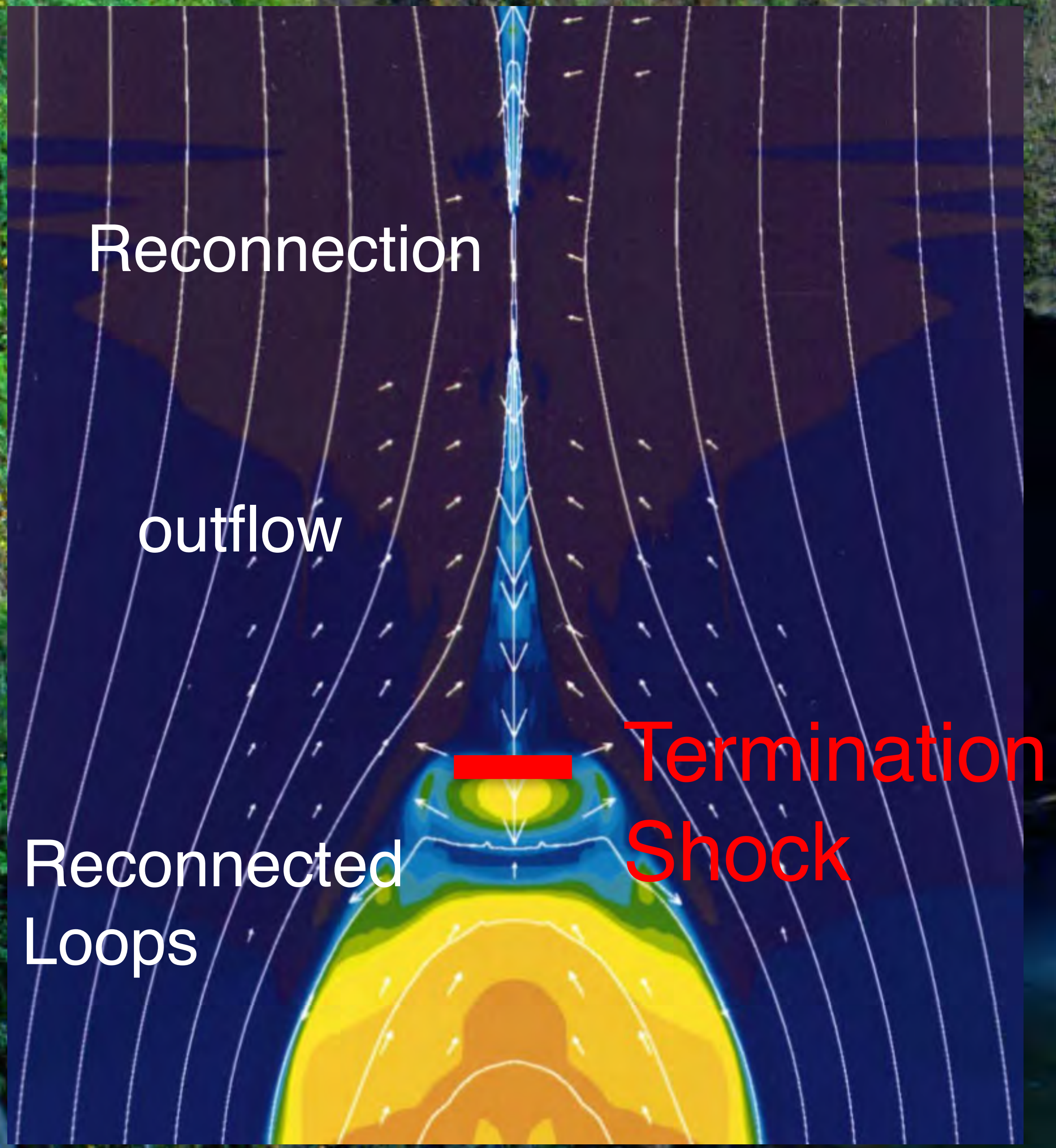
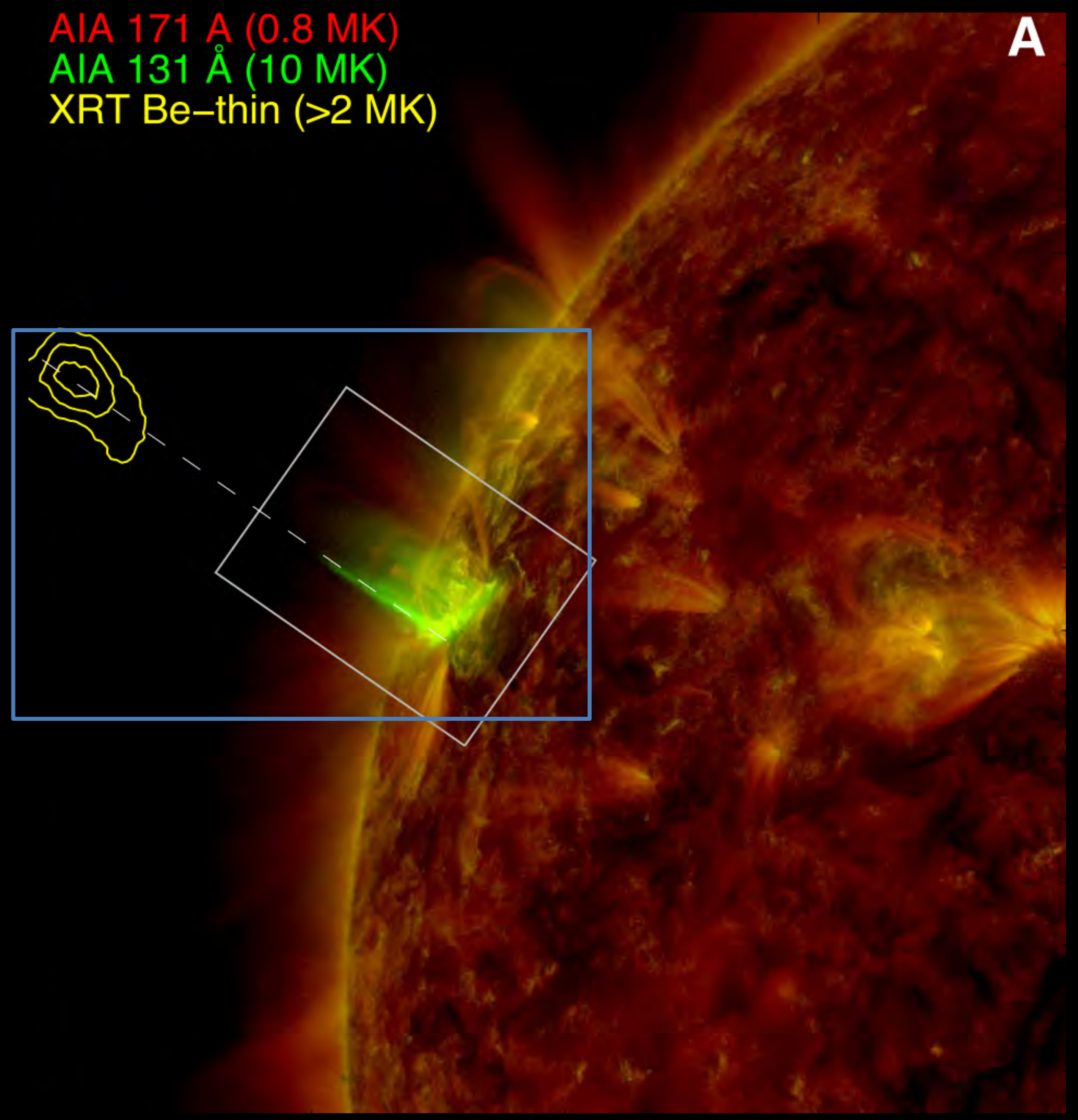
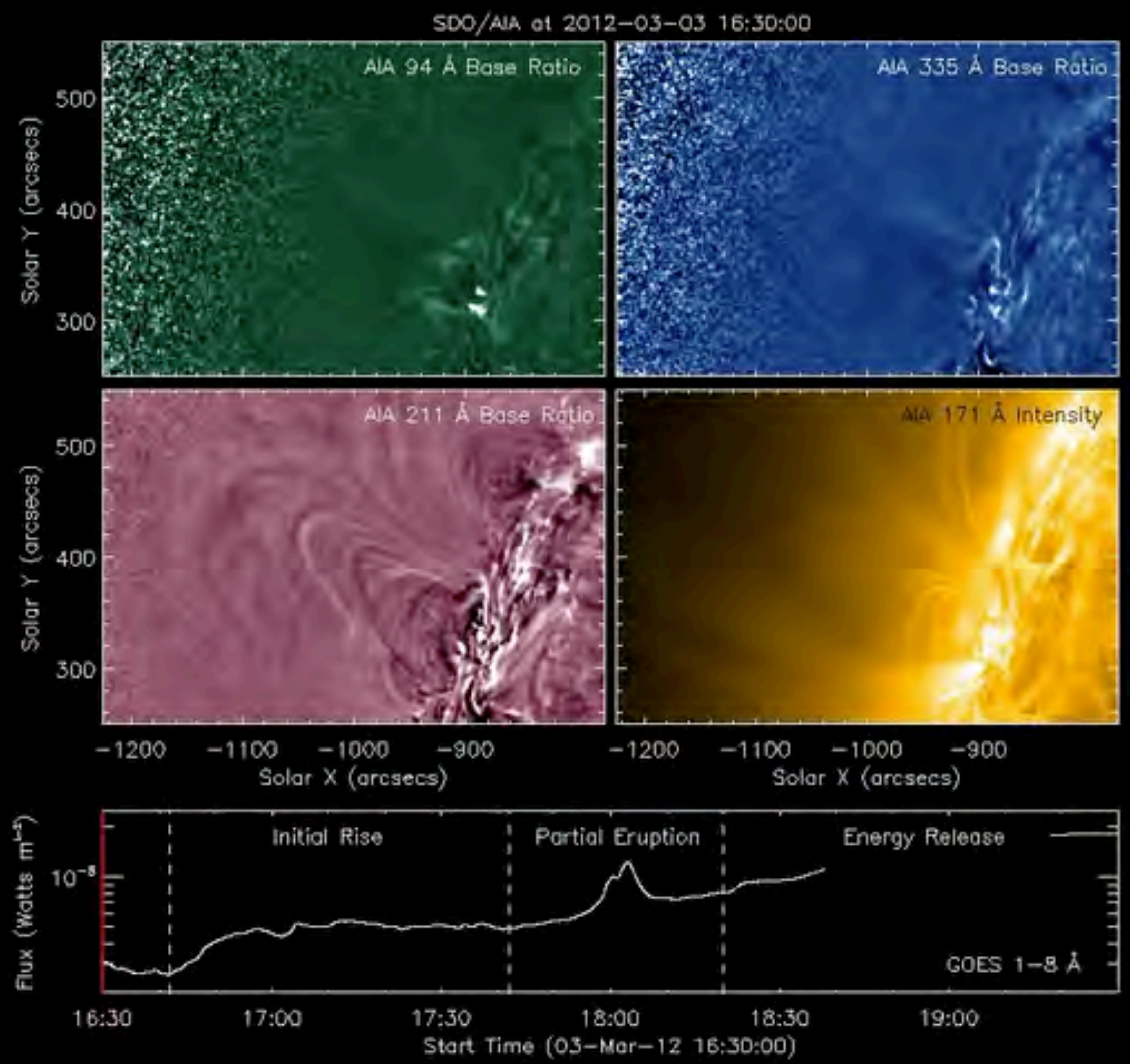
Solar Flare Termination Shock



- TSs suggested in the standard flare model as one important mechanism for accelerating electrons in flares (e.g., Forbes 1986; Masuda+1994; Aurass+ 2002, 2004; Mann+ 2009; Warmuth+2009; Guo+2012)
- However, solid observational evidence remains elusive

