PIERRE AUGER OBSERVATORY

AERA Auger Engineering Radio Array

Universidade Federal do Rio de Janeiro

Universidade Federal Fluminense

Study of solar activity with AERA data

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Speaker: Julian Rautenberg

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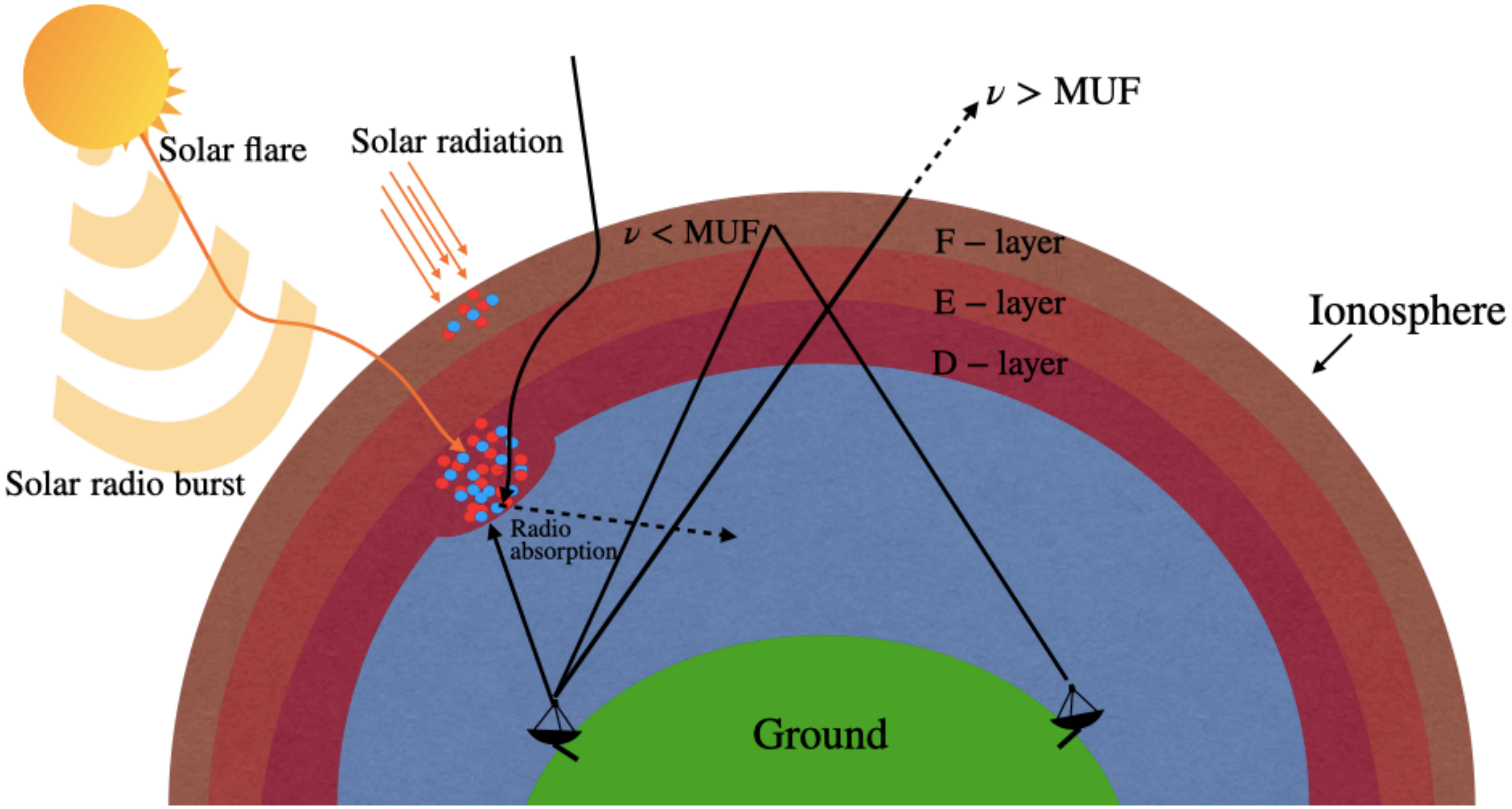
Overview

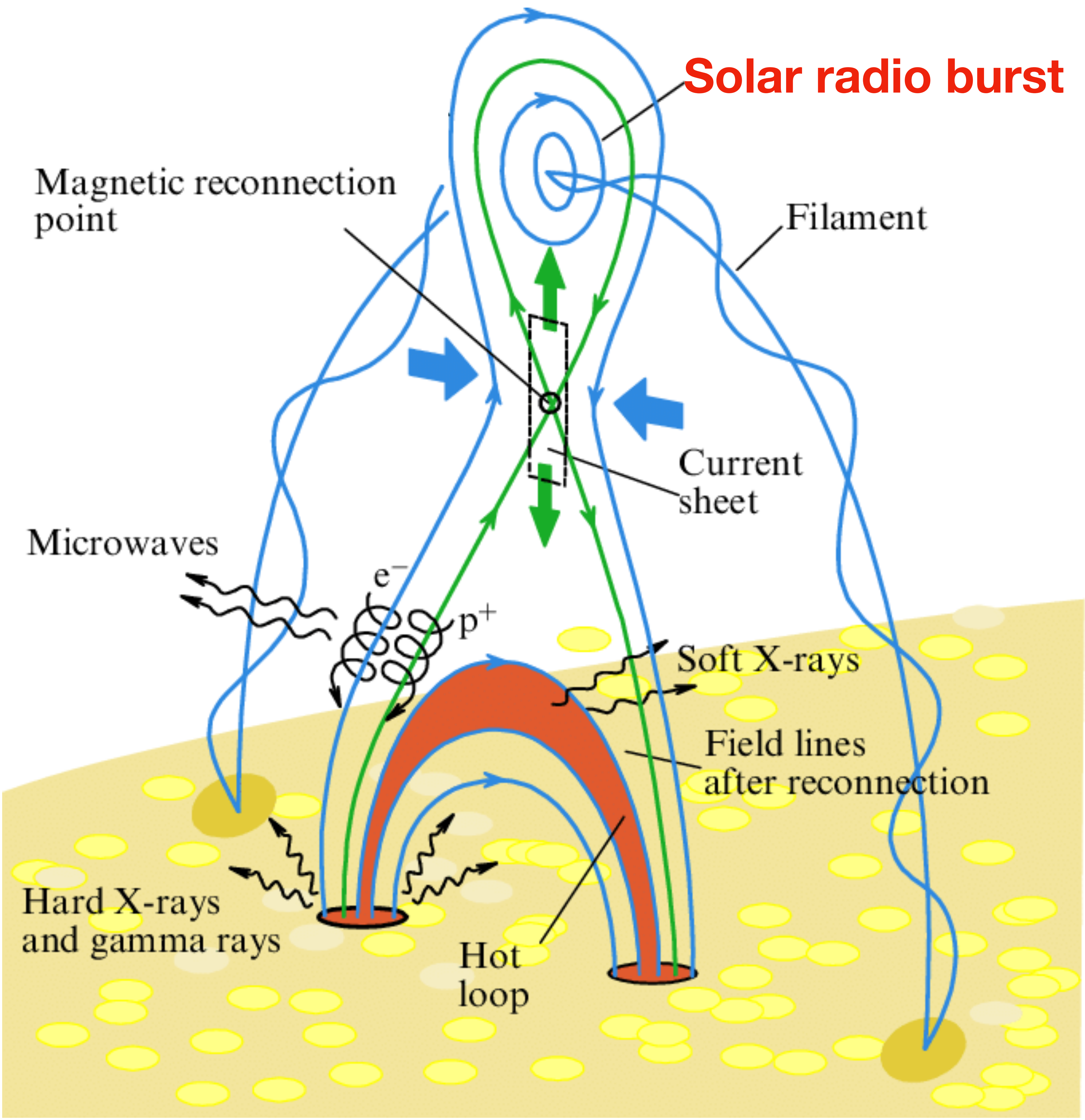
AERA frequency range (30-80 MHz) corresponds to radio emission from sources located in the upper solar corona.

- We investigate the effects of solar activity on AERA data:
  - Variation in the maximum usable frequency (MUF)
  - Radio blackout

  } Indirectly, resulting from changes in the ionosphere

  - Solar Radio Burst (directly)



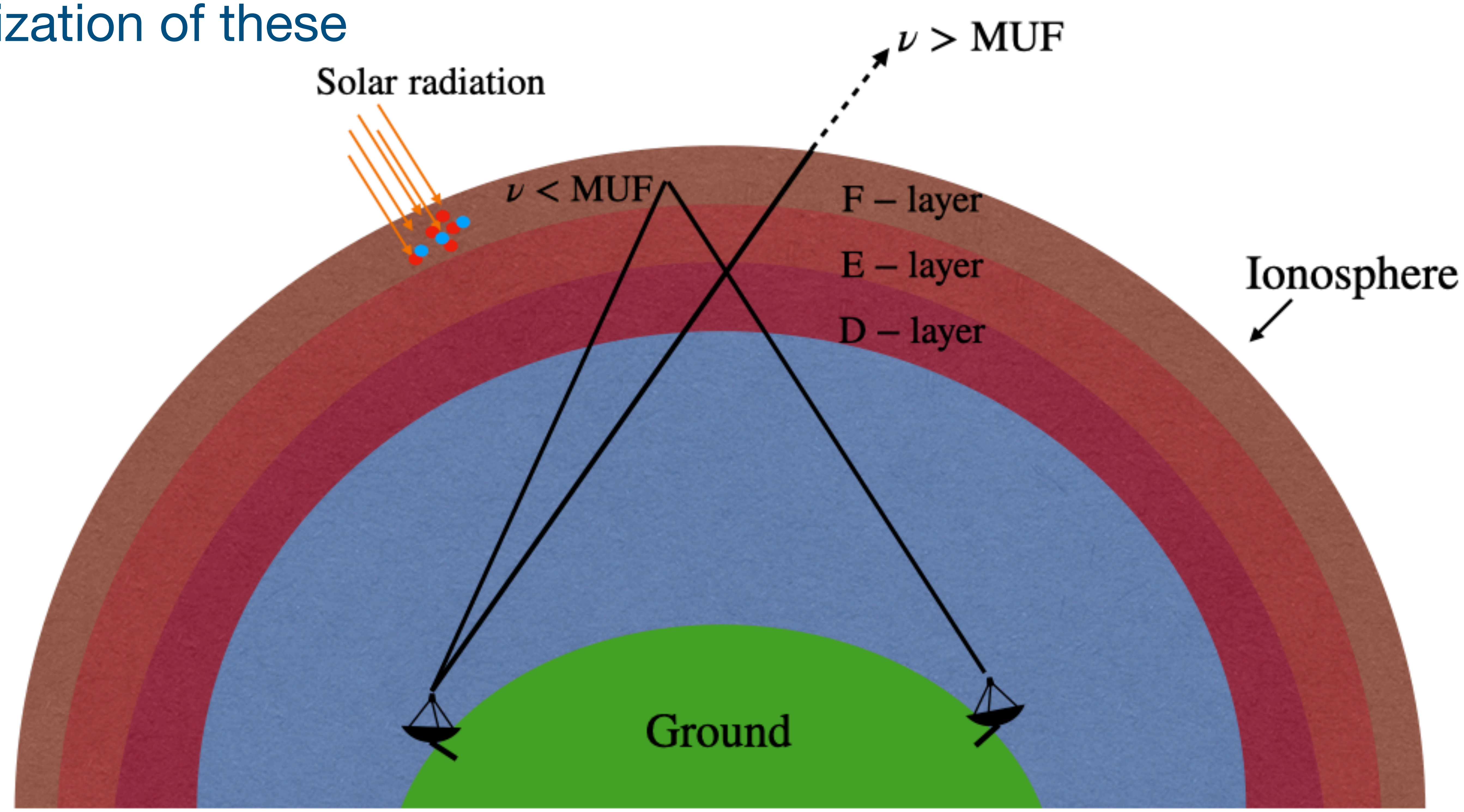


X-ray and gamma-ray emission of solar flares. Physics-Uspekhi. 63. 10.3367/UFNe.2019.06.038757

Maximum Usable Frequency - MUF

- Maximum Usable Frequency (MUF) represents the highest frequency that can be used for radio communication between two points located at Earth taking into account ionospheric conditions.
- The MUF is mainly influenced by the electron density in the ionosphere. When the electron density is high, the MUF is also high, allowing higher frequencies to be used for long-distance radio communication as these waves are reflected by the ionosphere.