2012 Mar 3 C1.9 Eruptive Flare

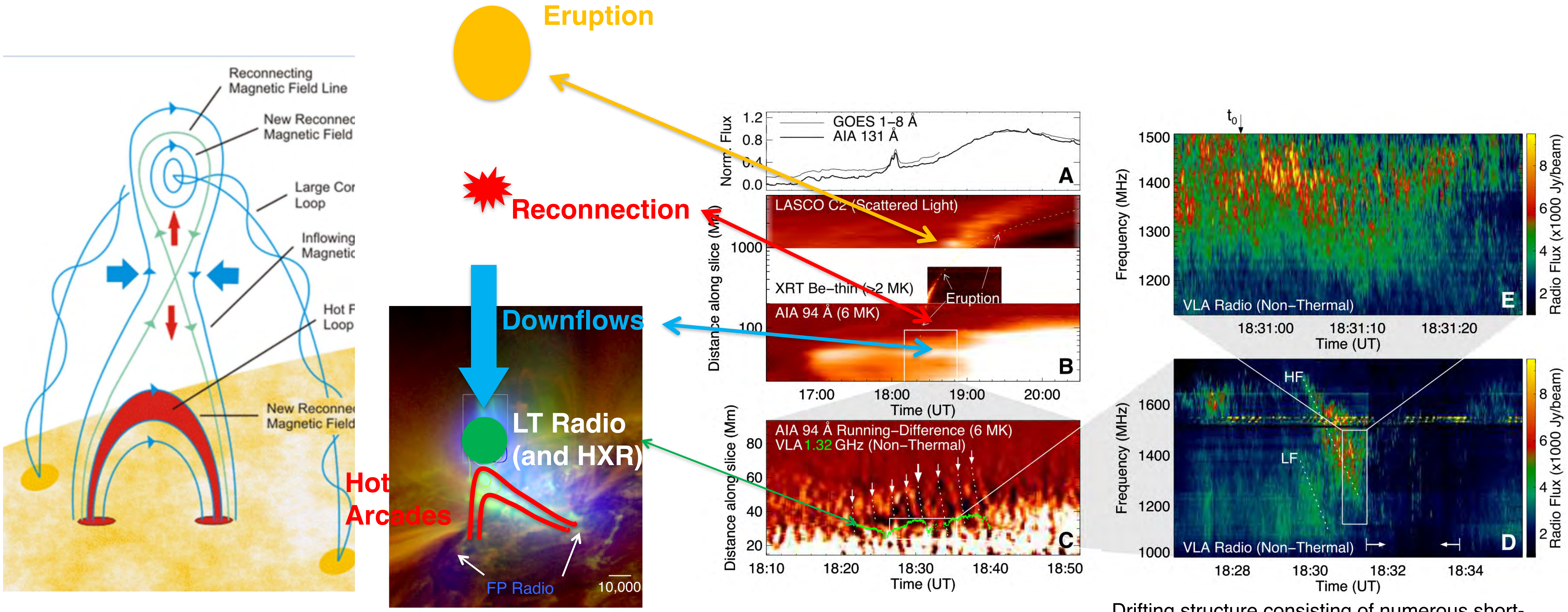




Observed by VLA, SDO, Hinode/XRT, SOHO/LASCO, and RHESSI

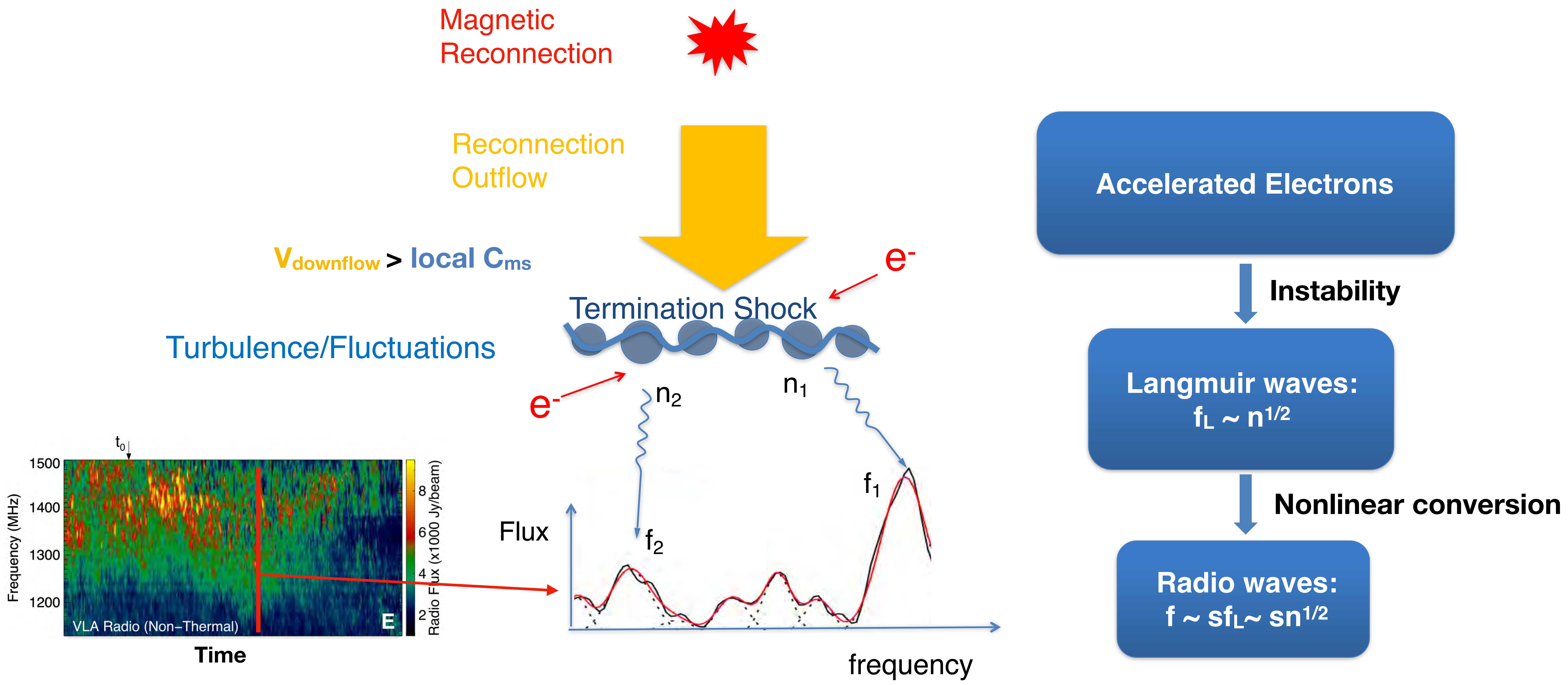
Chen et al. 2014, *ApJ*, 794, 149

Radio source at the front of reconnection downflows

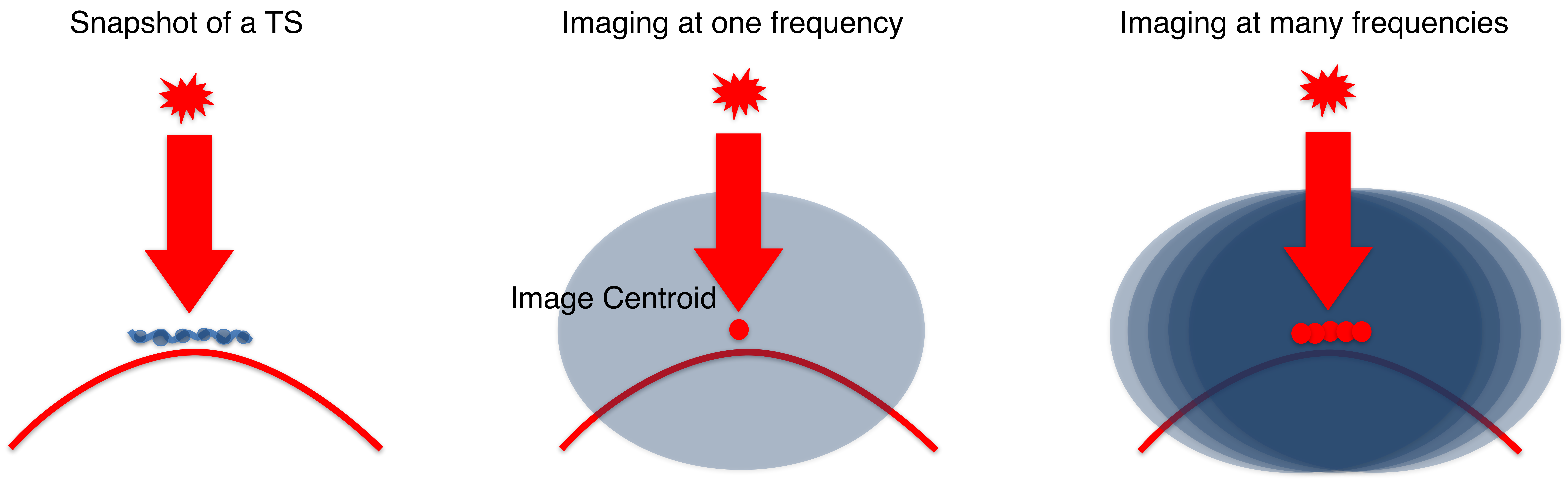


Drifting structure consisting of numerous short-lived, narrowband coherent radio bursts