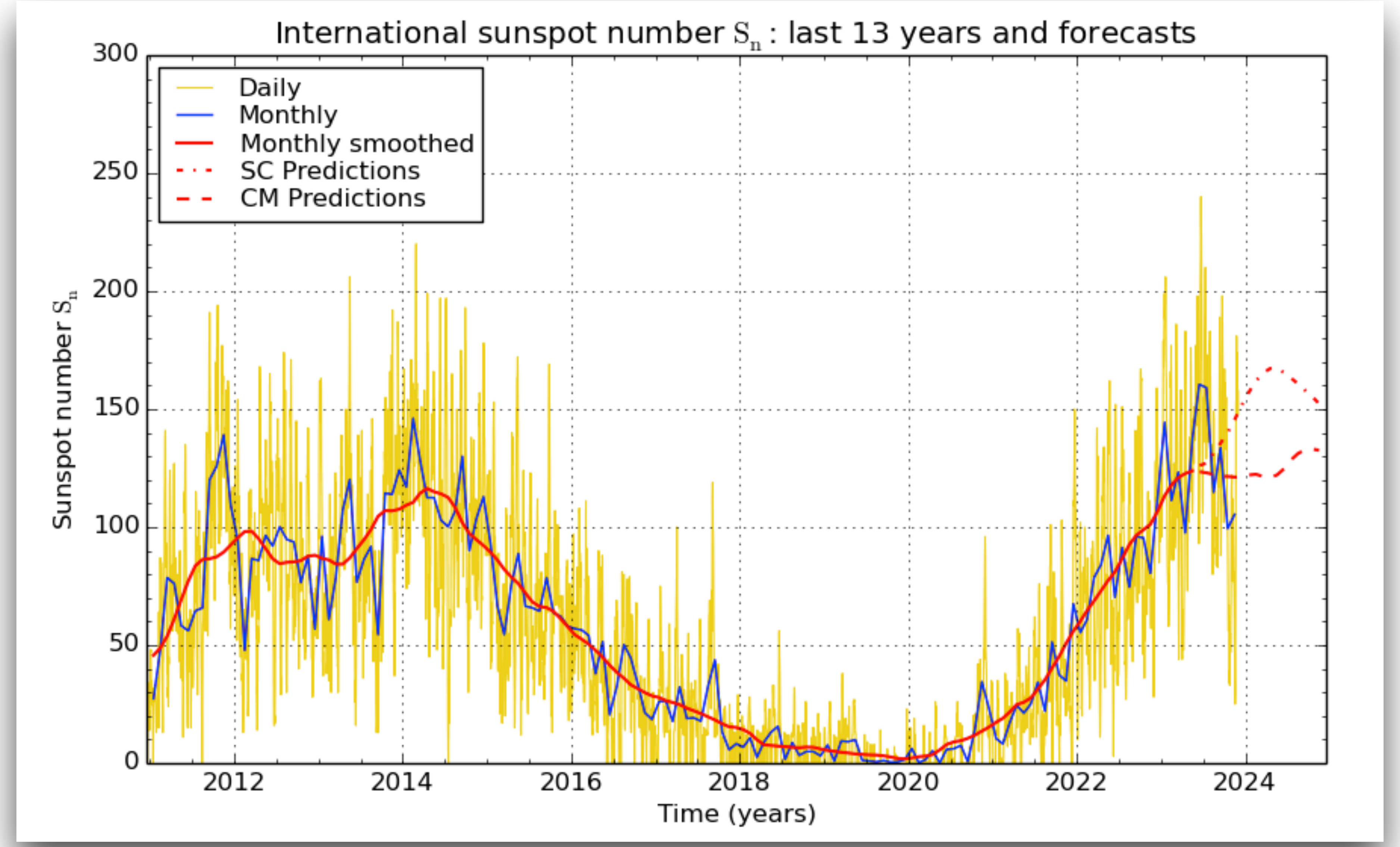
- During periods of high solar activity, the intensification of ultraviolet radiation results in a substantial increase in the ionization of these layers.
- For frequencies above the MUF, the atmosphere becomes transparent, allowing the radio wave to pass through the F layer.



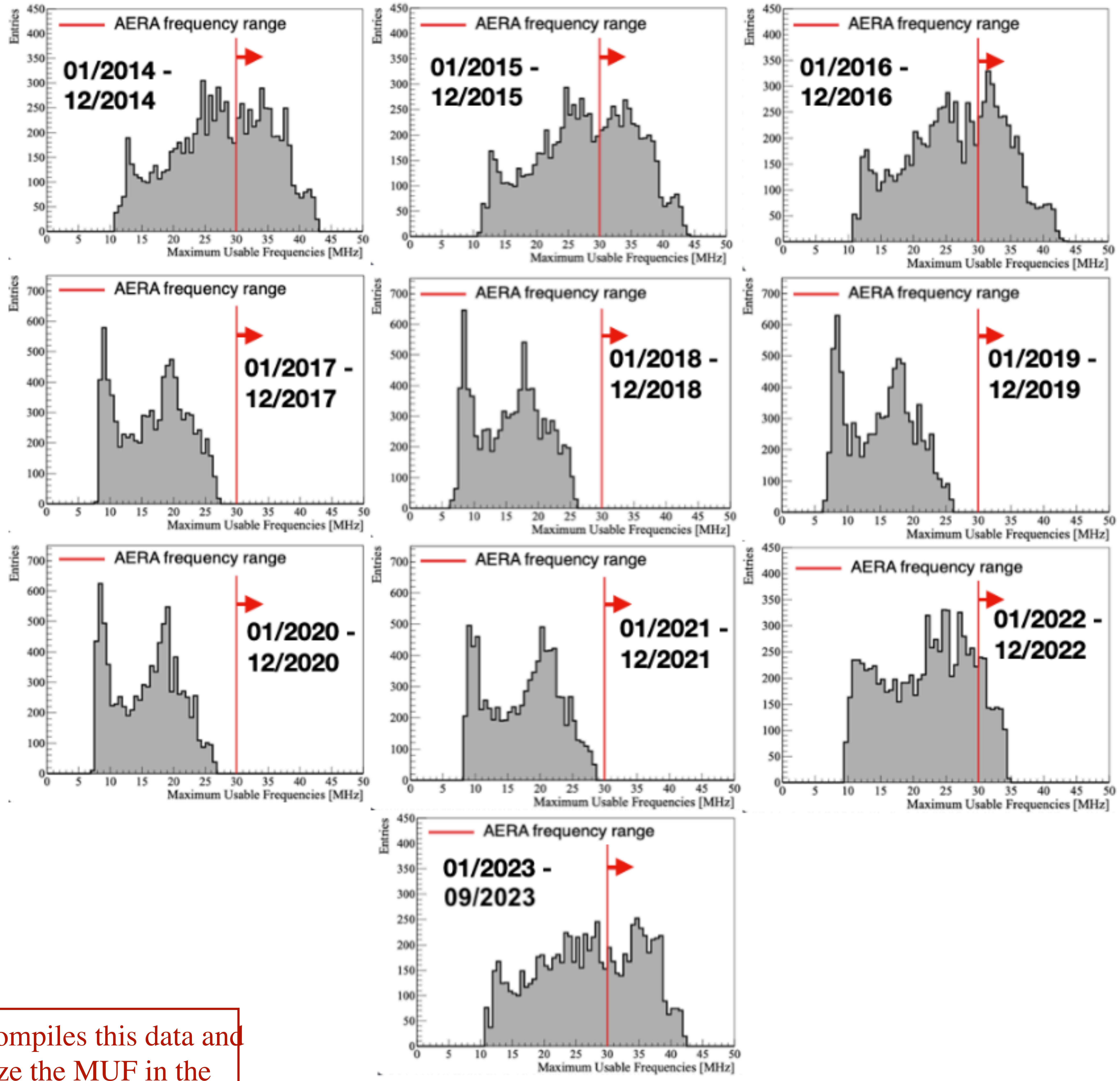
The Maximum Usable Frequency is monitored locally through various stations around the world. https://prop.kc2g.com/

MUF as a function of years

- Distribution of MUF for the region of Malargue recorded at every hour over the years 2014 to September 2023.
- MUF > 30 MHz was recorded in all periods of high solar activity (2014 to 2016 and after 2021).



Source: WDC-SILSO, Royal Observatory of Belgium, Brussels



The IRI software, available at https://kauai.ccmc.gsfc.nasa.gov/instantrun/iri/, compiles this data and interpolates to obtain the MUF in any region of the world. In this study, we utilize the MUF in the Malargüe region with coordinates: Latitude: -35.47, Longitude: -69.58.

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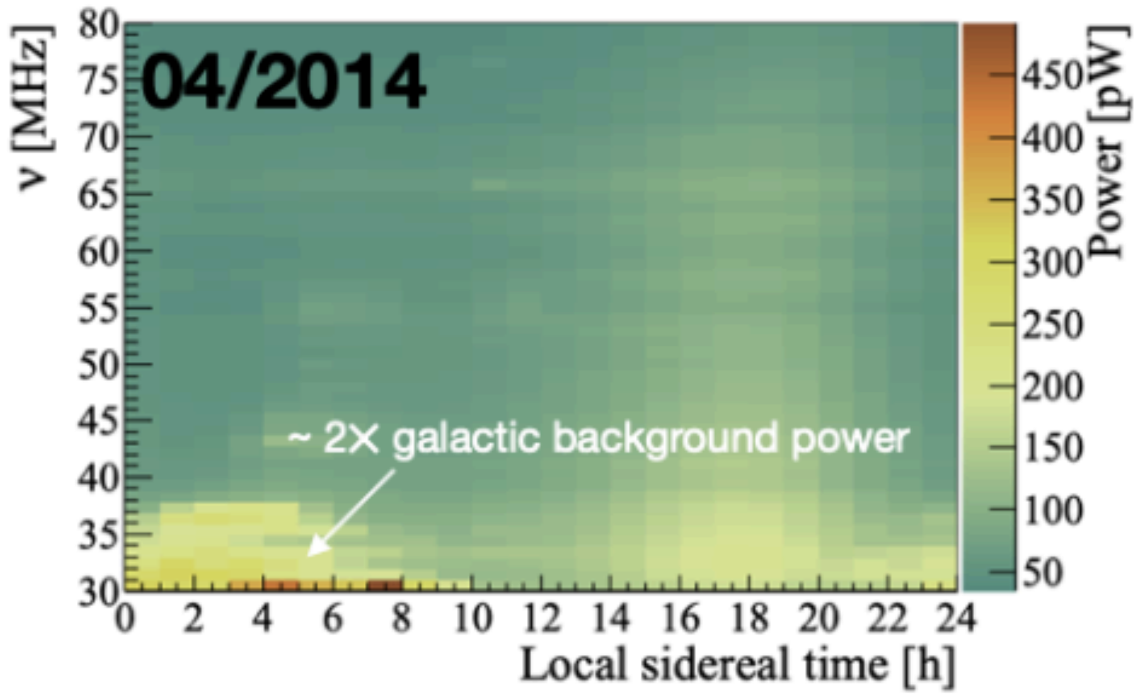

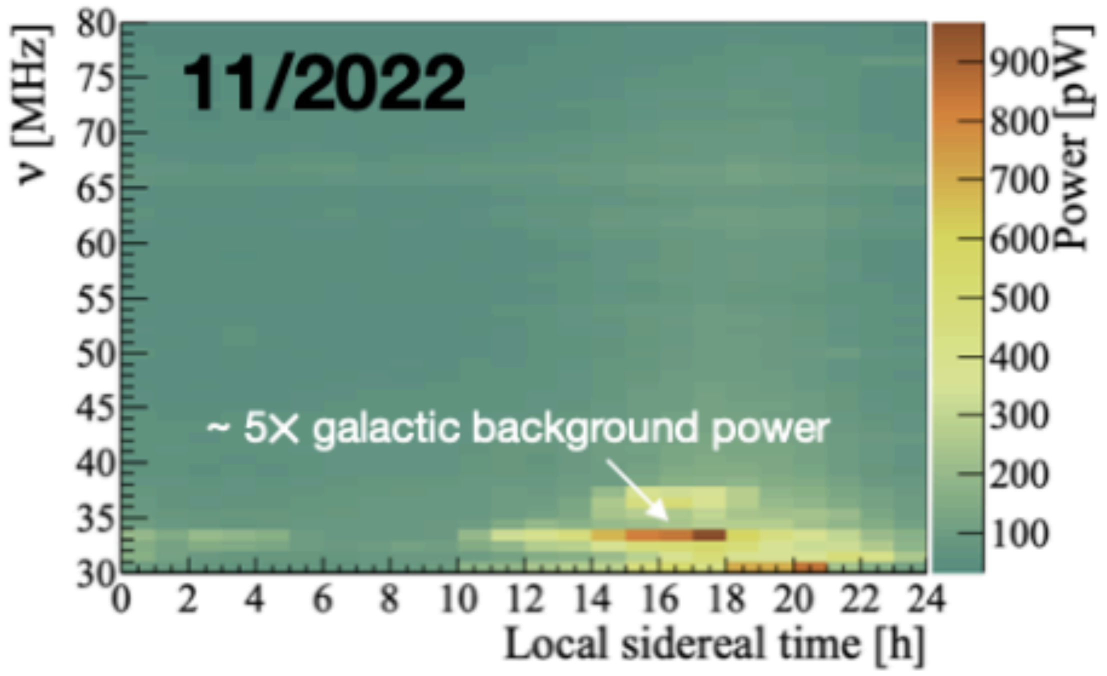

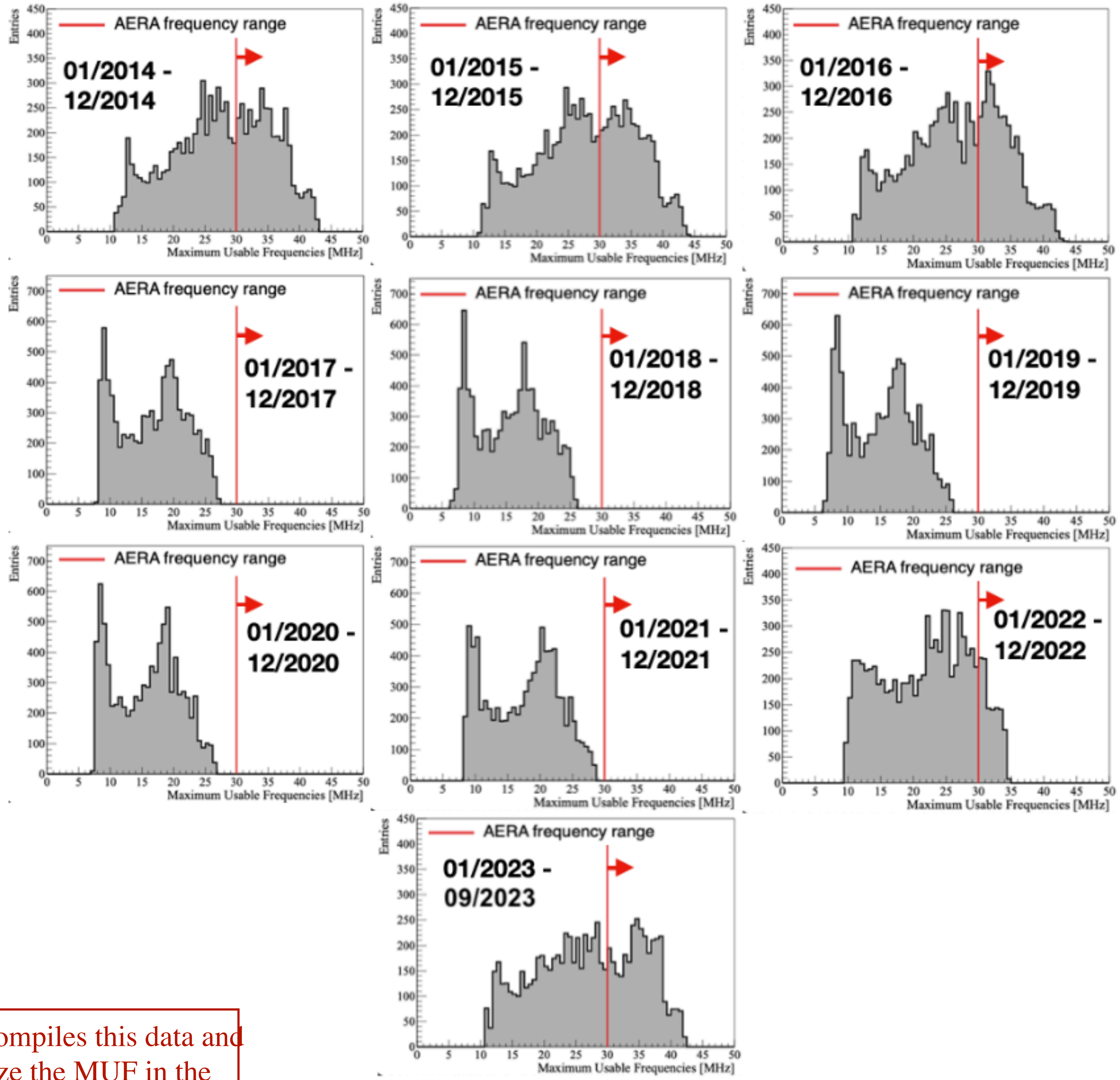

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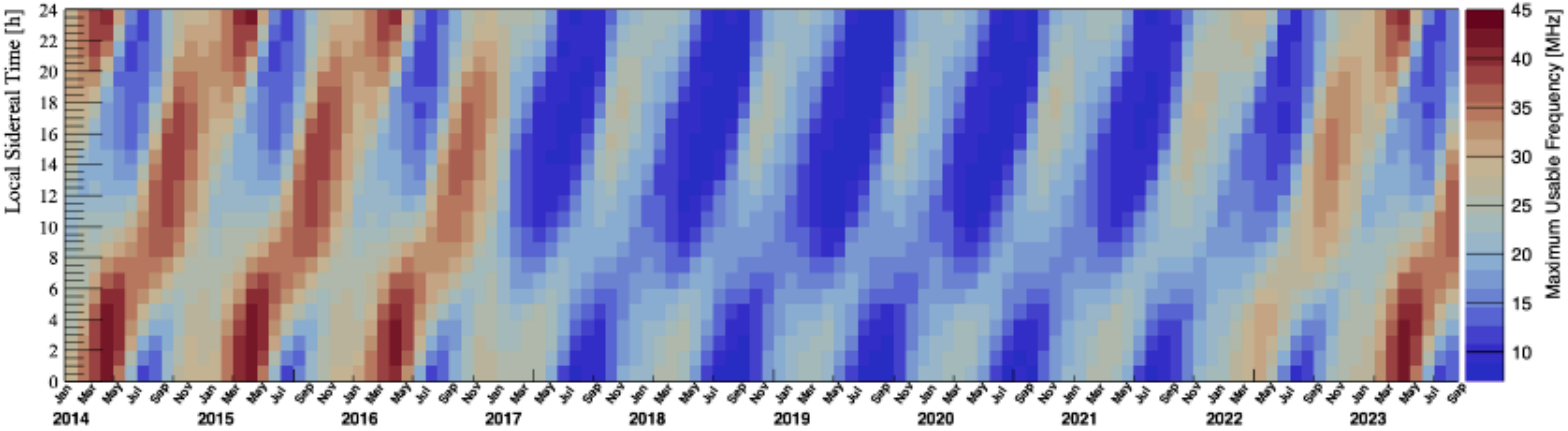
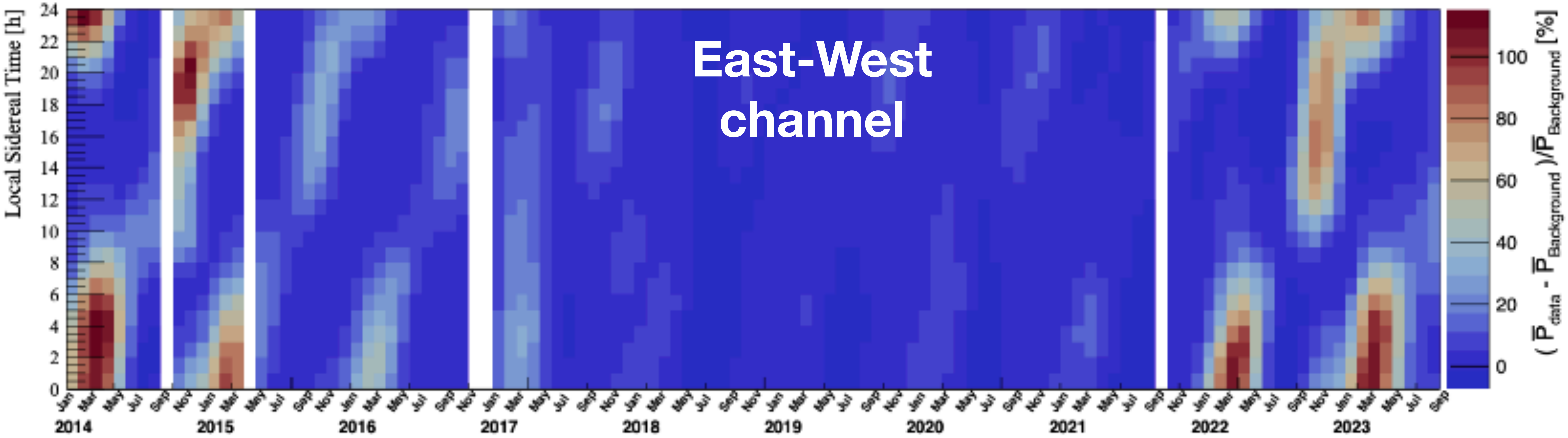
Correlation between MUF and broadband noise measured by AERA within the 30-40 MHz frequency range