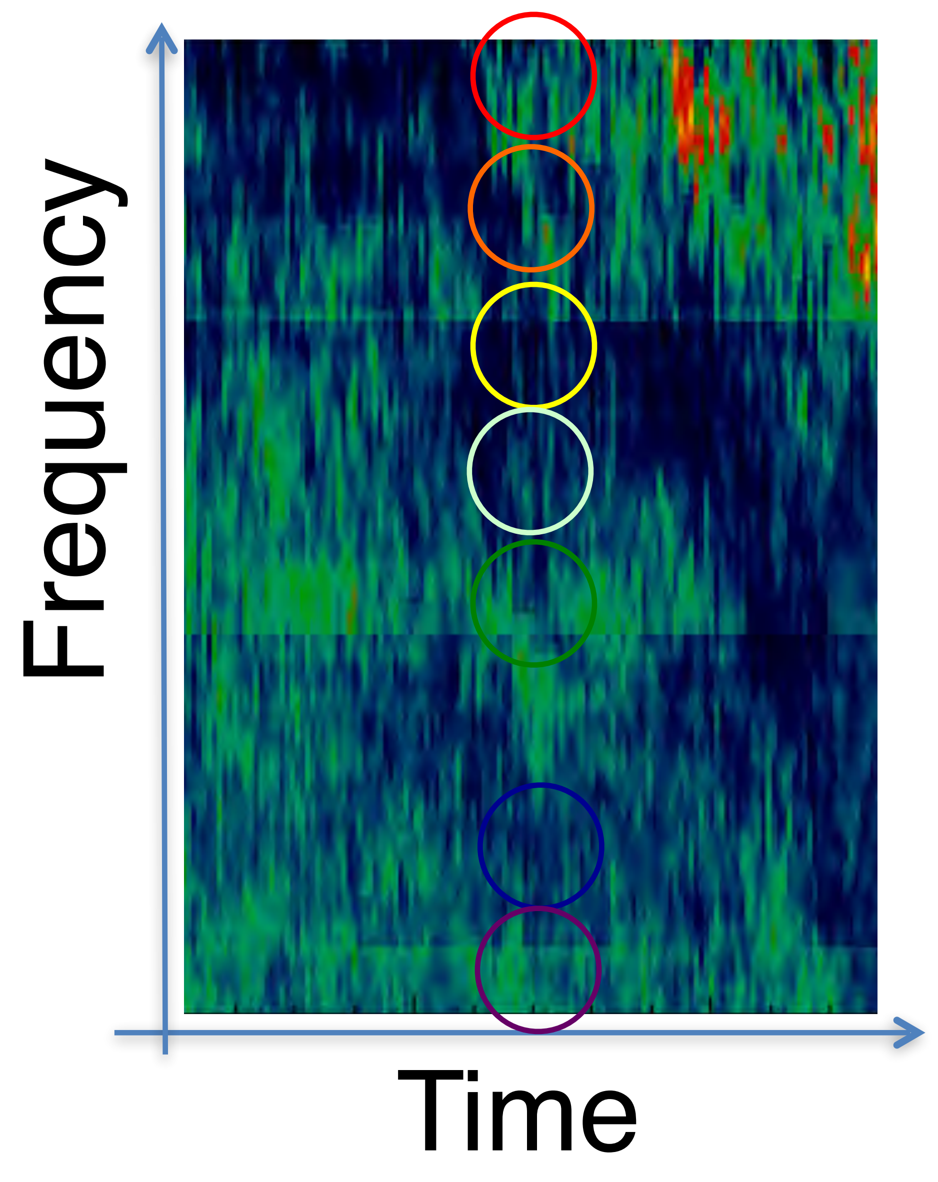
Radio Emission at a Termination Shock

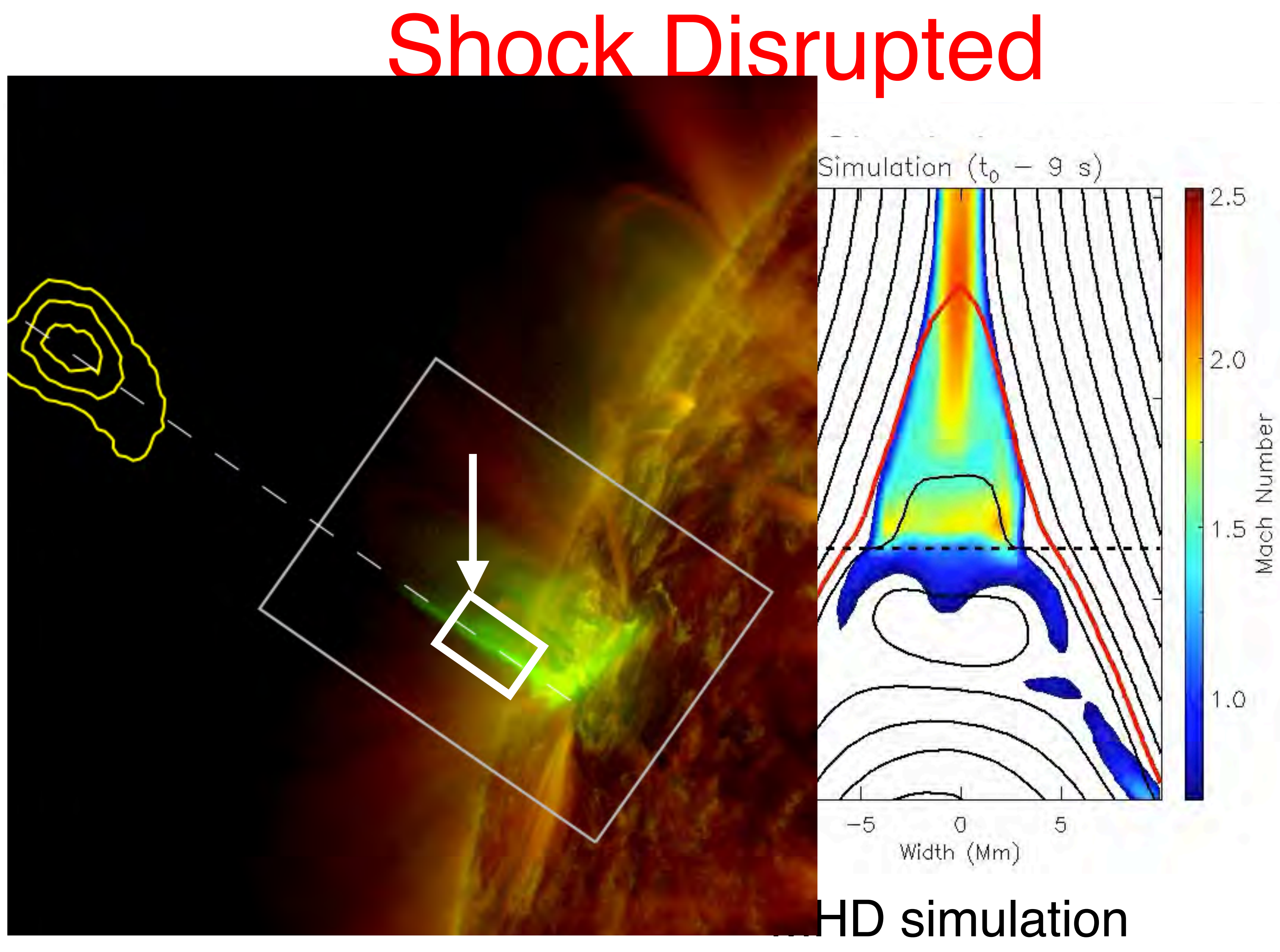


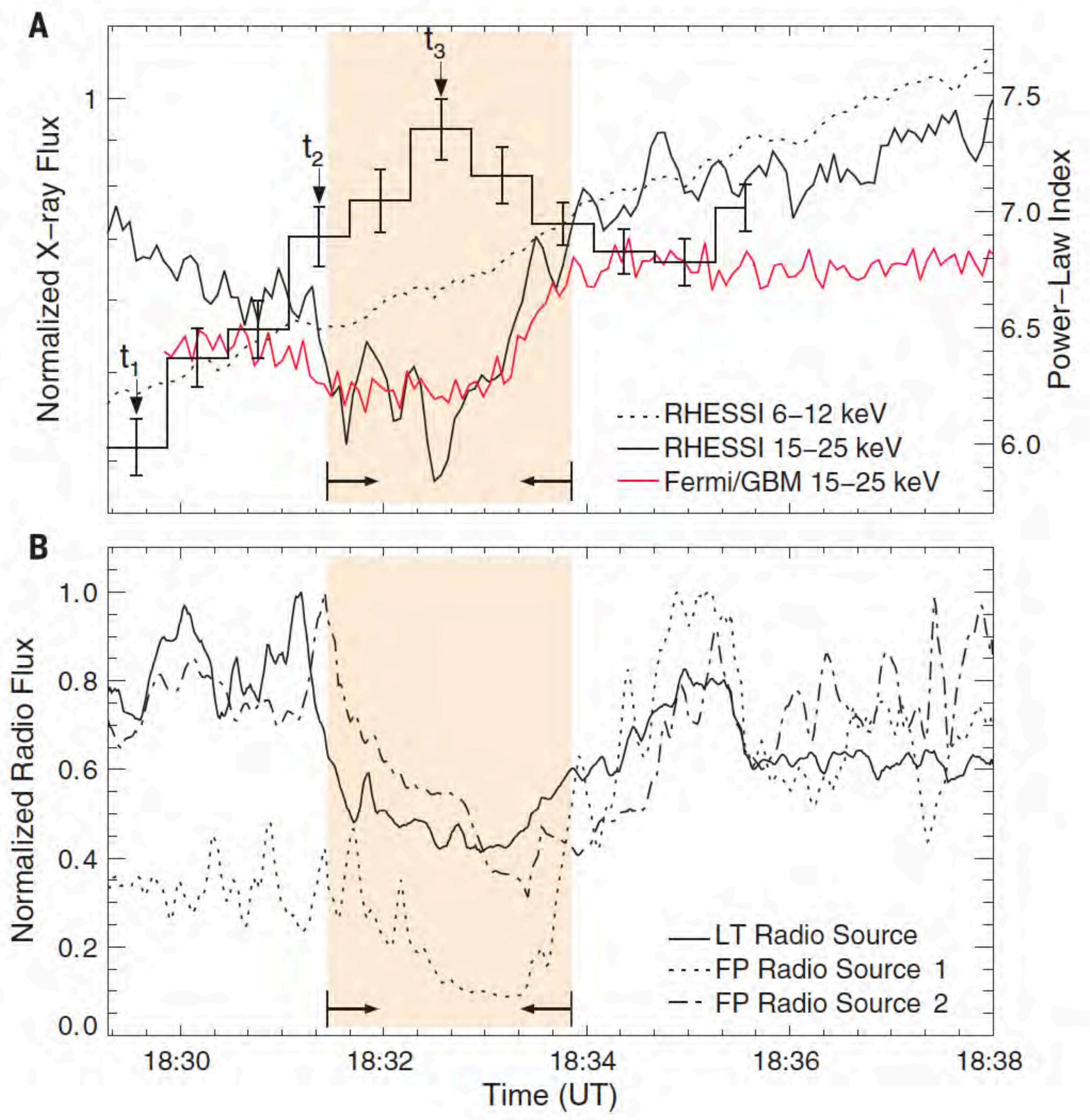
Mapping the termination shock with spectroscopic imaging



Dynamic shock surface outlined





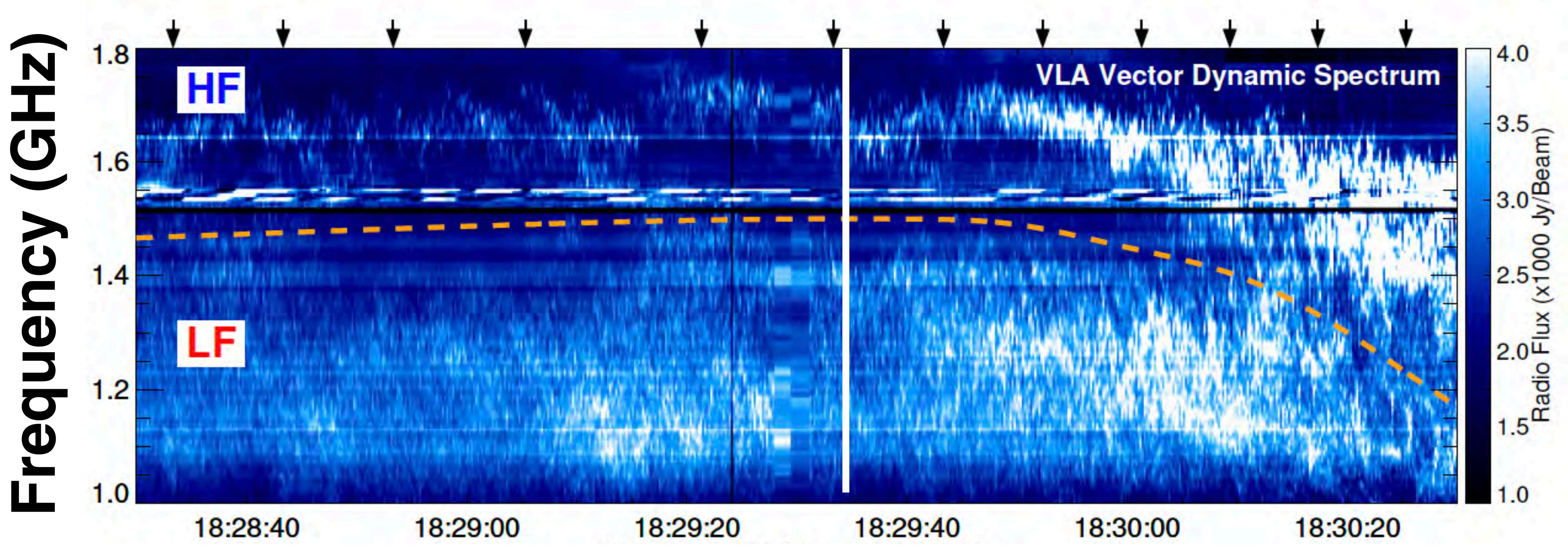


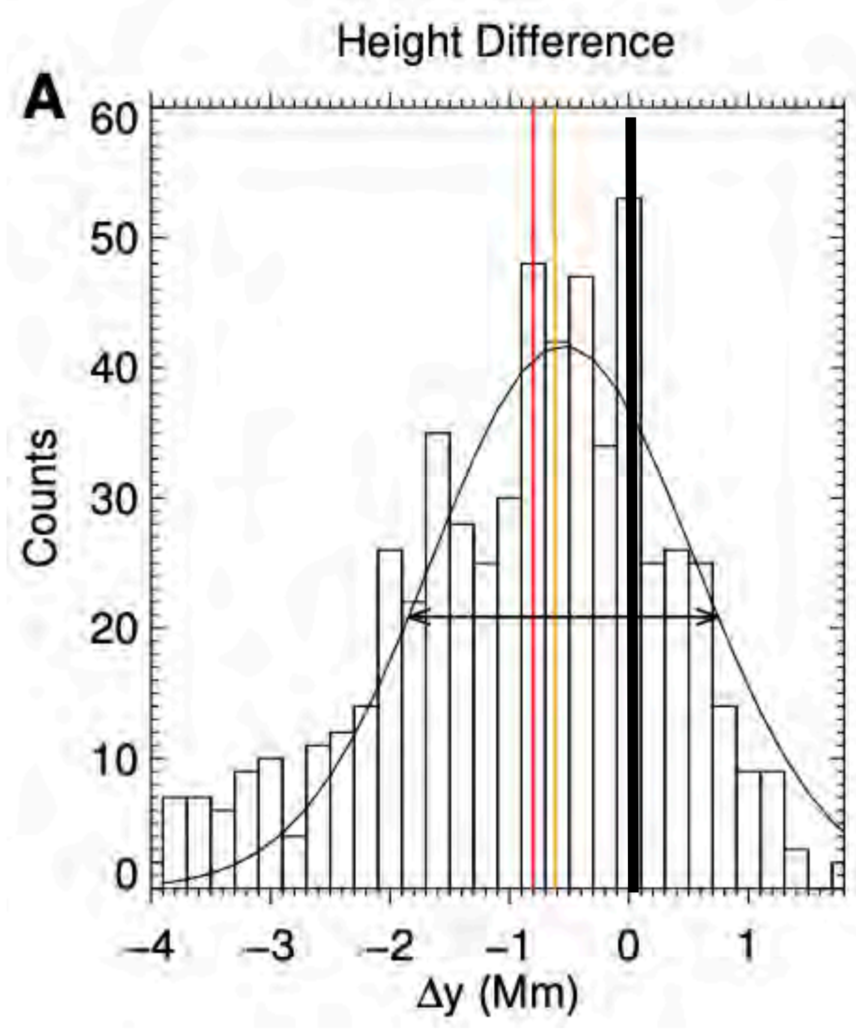
Main results:

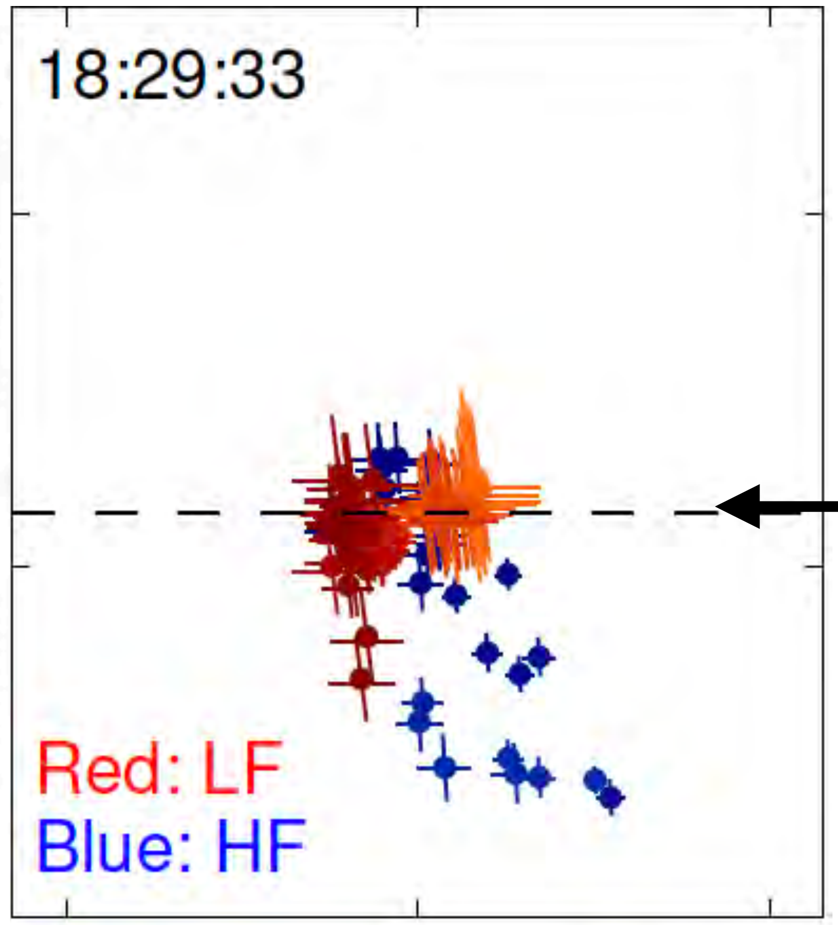
- **Observational identification and mapping** of a flare termination shock
- Demonstration of its **role in accelerating electrons** to at least 10s of keV

Chen et al. 2015, Science, 350, 1238

Measuring Shock Compression Ratio







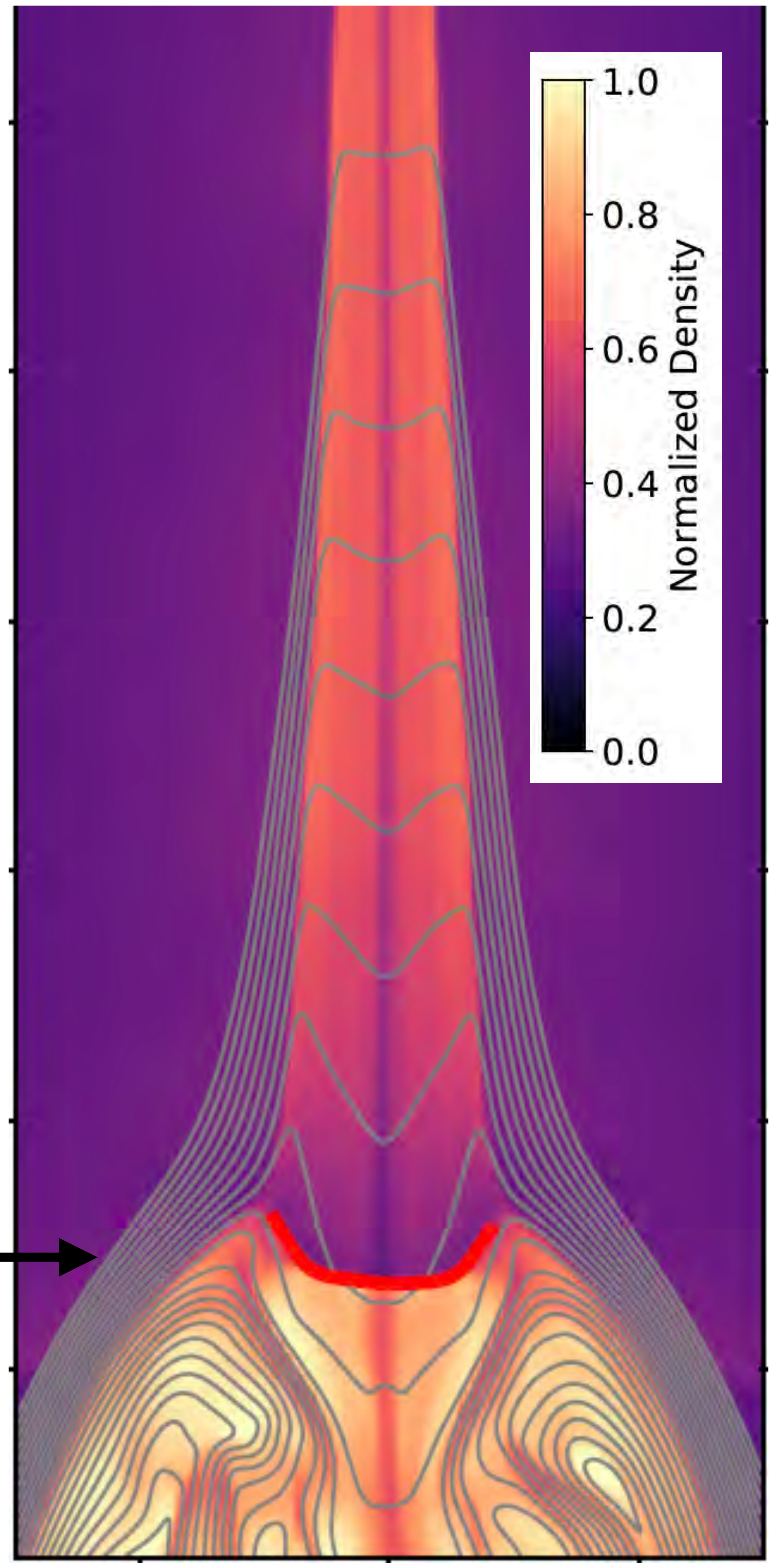
Upstream:

- Lower Density
- Lower frequency

Shock Front

Downstream:

- Higher density
- Higher frequency



Shock Compression Ratio

$$X = n_2/n_1 = (\nu_{\rm HF}/\nu_{\rm LF})^2$$
$$\approx 1.5 - 2.0$$

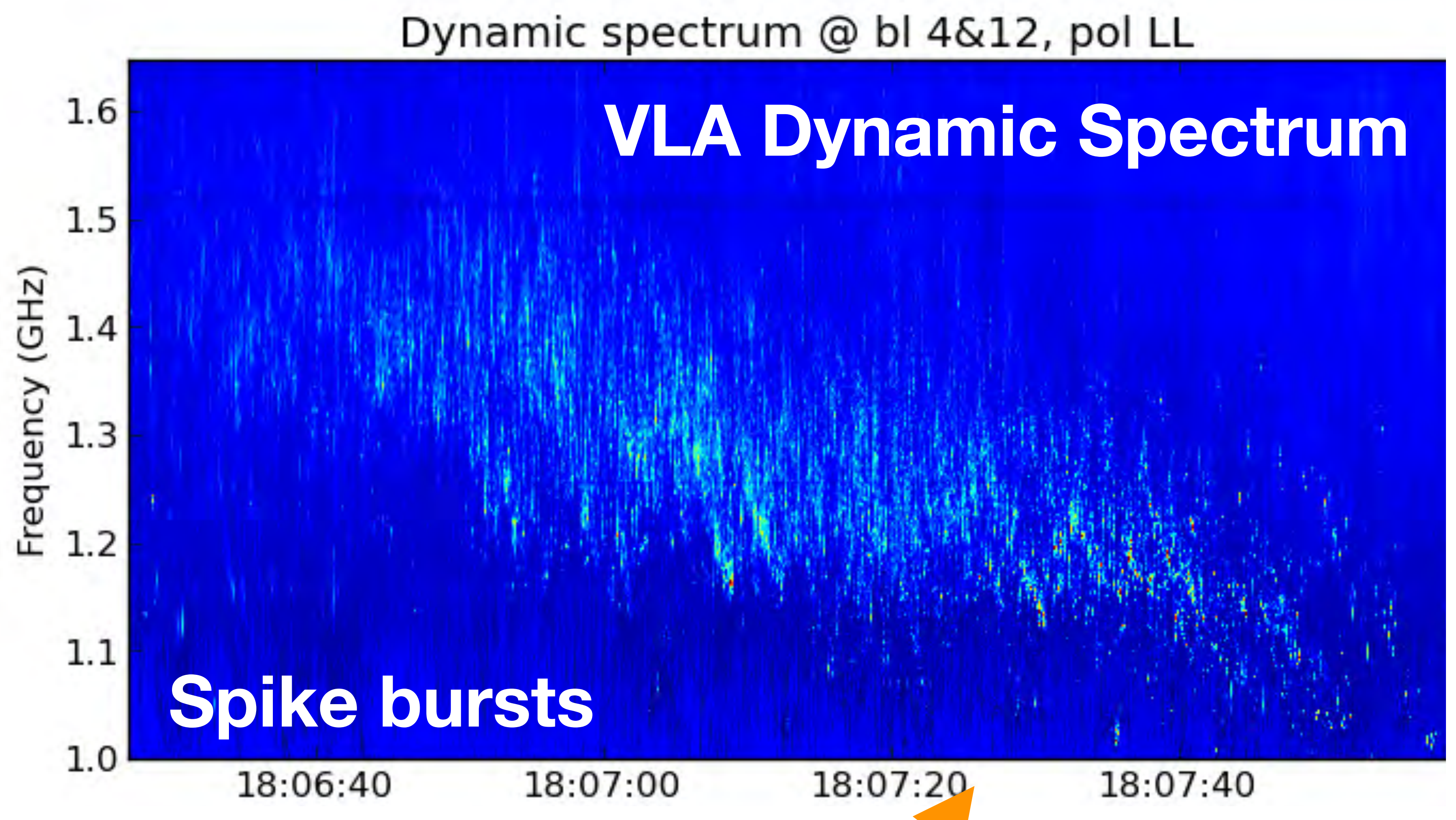
For hydrodynamic Shocks:

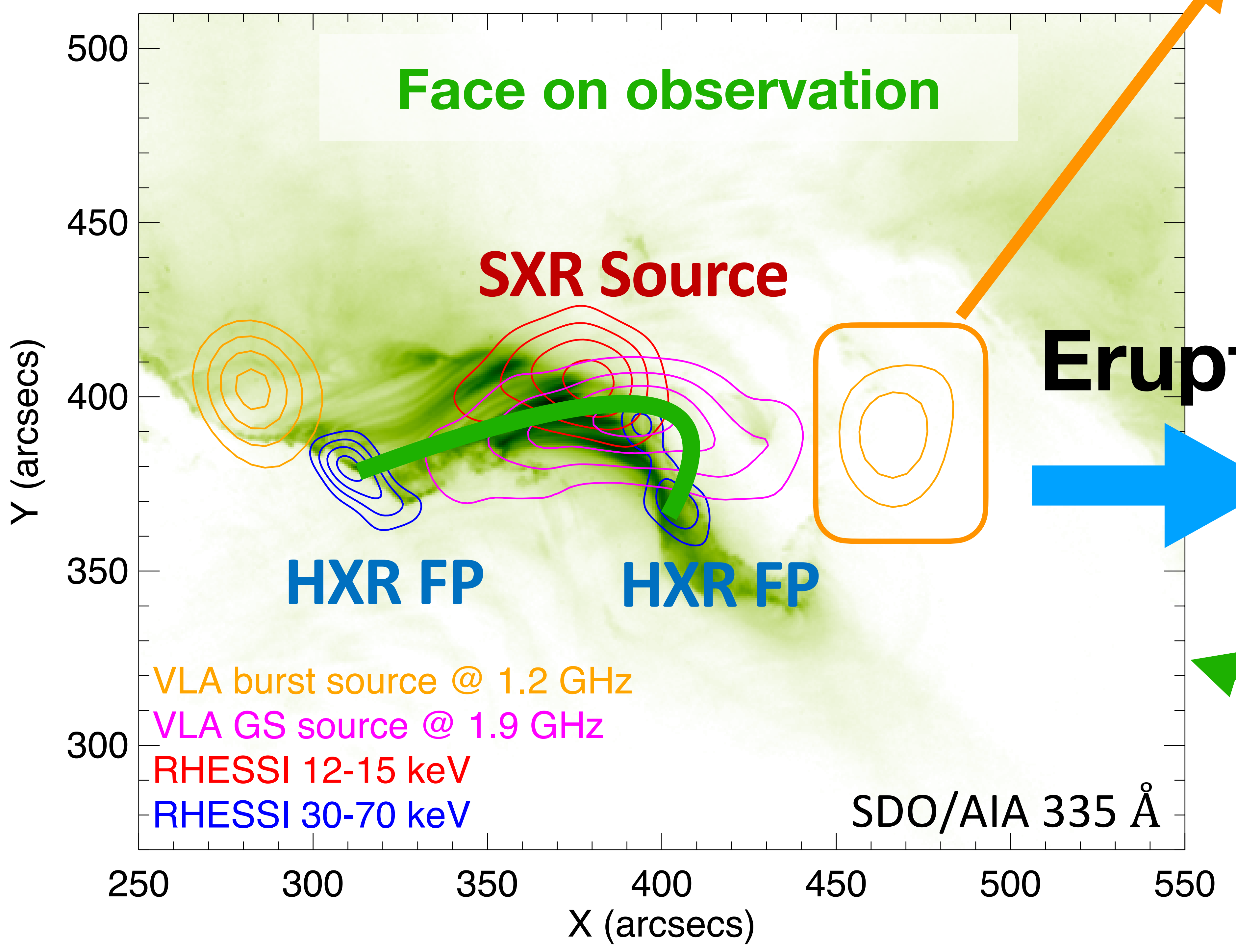
$$M_s \approx \sqrt{\frac{3X}{4-X}} \approx 1.3 - 1.7$$

Rather weak shock, but efficient electron accelerator!

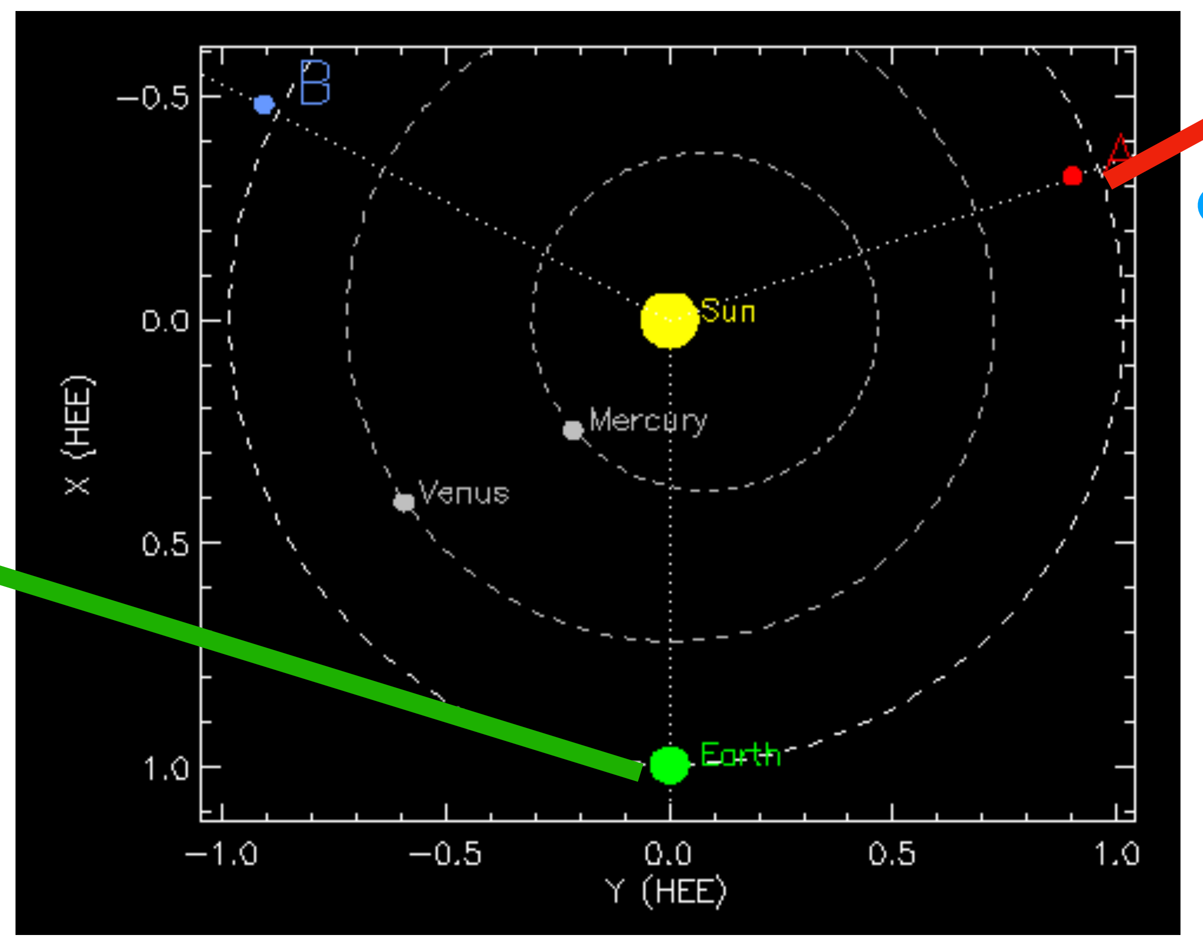
Chen et al. 2019, ApJ, 884, 63

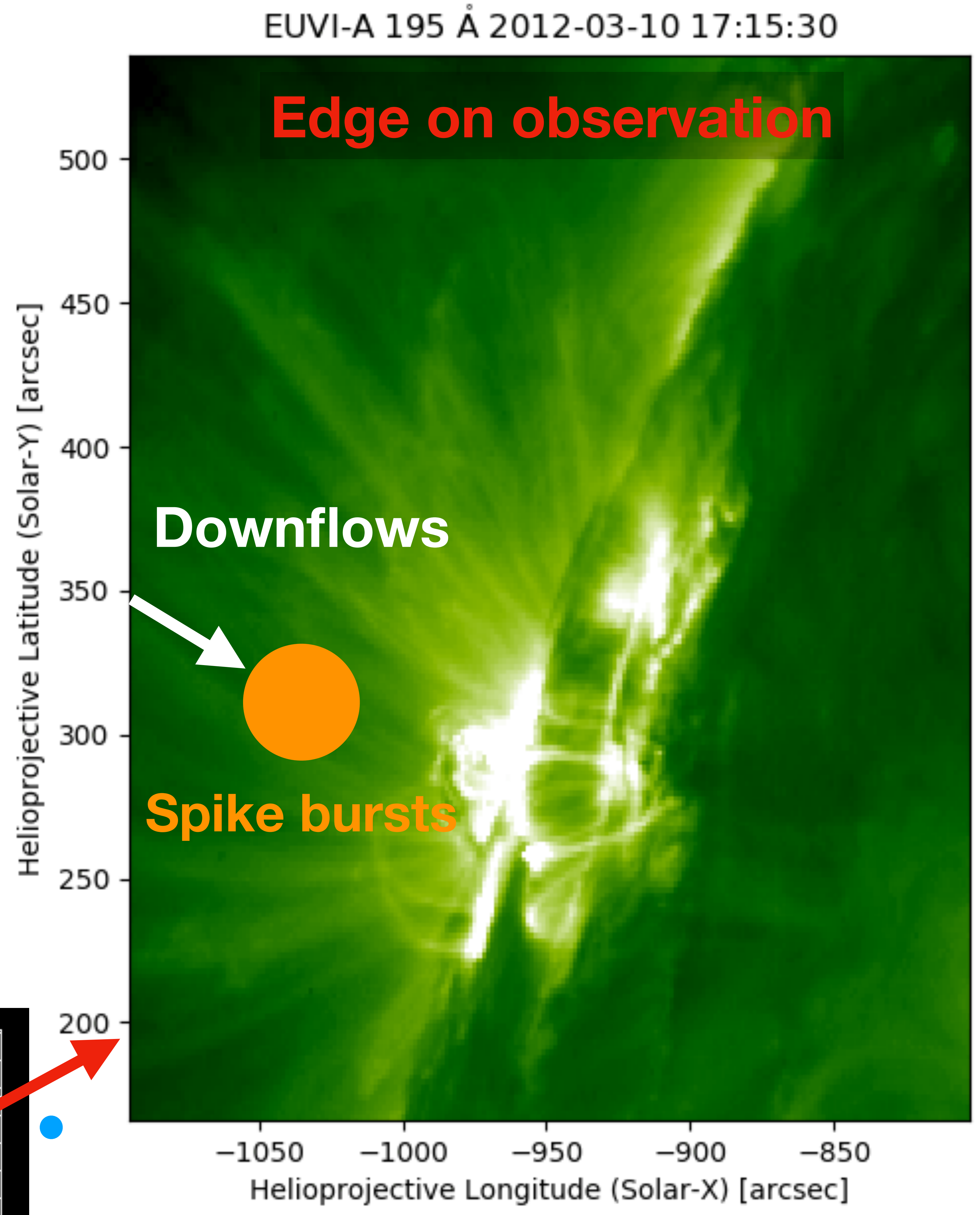
Flare Termination Shock: Another possible candidate