Maximum usable frequency

MUF

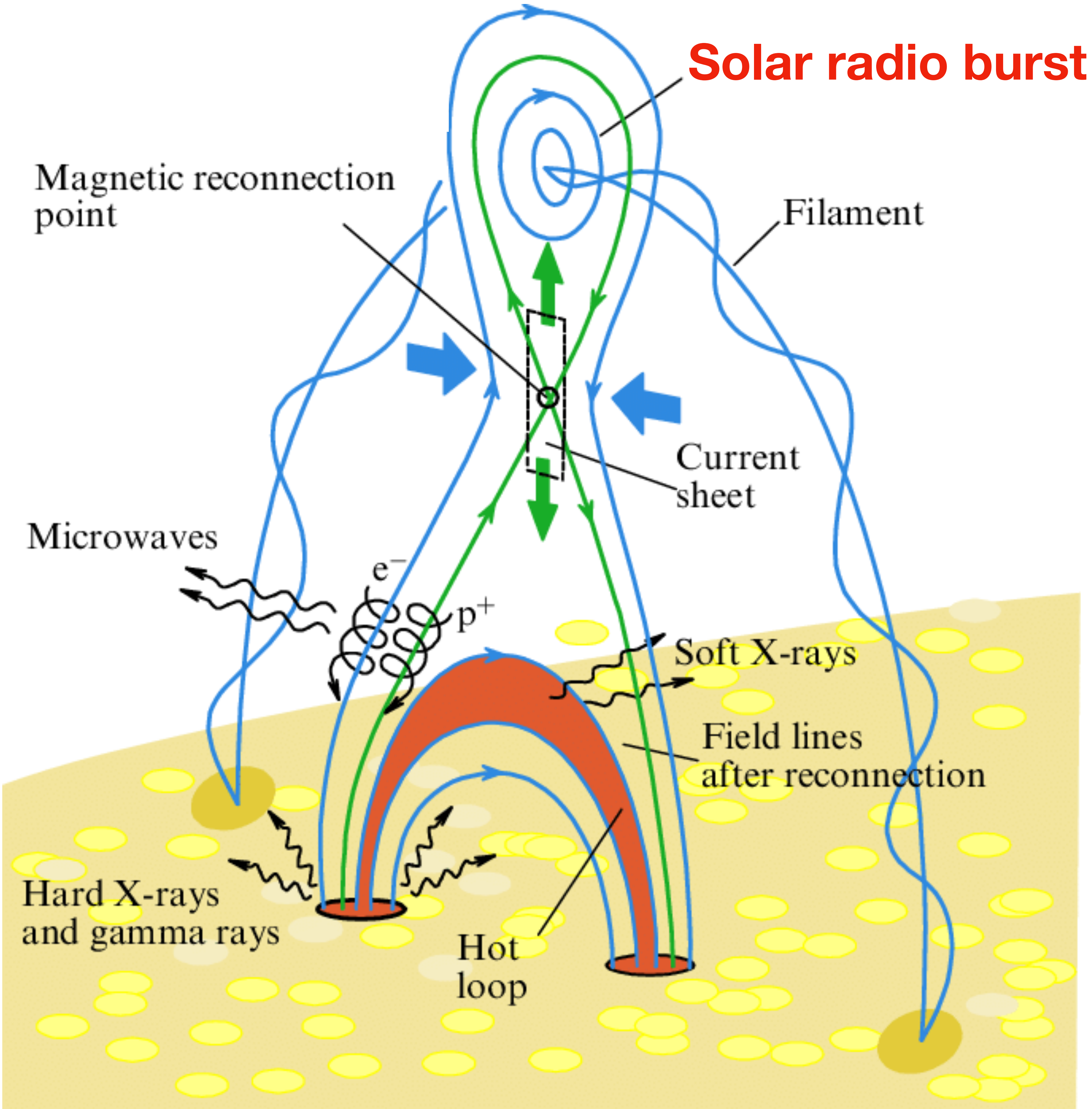


AERA data (30 - 40 MHz)

$$\frac{\bar{P}_{\mathrm{data}} - \bar{P}_{\mathrm{background}}}{\bar{P}_{\mathrm{background}}}$$

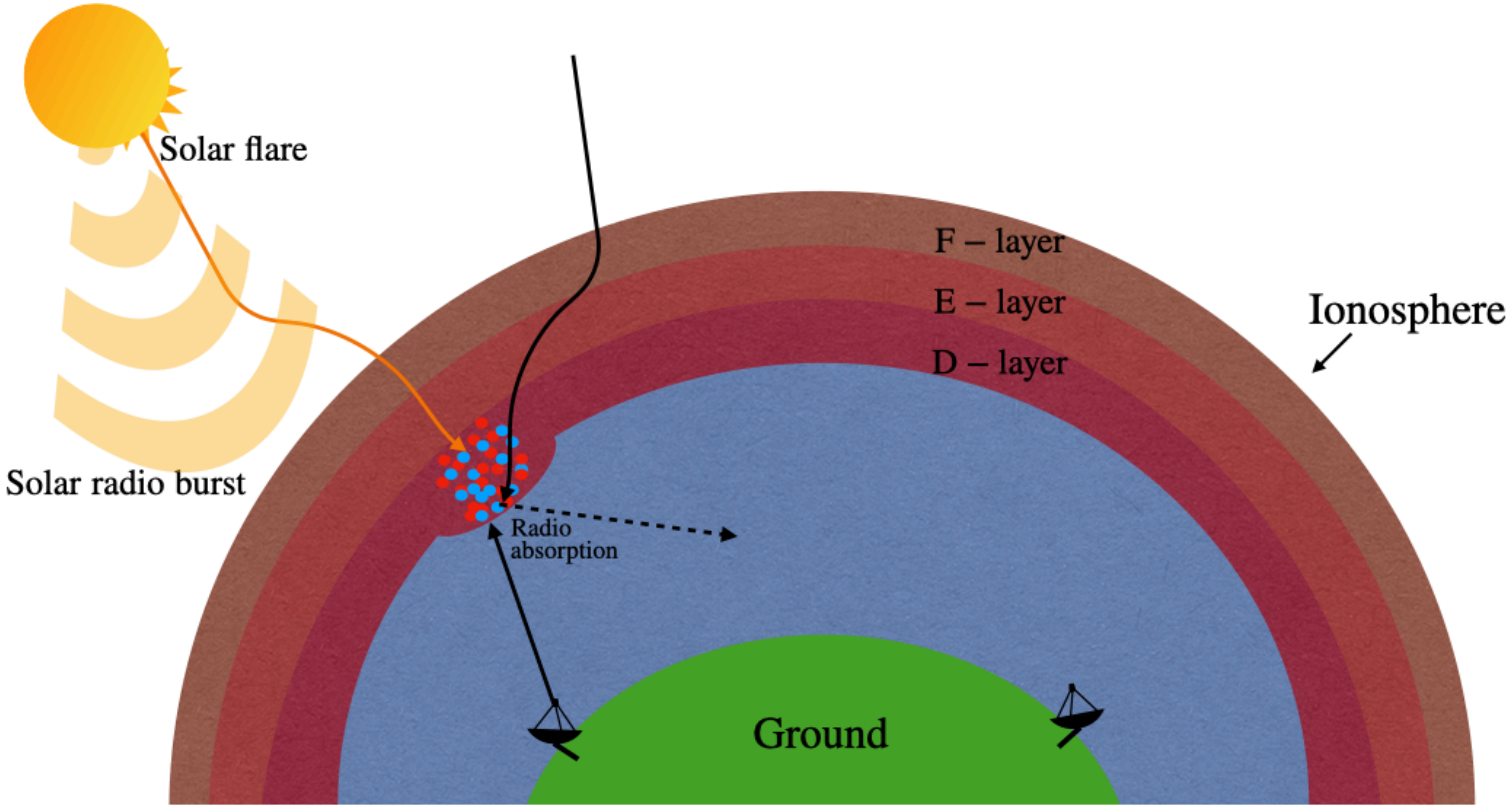
Detection of solar flares - Radio Blackout

- The increased level of X-ray and extreme ultraviolet (EUV) radiation results in ionization in the lower layers (D layers) of the ionosphere on the sunlit side of Earth. Radio waves that interact with electrons in this layer lose energy due to more frequent collisions, leading to considerable absorption. This phenomenon can result in **Radio Blackout**, where high frequency communication is impaired or completely absorbed mainly in the 3 to 30 MHz range.