Eruption





Luo et al., in prep

Examples of recent solar flare studies with Jansky VLA

- **Tracing fast electron beams**
  - Chen et al. 2018, ApJ, 866, 62
  - Chen et al. 2013, ApJL, 763, 21
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- **Imaging waves and oscillations**
  - Yu & Chen, 2019, ApJ, 872, 71
  - Wang, Chen & Gary 2017, ApJ, 848, 77
- **Microflares**
  - Battaglia et al., in prep
  - Sharma et al., in prep

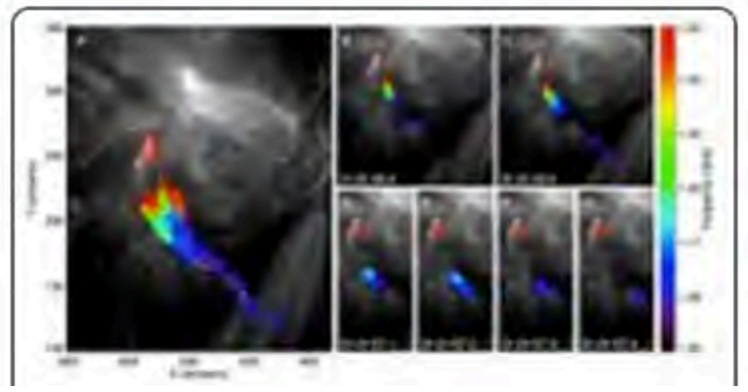
Particle acceleration by a solar flare termination shock

BY BIN CHEN, TIMOTHY S. BASTIAN, CHENGCAI SHEN, DALE E. GARY, SÄM KRUCKER, LINDSAY GLESENER

SCIENCE | 04 DEC 2015 : 1238-1242

NRAO 2013 Science Highlights

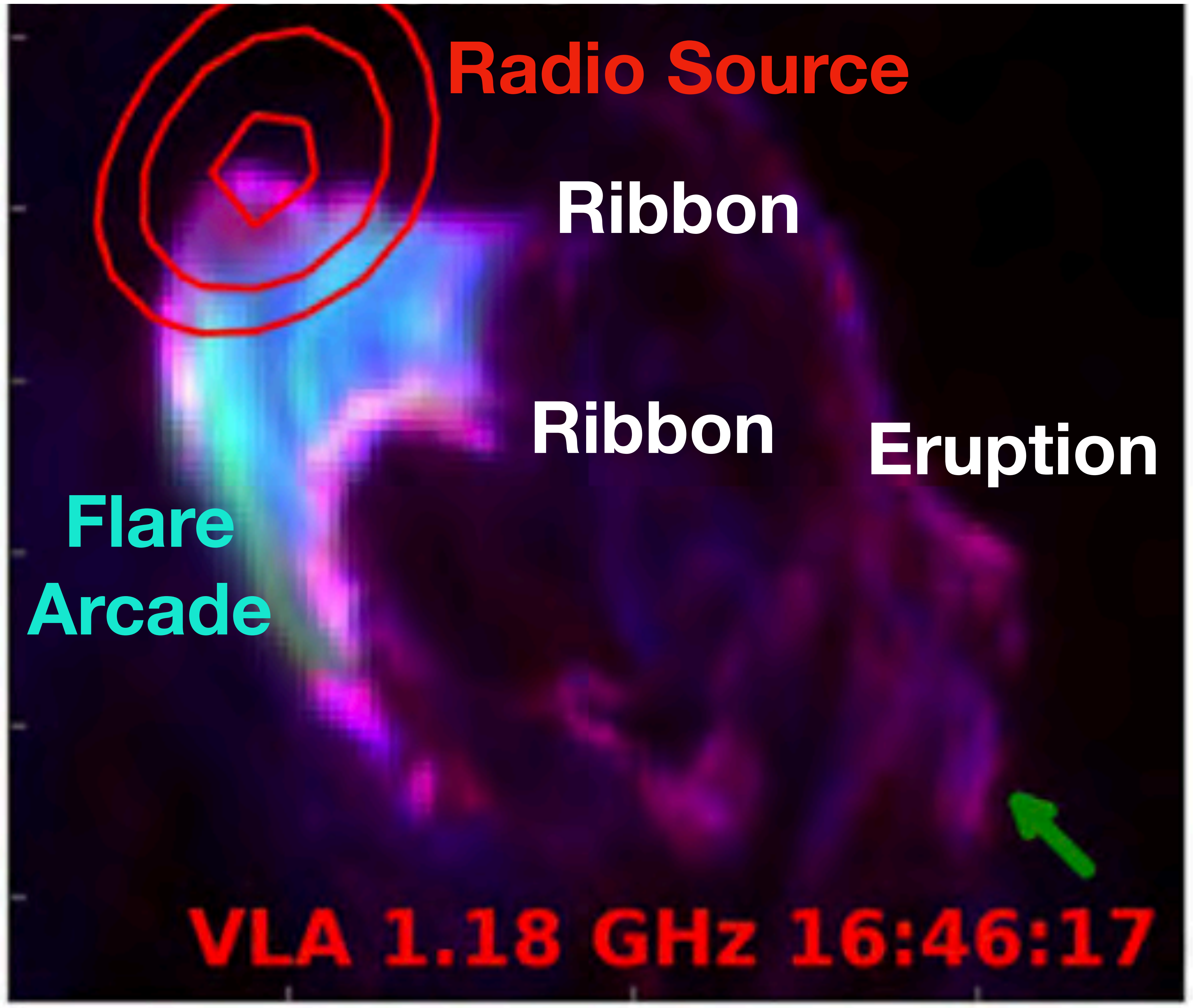
Imaging Magnetic Reconnection on the Sun



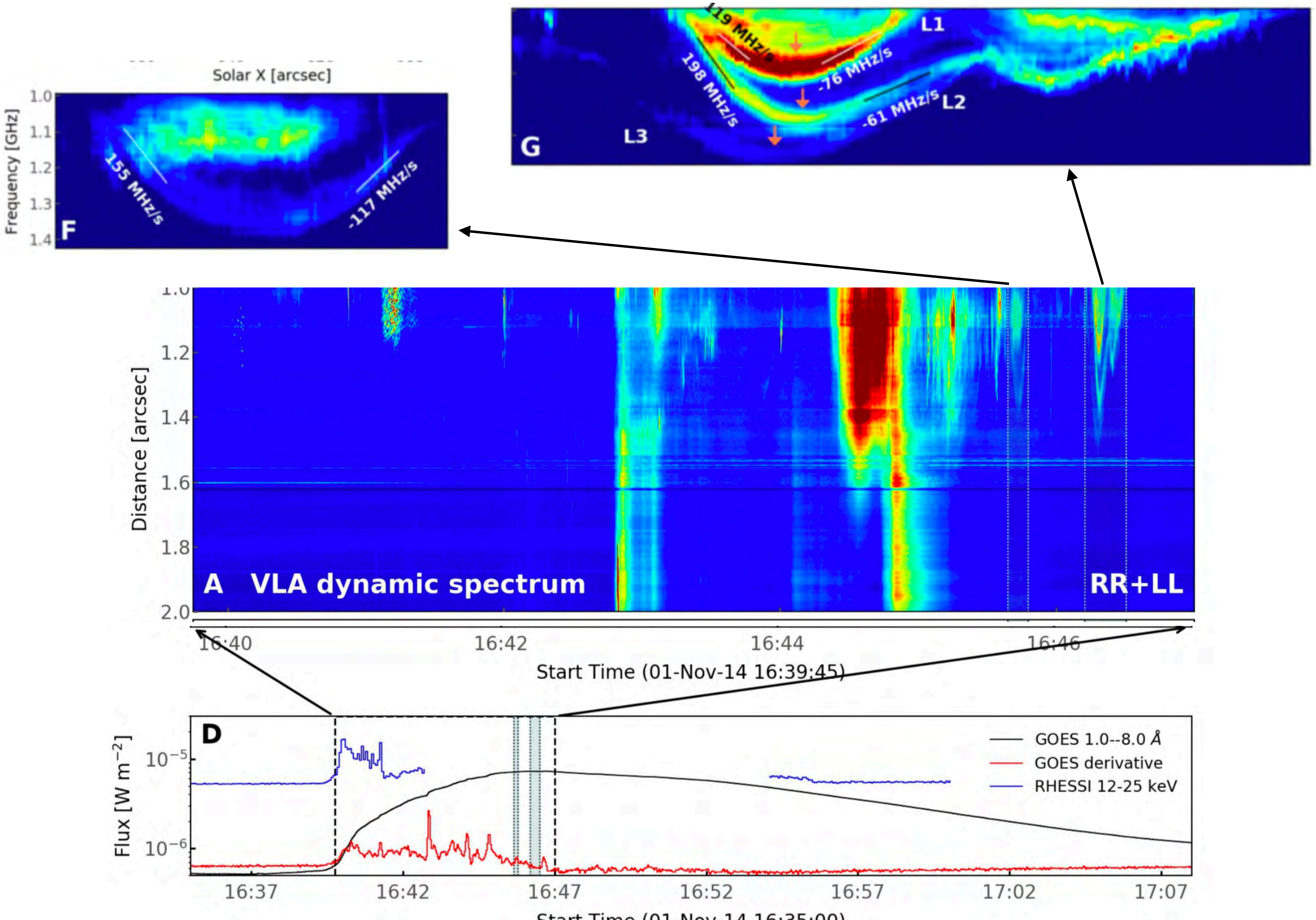
Type III radio bursts from the Sun **VLA** has imaged these bursts on tir located in the low corona and propa diameter of these loops is less than of the Sun's corona. The localized e reconnection model that involves se

Wave Signature in the Radio Dynamic Spectrum

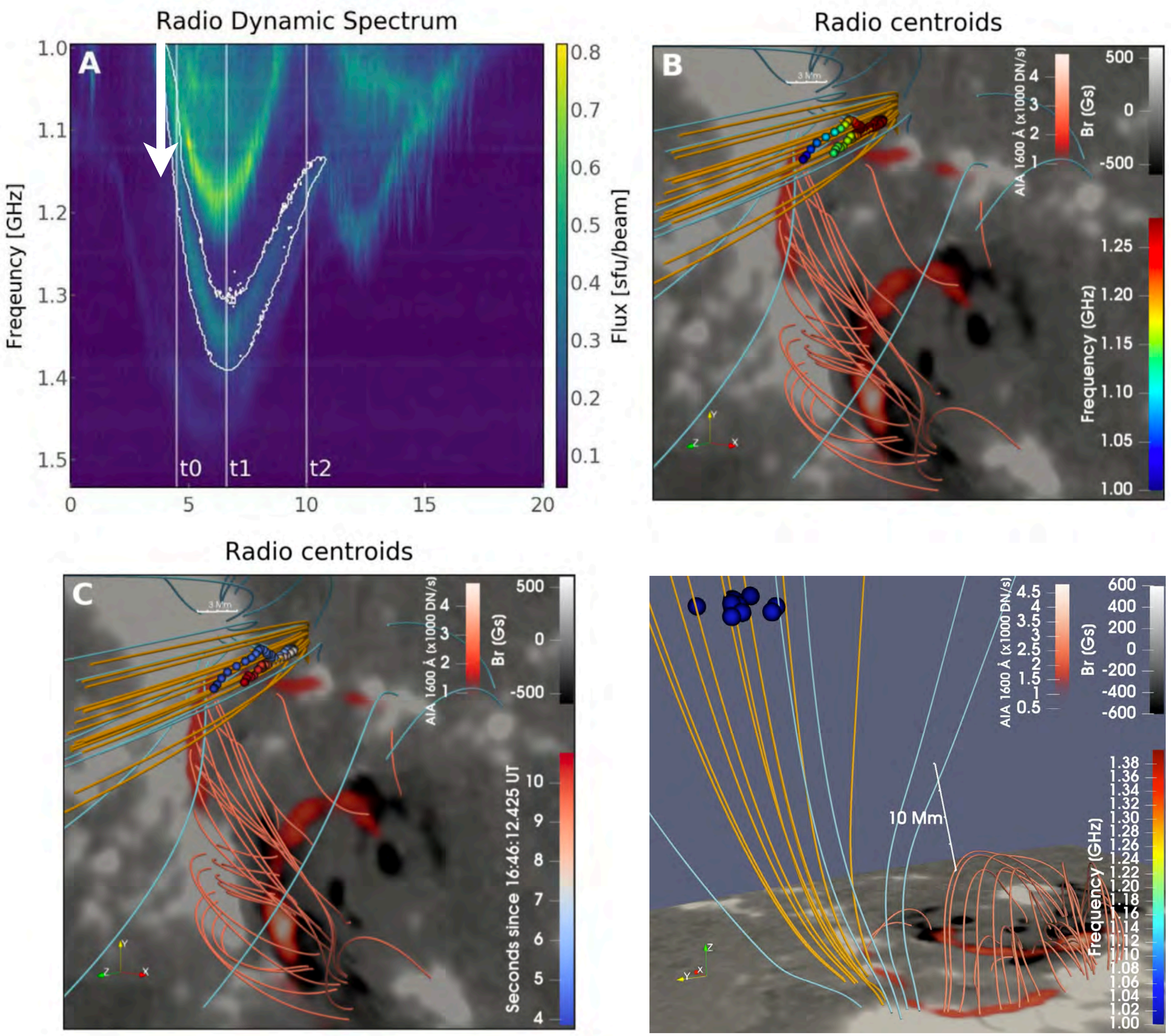
- VLA observed a C7.2 flare with a failed eruption on 2014 Nov 1
- Large-scale EUV waves