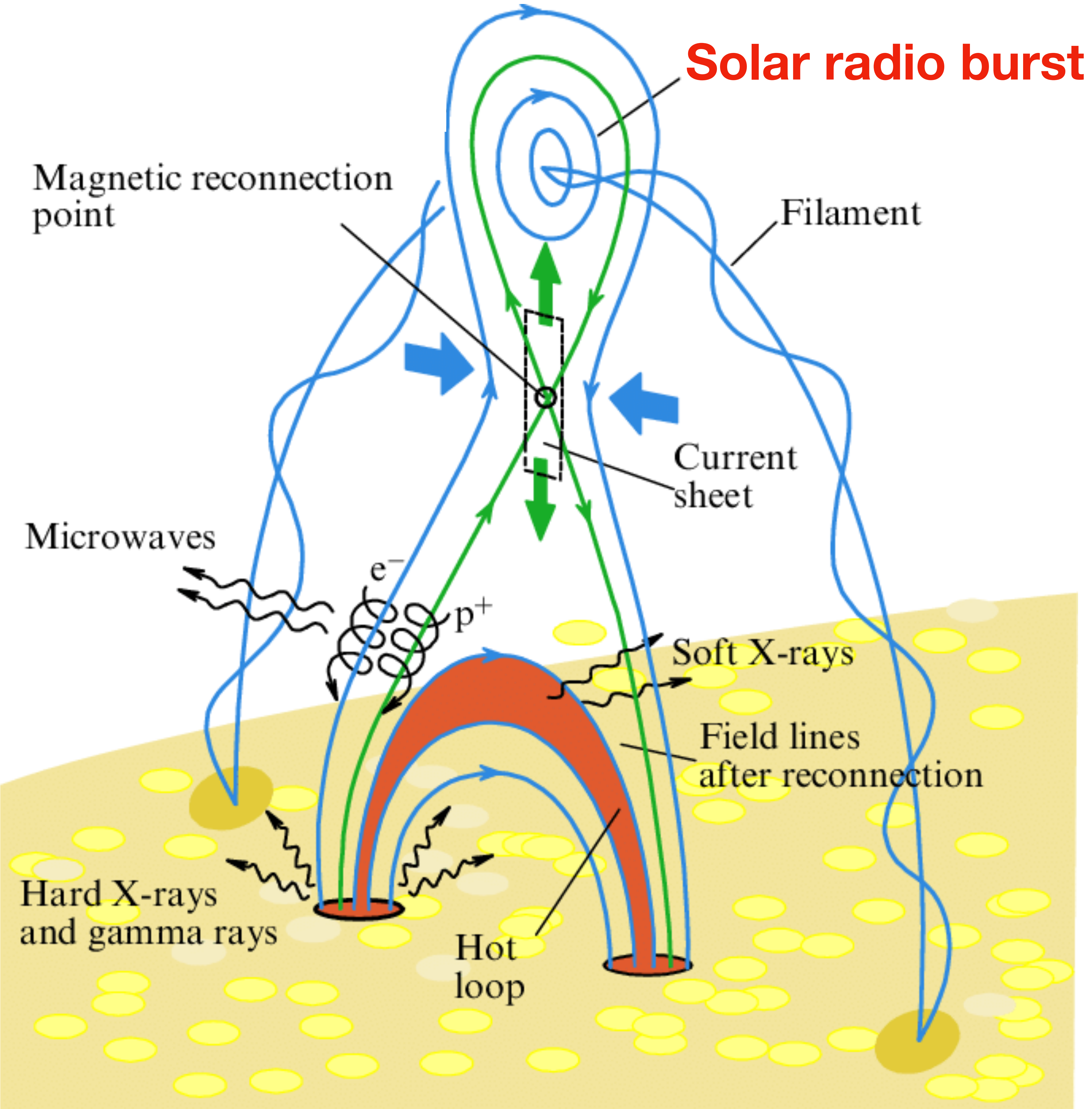
Radio blackout classification

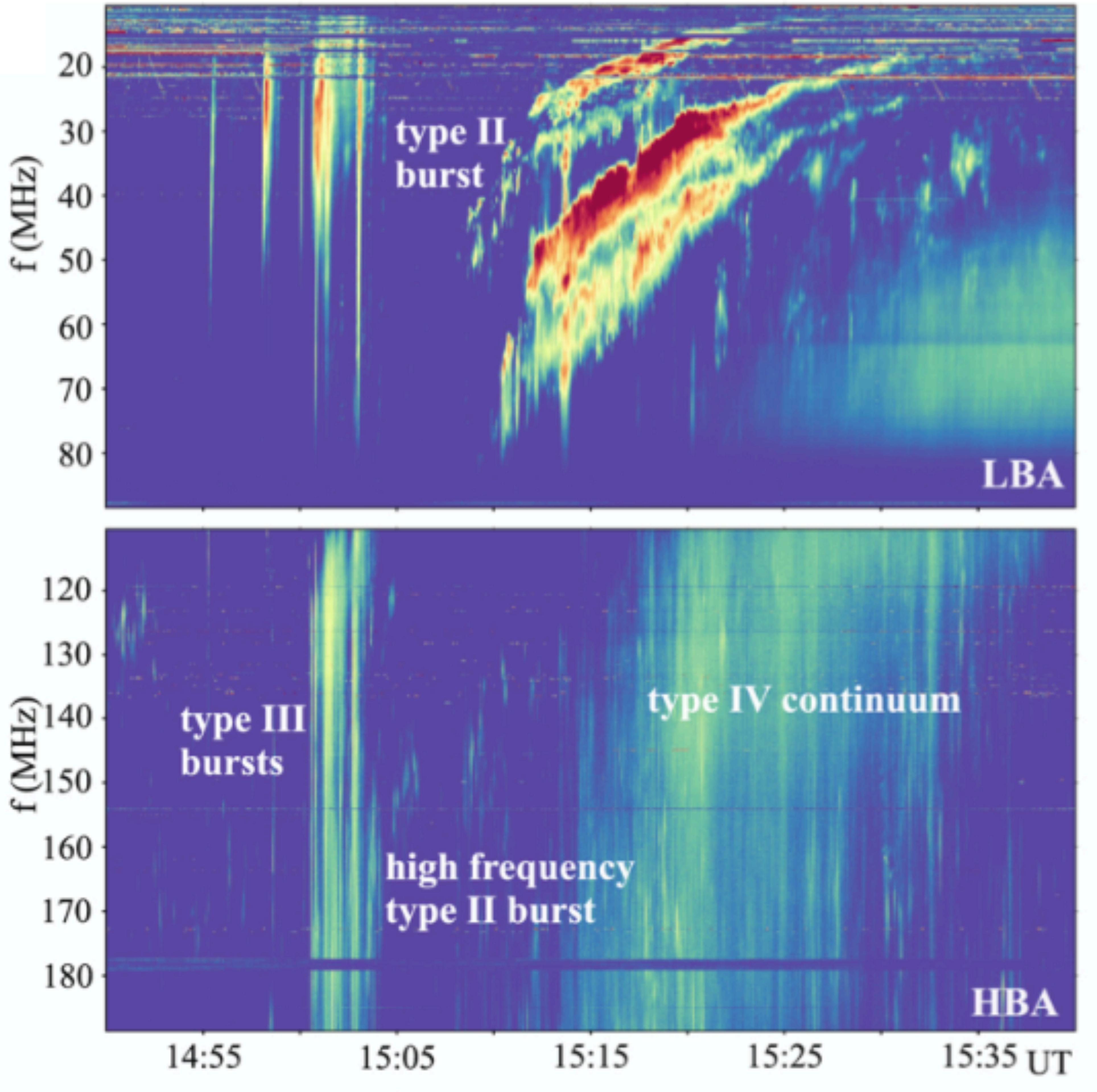
Radio Blackout	X-ray Flare	Flux (W/m^2)	Severity Descriptor
R1	M1	0.00001	Minor
R2	M5	0.00005	Moderate
R3	X1	0.0001	Strong
R4	X10	0.001	Severe
R5	X20	0.002	Extreme



Detection of solar flares - Solar Radio Burst

- Solar Radio Bursts (SRBs) are intense emissions of radio waves from the Sun, usually associated with solar eruptions.
- Directly measured by AERA





Examples from LOFAR Collaboration, ApJ 897:L15 (8pp), 2020

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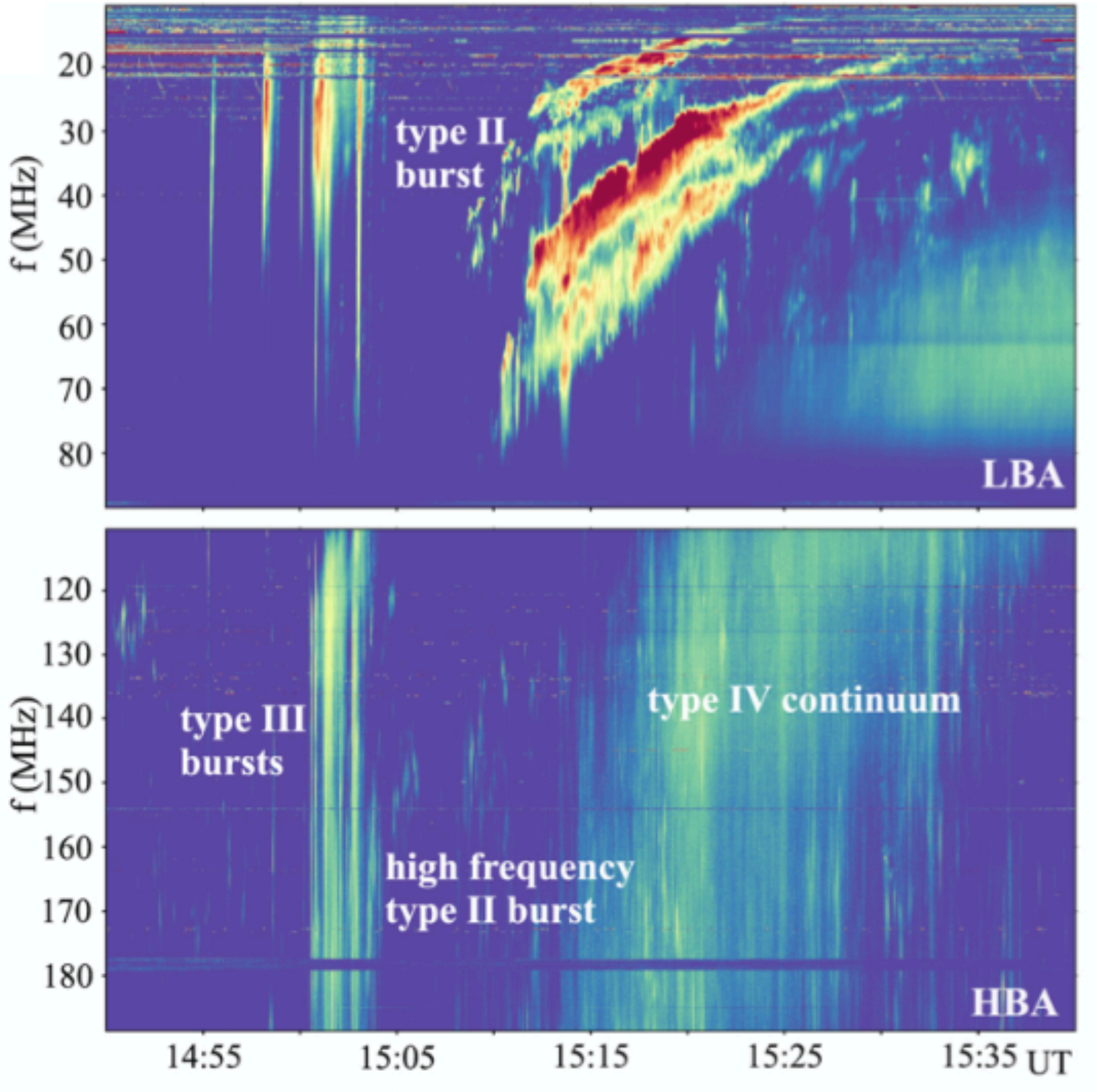
Type	Characteristics	Duration
Type I	Narrow band, observed in metric wavelength up to about 400 MHz. Associated with electron cyclotron maser instability in the corona.	0.1 to 2 seconds
Type II	Shows a slow frequency drift from high to low frequencies. Associated with electrons accelerated by shock waves from coronal mass ejections.	10 to 30 minutes
Type III	Rapid frequency drift from high to low frequencies, from hundreds of MHz to tens of MHz within seconds. Indicates energetic electrons in solar corona and wind.	10 seconds to 1 minute
Type IV	Persistent and broadband continuum emission. Associated with major solar flares, often follows Type II or III bursts.	Less than 1 hour to several days
Type V	Continuous emissions post Type III bursts. Generally below approximately 120 MHz. (Not well defined)	1 to a few minutes



Examples from LOFAR Collaboration, ApJ 897:L15 (8pp), 2020

Search for traces of solar flares with AERA Data

- We investigated 16 events reported by NOAA from 2014 to 2024 that triggered significant disturbances in radio waves and temporary interruptions due to blackouts types R2 and R3 as a proxy to search for traces of solar flares in AERA data.

- All events occurred on the sunlit side of South America

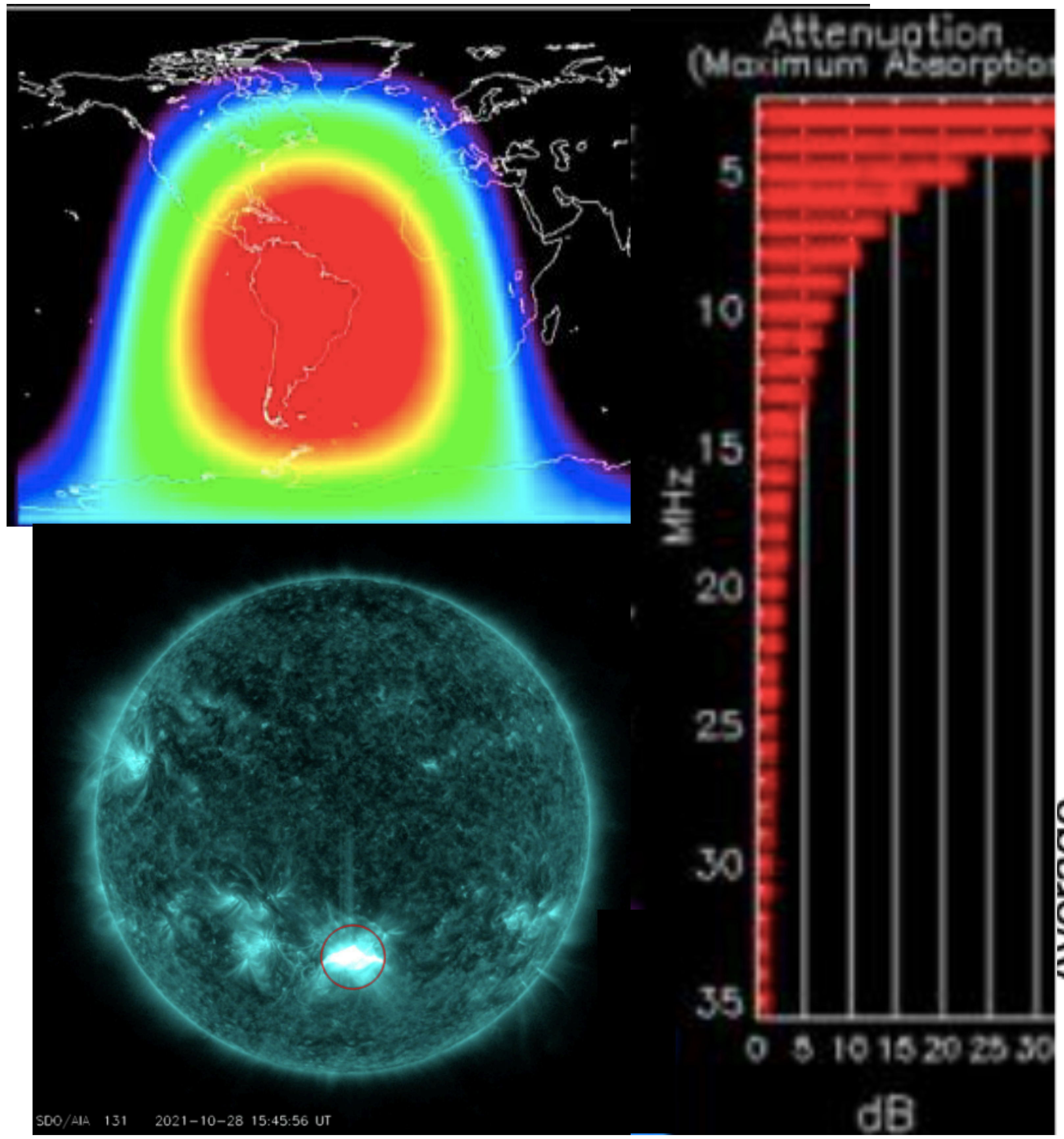
N°	Date	UTC Start	UTC Maximum	UTC End	Maximum flux	Radio Blackout	Severity Descriptor
1	2014/09/10	17:21	17:45	18:20	X2.39	R3	Strong
2	2014/10/02	18:49	19:01	19:14	X1.05	R3	Strong
3	2014/10/22	14:02	14:28	14:50	X2.39	R3	Strong
4	2014/10/27	14:12	14:47	15:09	X2.96	R3	Strong
5	2017/09/10	15:35	16:06	16:31	X11.88	R3	Strong
6	2021/07/03	14:18	14:28	14:34	X1.59	R3	Strong
7	2021/10/28	15:17	15:35	15:48	X1.0	R3	Strong
8	2022/03/31	18:17	18:35	18:45	M9.67	R2	Moderate
9	2023/02/11	15:40	15:48	15:54	X1.1	R3	Strong
10	2023/02/28	17:35	17:50	17:56	M8.62	R2	Moderate
11	2023/03/03	17:42	17:52	17:59	X2.07	R3	Strong
12	2023/11/28	19:35	19:50	20:09	M9.82	R2	Moderate
13	2023/12/14	16:47	17:02	17:12	X2.87	R3	Strong
14	2024/05/09	17:23	17:44	18:01	X1.1	R3	Strong
15	2024/05/14	16:46	16:51	17:02	X8.79	R3	Strong
16	2024/05/15	14:20	14:38	14:51	X2.9	R3	Strong

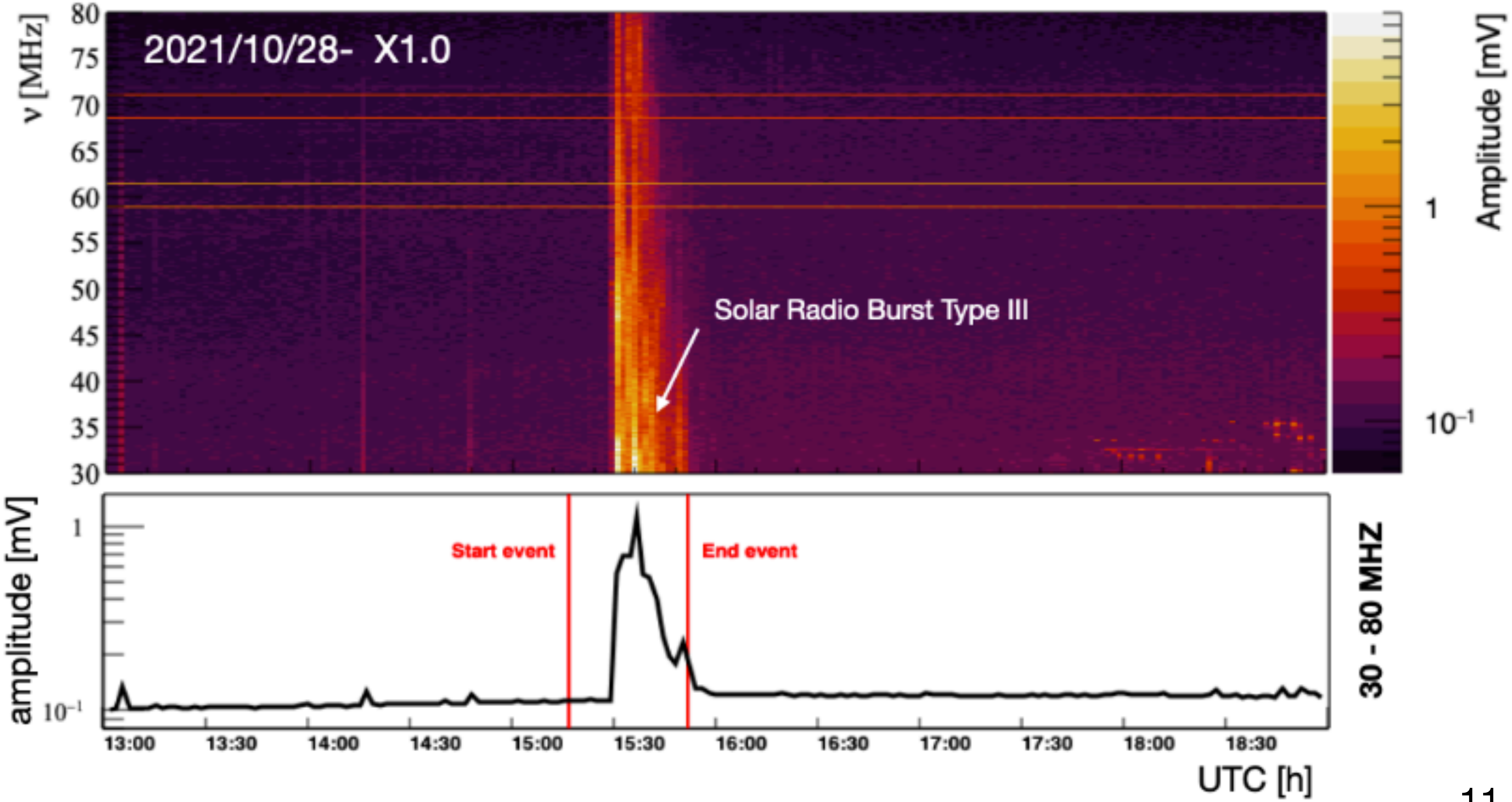
3 new events last month (events 14–16)

Large solar flares, with possible radio blackouts, are monitored and recorded by the National Oceanic And Atmospheric Administration (NOAA) https://www.swpc.noaa.gov/

Detection of SRBs with AERA Data

- Event Number 6, classified with **intensity X1.0**, triggered a SRB and lasted for 31 minutes. Throughout its occurrence, this event left a clear signature in the average dynamic frequency spectrum measured by AERA, covering the entire range of frequency.
- We can clearly see the type III SRB characteristic signature of this even precisely during the flare occurrence. The bottom panel highlights the signal average over the whole frequency range as a function of time, providing another view of the peak associated with the event.