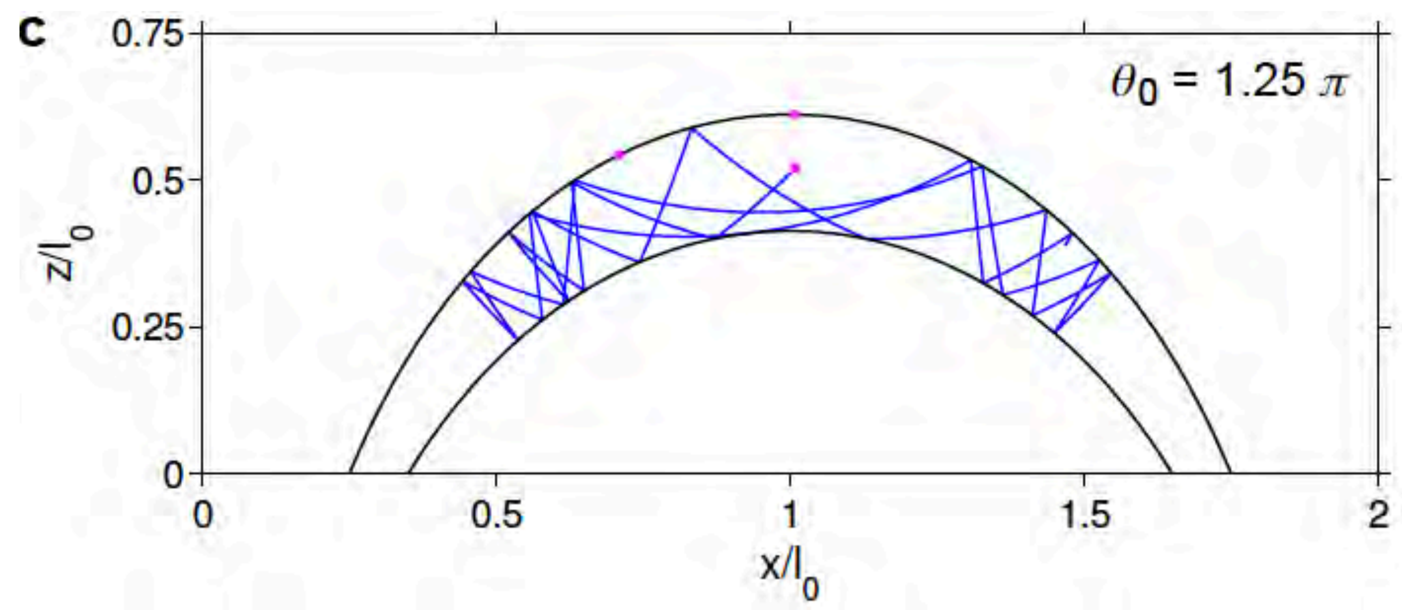
- Nearly 100% polarized, high brightness temperature
- df/dt ~ 60~200 MHz/s, indicative of MHD-type speeds under typical coronal conditions (as f is a function of height)



Imaging of the source motion

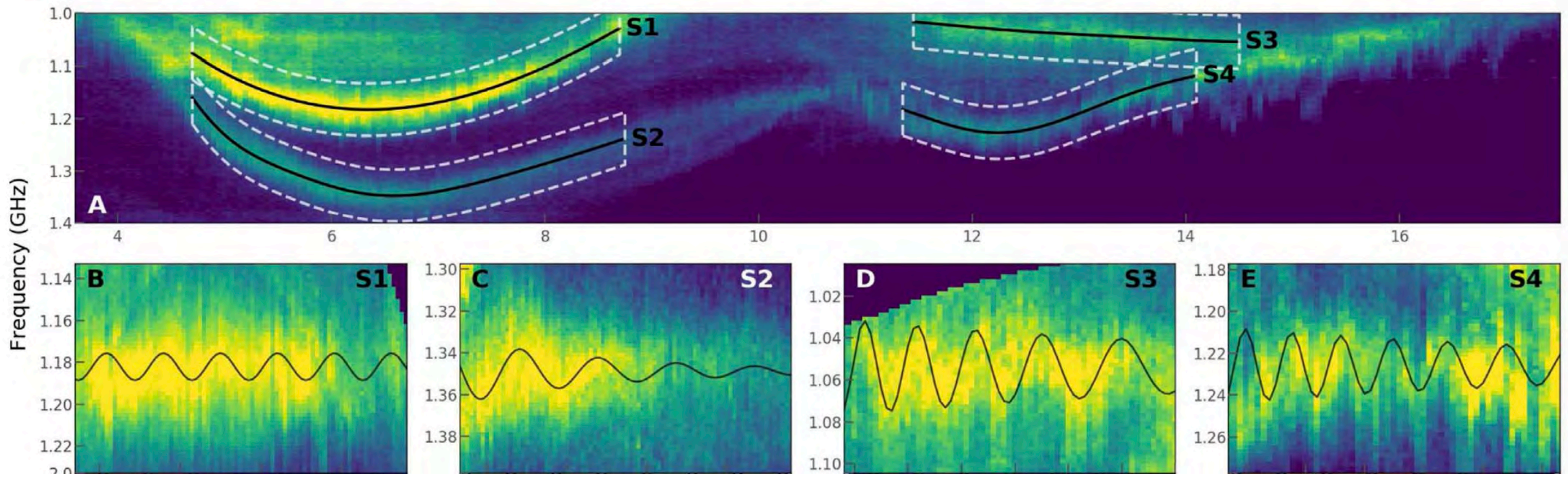


- ◉ Source speed **1,000–2,000 km/s** in projection
  - Typical for **Alfvenic or fast-mode MHD** wave speeds in the low corona
  - Too fast for slow-mode MHD or sound waves
- ◉ **Bounce back** near the flare ribbon → reflective wave phenomenon
  - Encounters a large gradient
  - Torsional waves
  - Multiple reflections in a waveguide

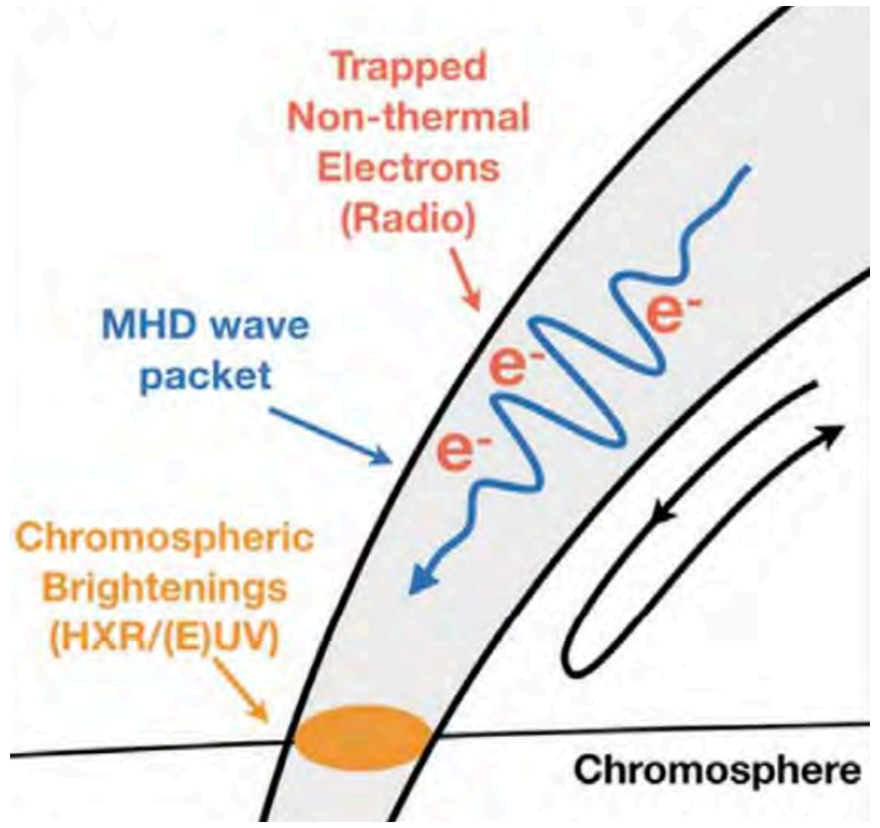


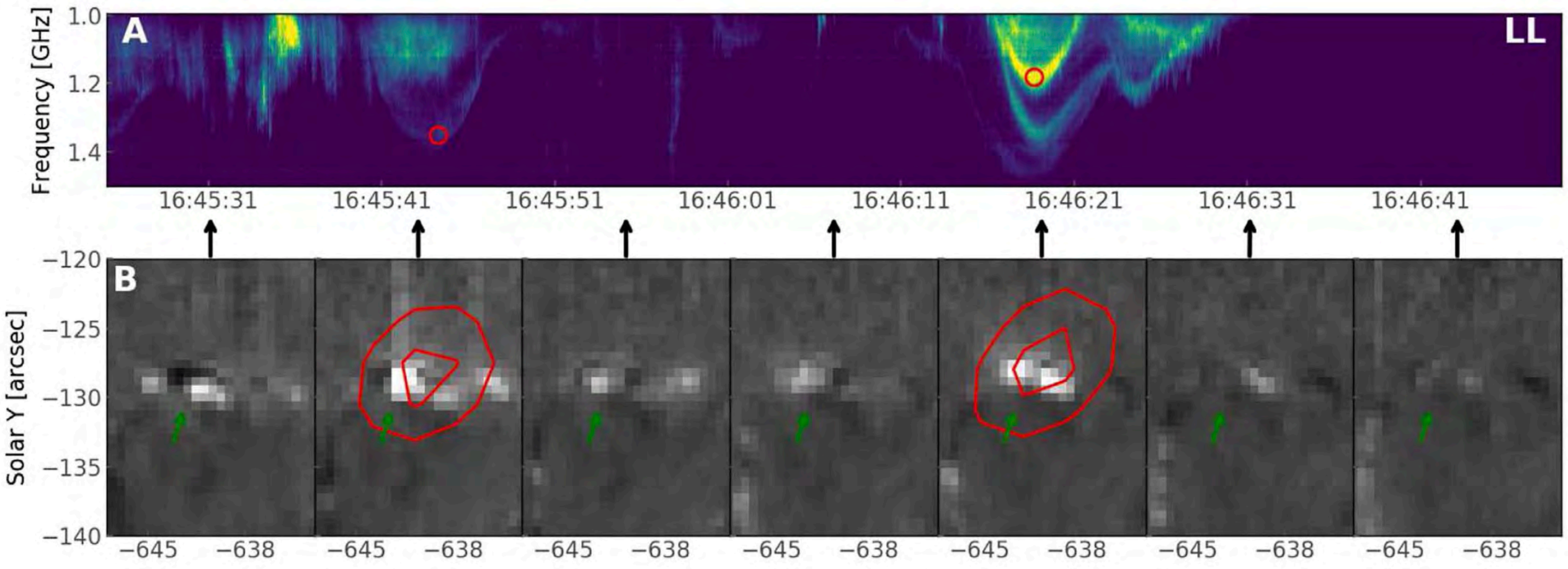
Russel & Stackhouse 2013, A&A, 558, 76

Subsecond-period density oscillations



Short-period oscillations in a propagating wave packet?





Estimated energy flux is comparable with that needed to account for the UV ribbon brightening

If ubiquitous enough, perhaps energetically important in transporting released energy