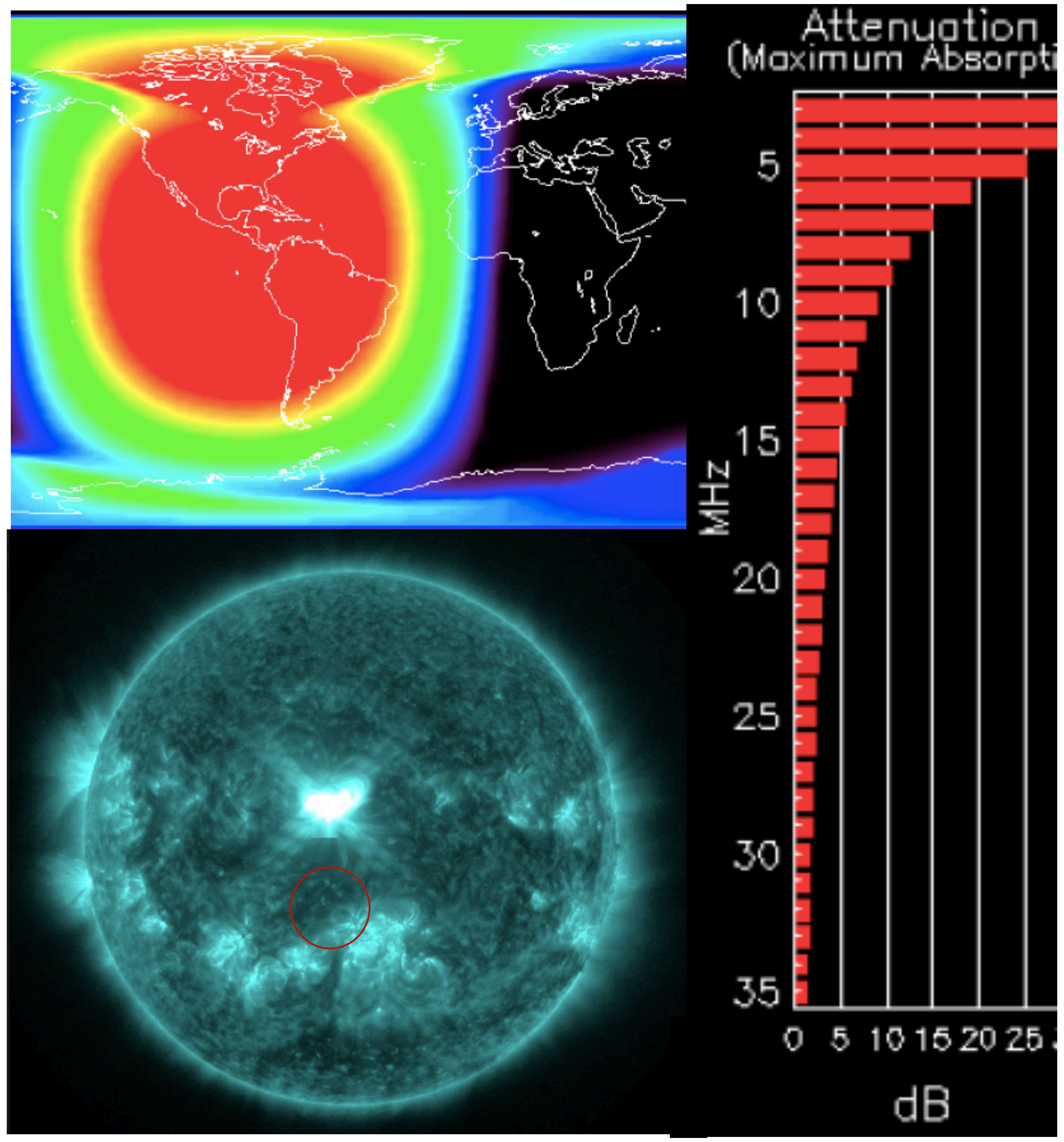




https://www.swpc.noaa.gov/news-archive

Detection of SRBs with AERA Data

- Event Number 1, of **intensity X2.39**, exhibited a signature of a type III SRB characterized by its well-defined location and rapid frequency drop. The signature appears within the first 10 minutes of the start of the event. Additionally, during this event, we also observed the presence of a type IV solar radio burst, which extended for more than 4 hours after the initial burst, leaving a distinct and solid signature in the data.



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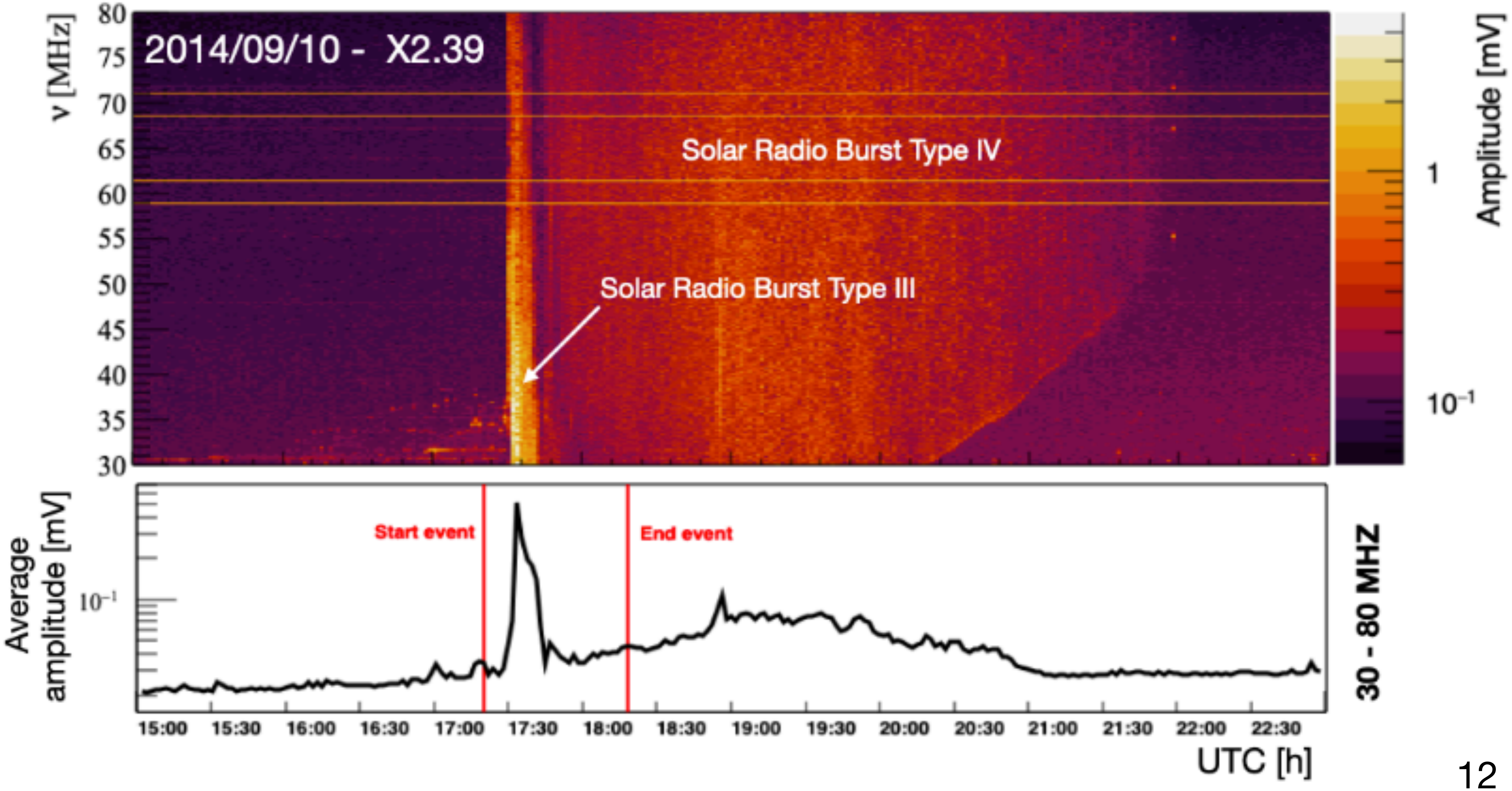
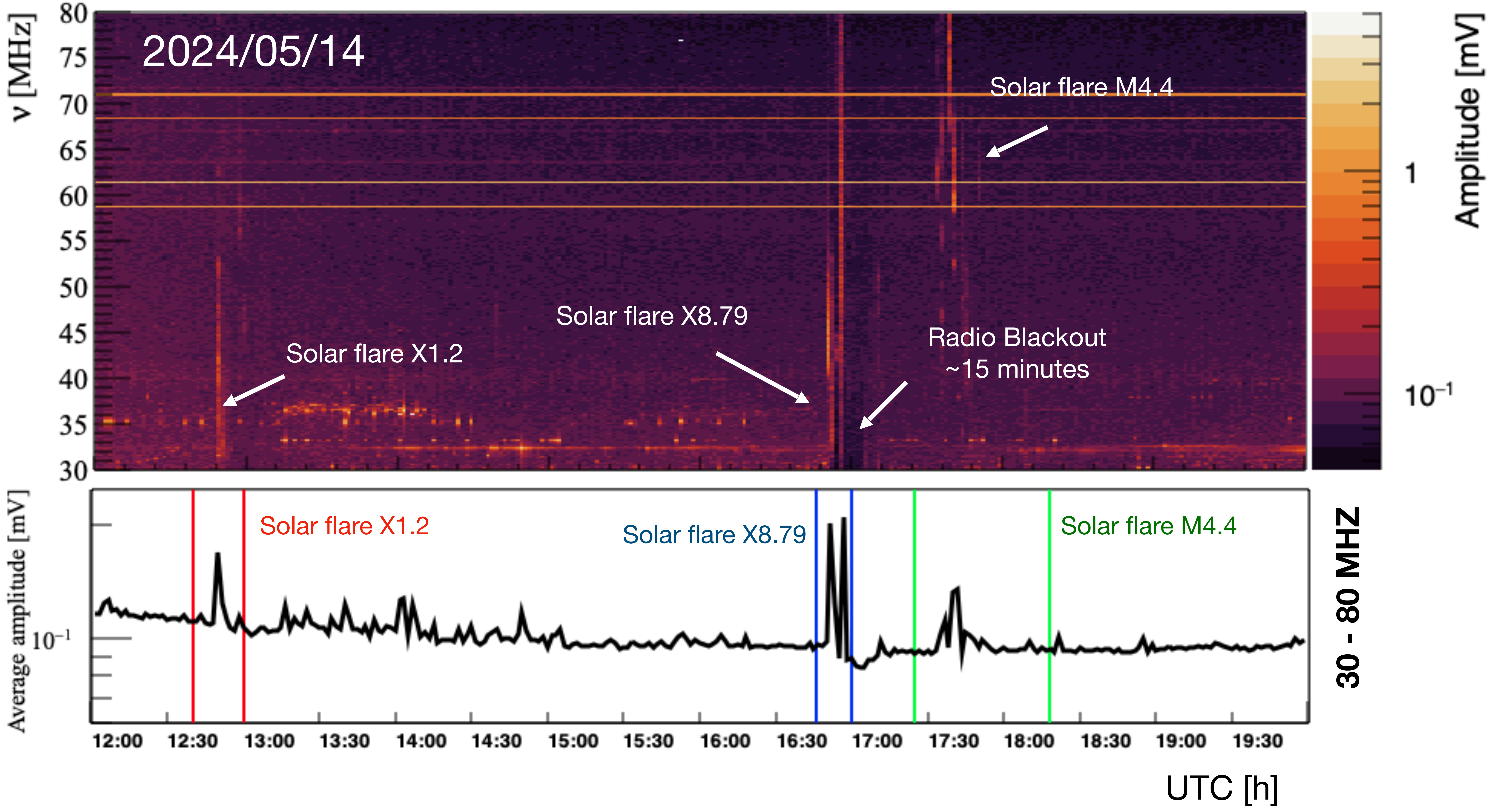