Yu & Chen 2019, ApJ, 872, 71

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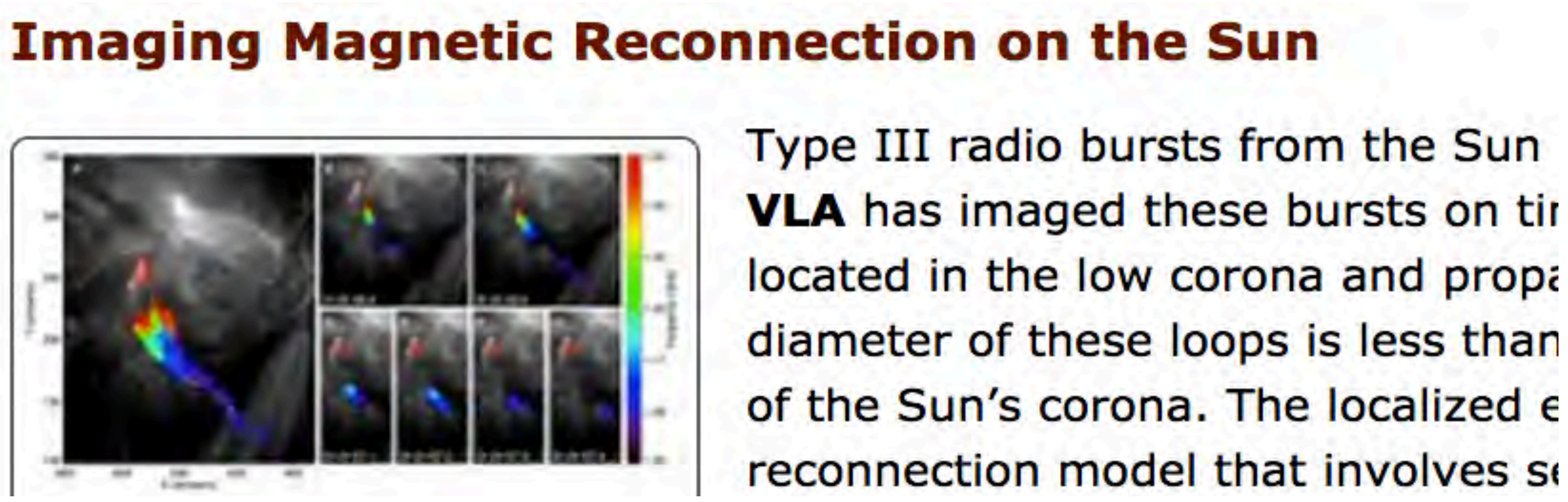
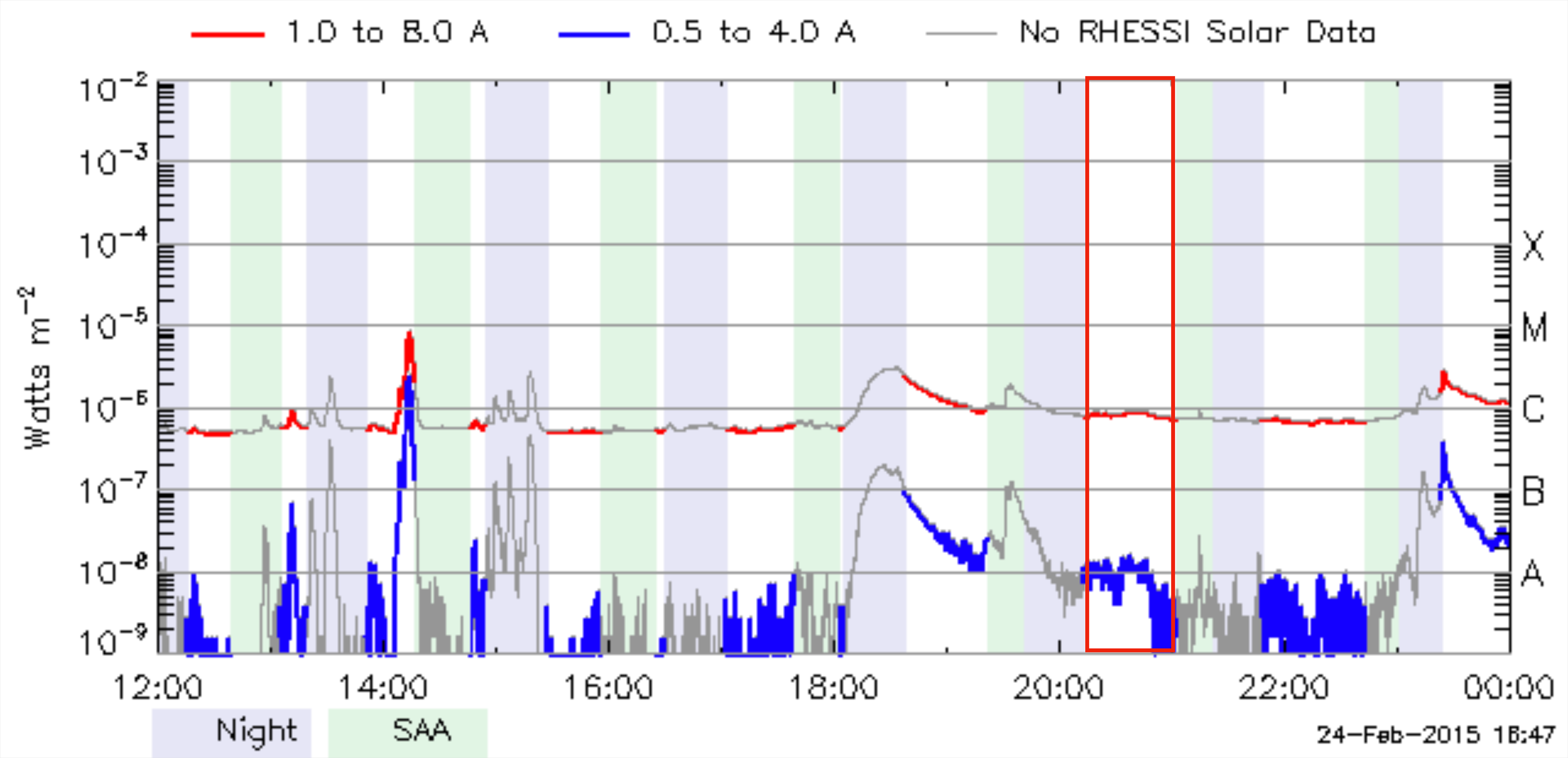
NRAO 2013 Science Highlights

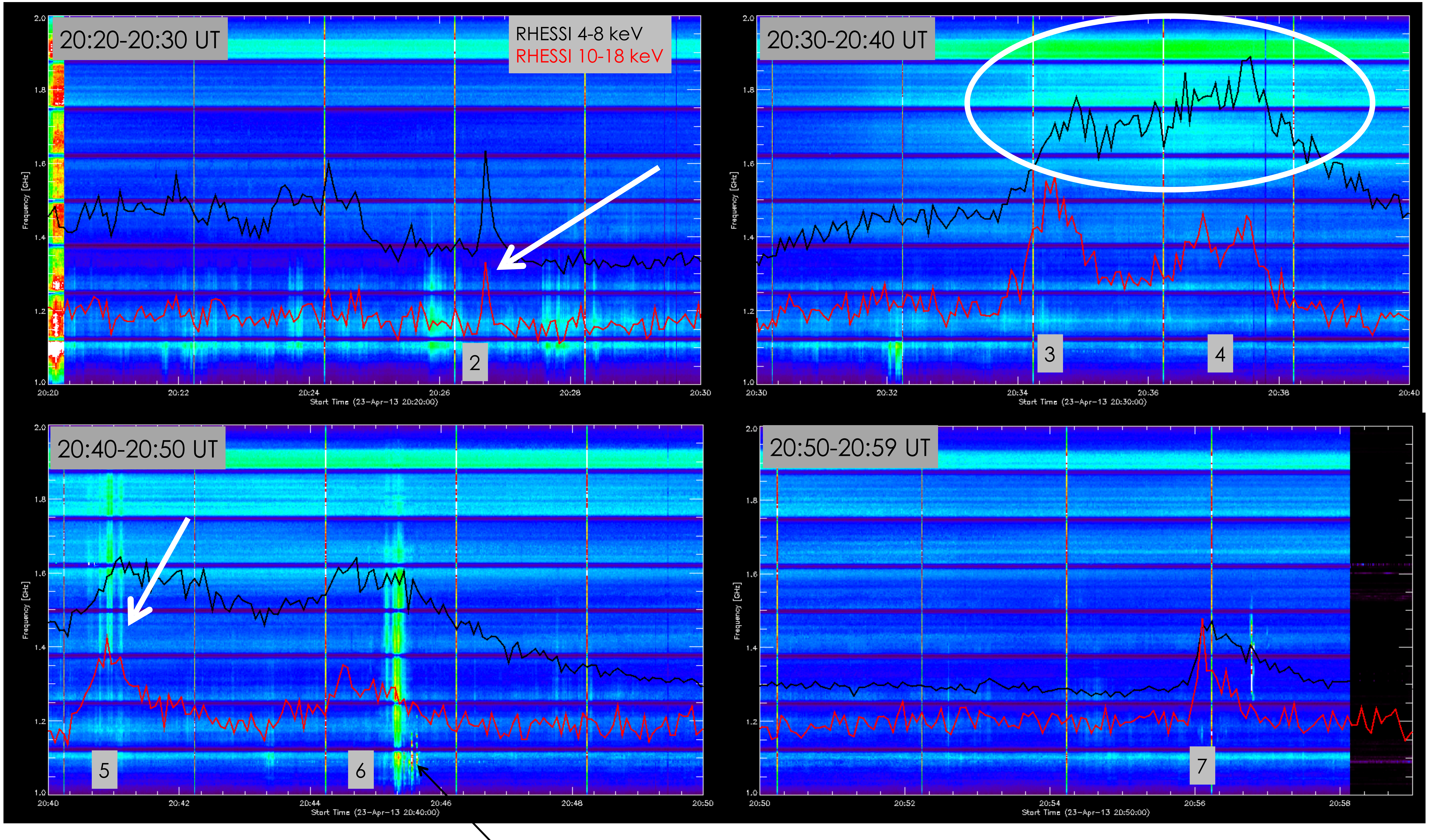


Microflares with Jansky VLA

VLA has the sensitivity to observe myriad radio bursts from microflares

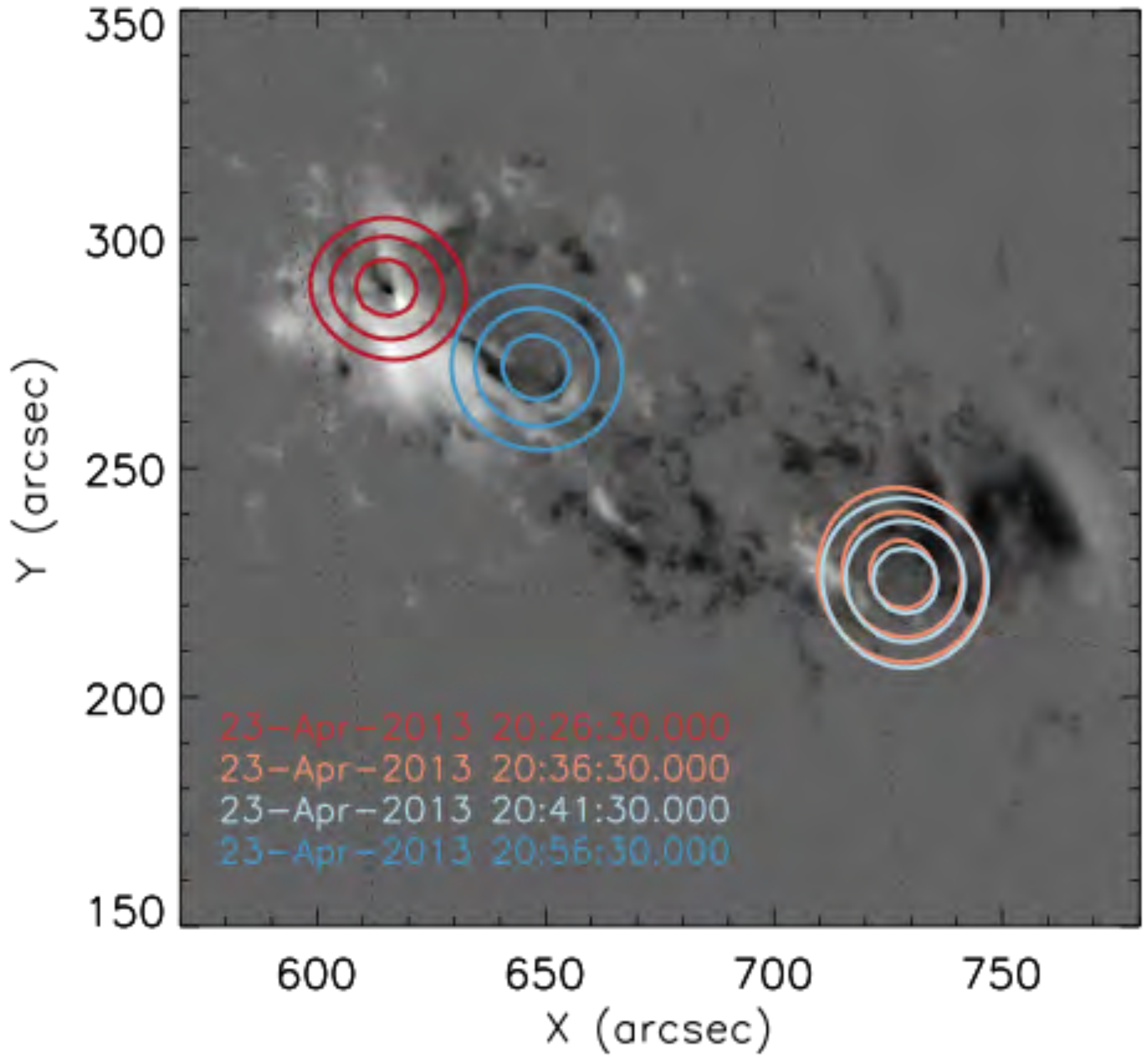


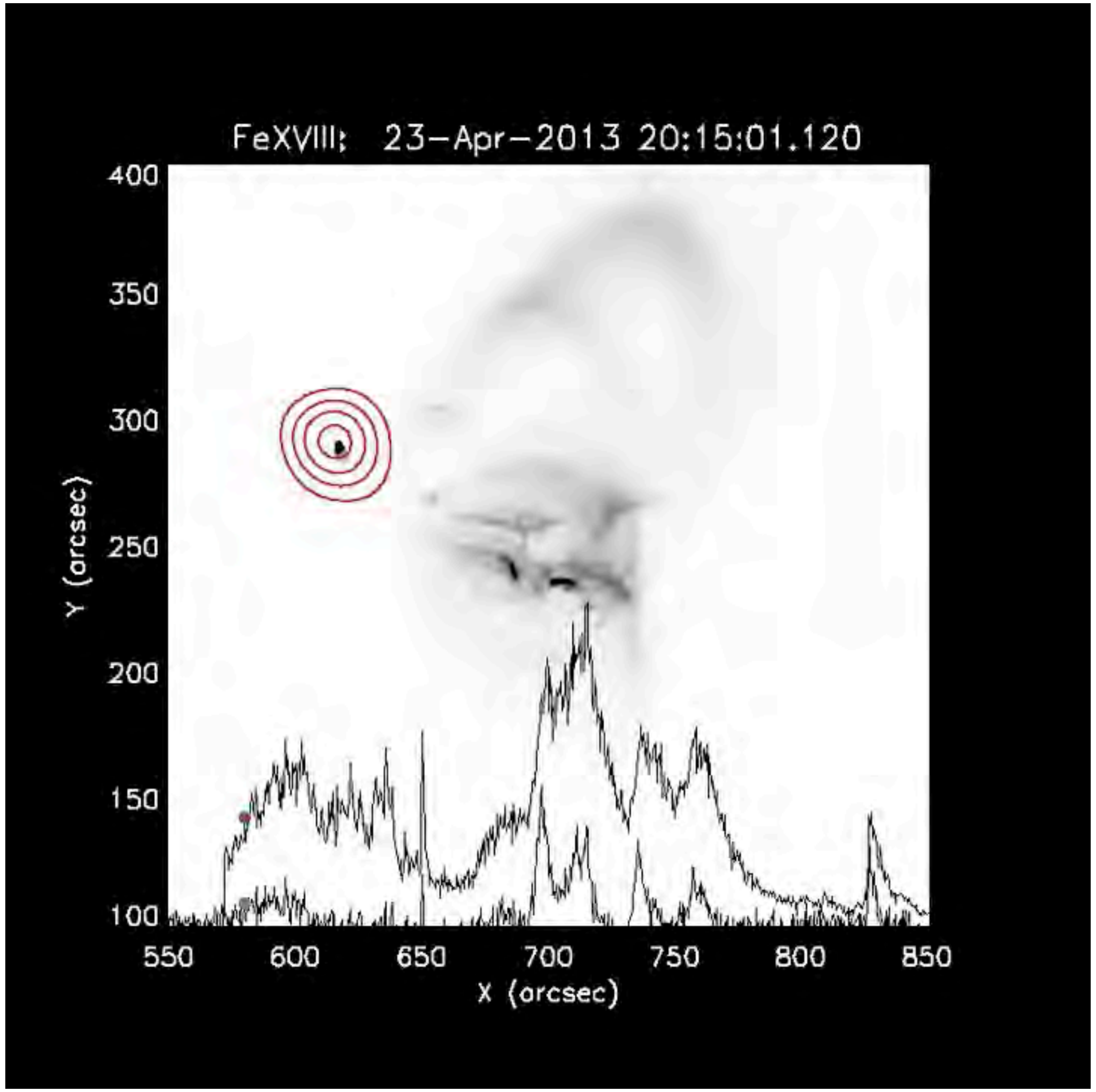
Extremely rich and diverse features at 1 GHz to 2 GHz
Some X-ray flares had associated radio emission (e.g. flare 5 and 6), others did not



Active Region and Flare Morphology

Locations of RHESSI thermal source at different times





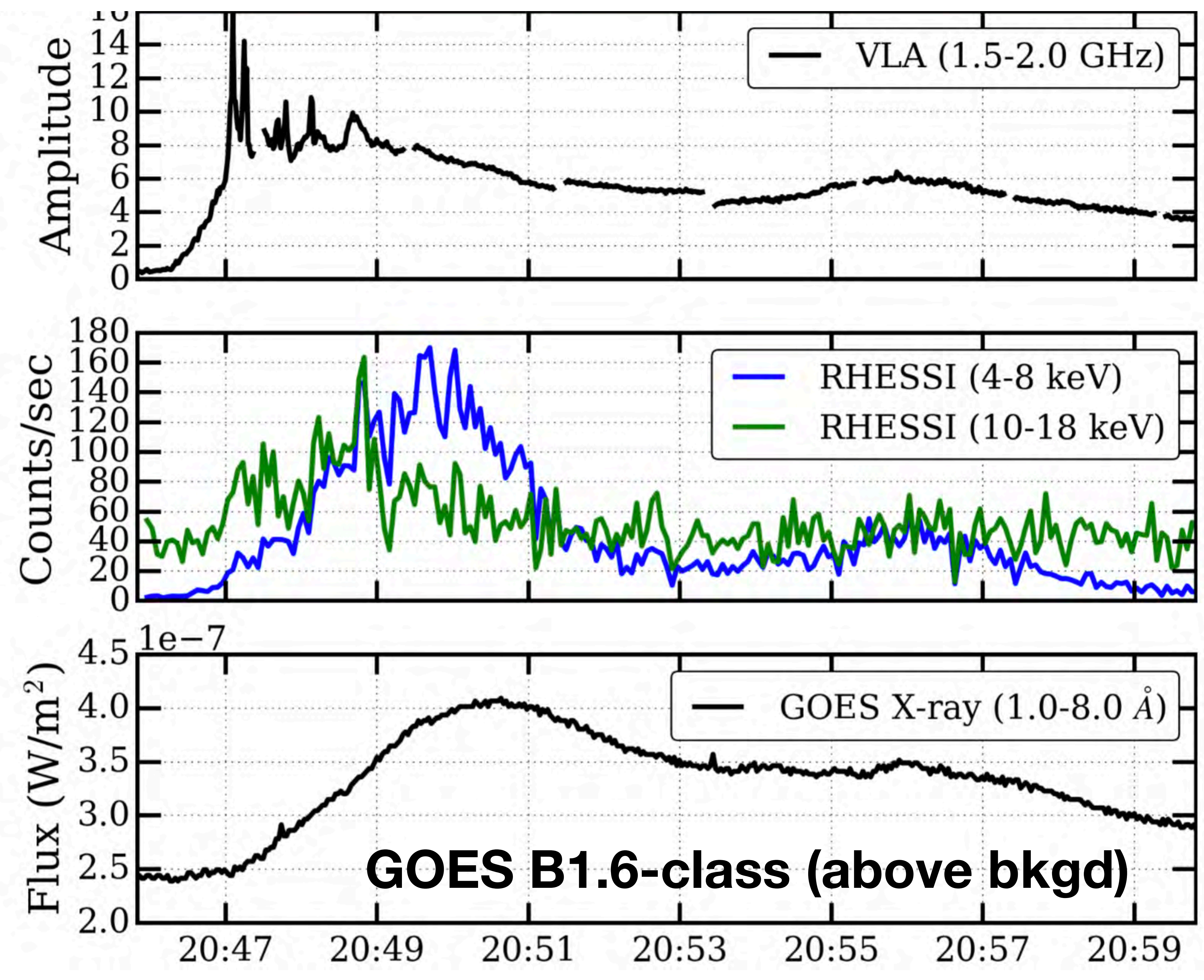
Where did the radio emission originate from?

Preliminary analysis suggests no (one-to-one) spatial correspondence between X-ray sources and radio sources at any time.

Battaglia et al., in prep

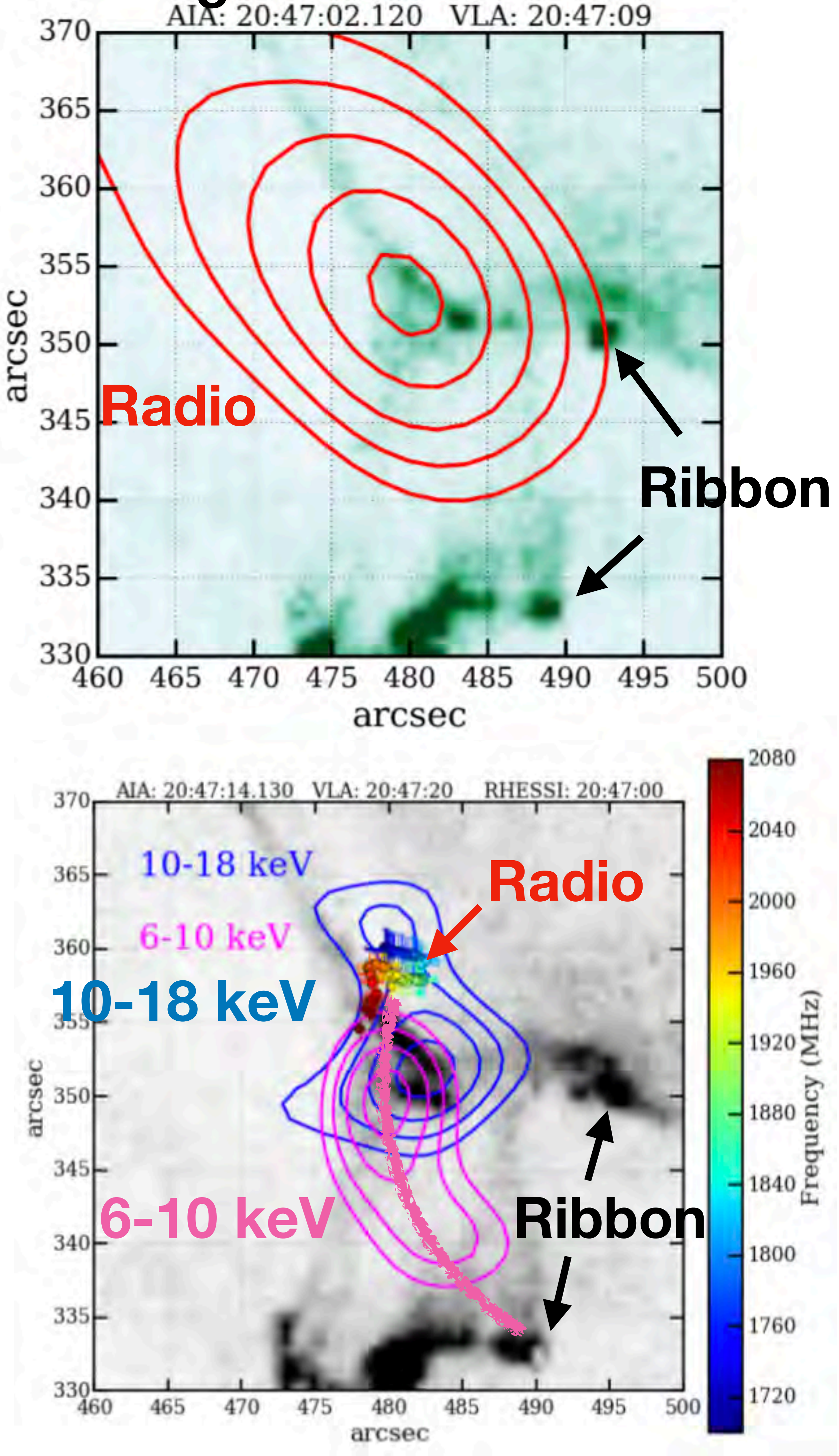
Radio Bursts in a Low B-class Microflare

Light curves

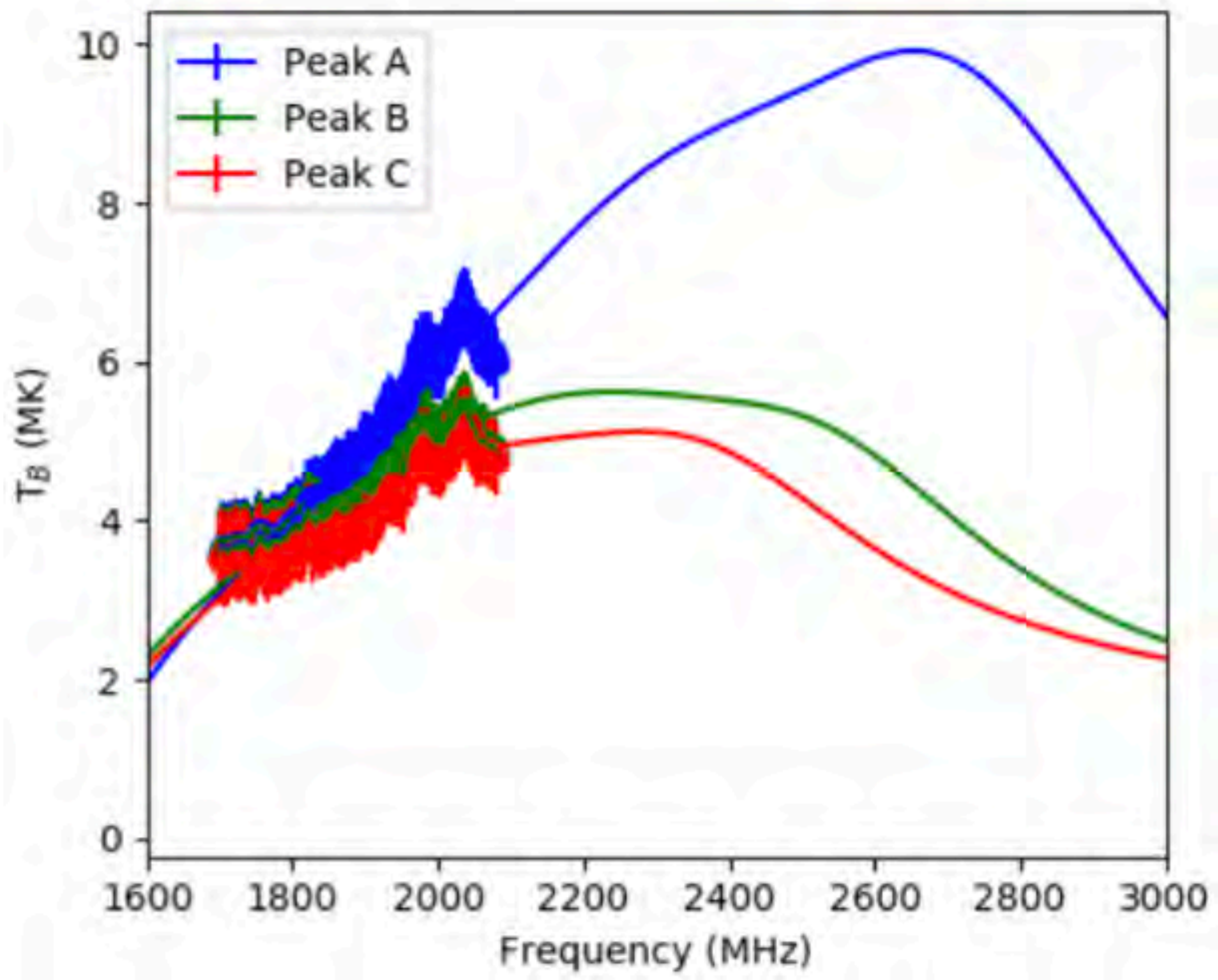


Sharma et al., in prep

Image



Spectrum



- Complex radio bursts in a two-ribbon microflare
- In X-rays, the flare has a footpoint at higher energies (10-18 keV) and a 6-10 keV source resembling a flare arcade
- Radio source co-located with HXR footpoint source
- Radio source likely due to gyrosynchrotron radiation near the footpoint where B is rather strong

Concluding Remarks

- Solar radio astronomy has entered a new era. Thanks to the new instruments (VLA, ALMA, EOVSA, LOFAR, MUSER…) that provide **broadband radio imaging spectroscopy**

- Exciting new opportunities in solar physics
  - **Jansky VLA** only demonstrates a small subset of science we could do with this technique

- **Expanded Owens Valley Solar Array**
  - Frequency agile, covering 1-18 GHz
  - Currently most advanced in microwaves, but has limited number of elements (13 2.1-meter antennas; difficult to achieve high-fidelity snapshot imaging of flaring and non-flaring Sun → particularly important for measuring coronal magnetic field)

- What we would like to have: **Frequency Agile Solar Radiotelescope (FASR)**
  - Large number of antennas (50-100) for good instantaneous UV coverage
  - Frequency coverage as wide as possible, from 10s MHz to 10s of GHz
  - Adequate spectral resolution (~1%) + sub-second time cadence
  - Technology ready; Recommended by **four decadal surveys** as a high-priority mid-scale project: most recently Astro2010 + Solar and Space Physics Decadal Survey 2013)

Thank you