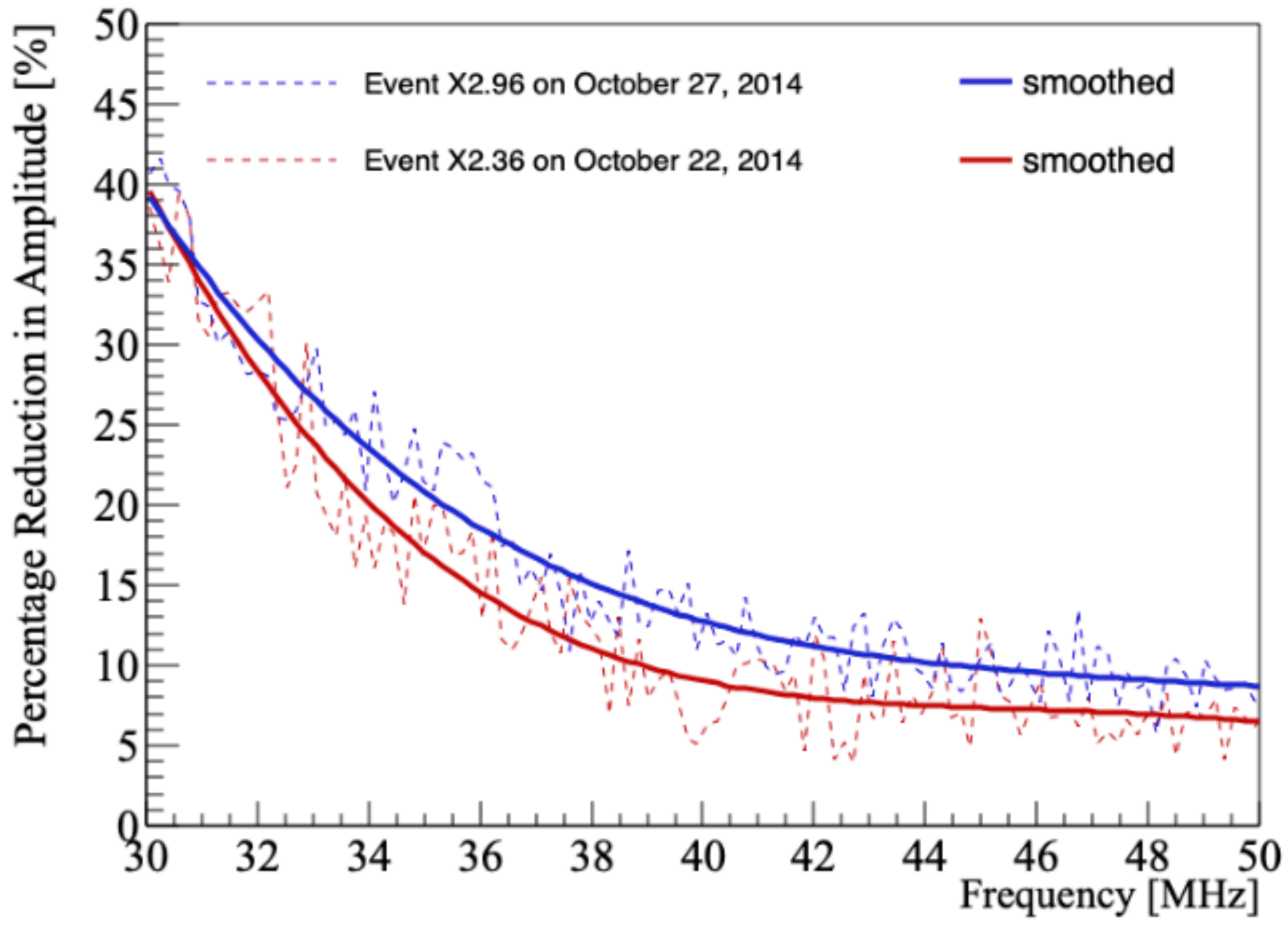
Detection of SRBs with AERA Data

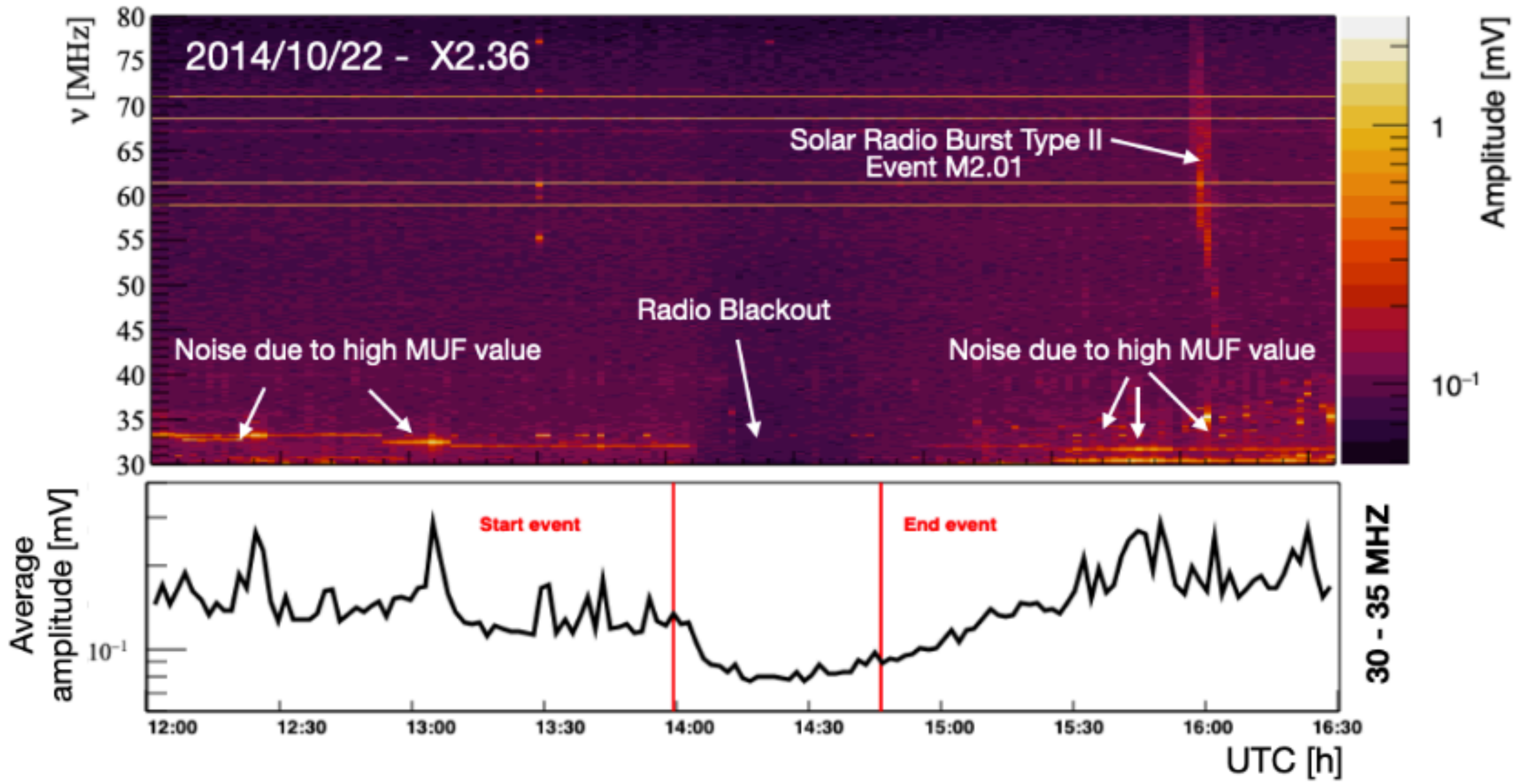
- Event Number 15, of **intensity X8.79**, was one of the largest of cycle 25. The Flare left a strong signal on the AERA spectrogram. Furthermore, it is possible to observe a short blackout after the event, as well as two other small flares of lower intensities.

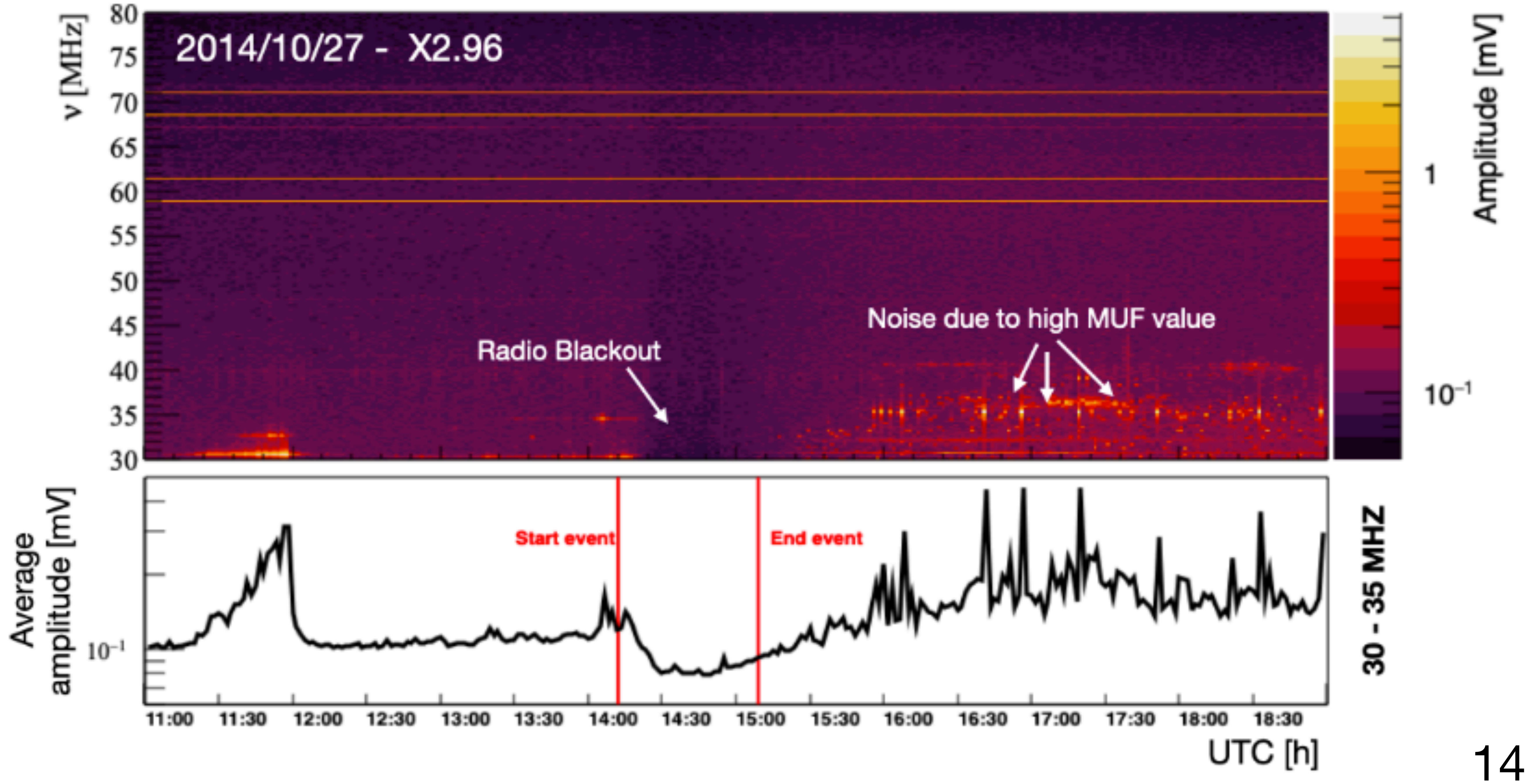


Detection of SRBs with AERA Data

- Events 2 and 3 triggered a radio blackout in AERA data
- It is important to highlight that approximately 2 hours after event number 2, another event of M2.01 intensity was detected a signature of a type II solar radio burst.
- We calculate the percentage reduction for each frequency bin within the event time window using data from the day before the event.

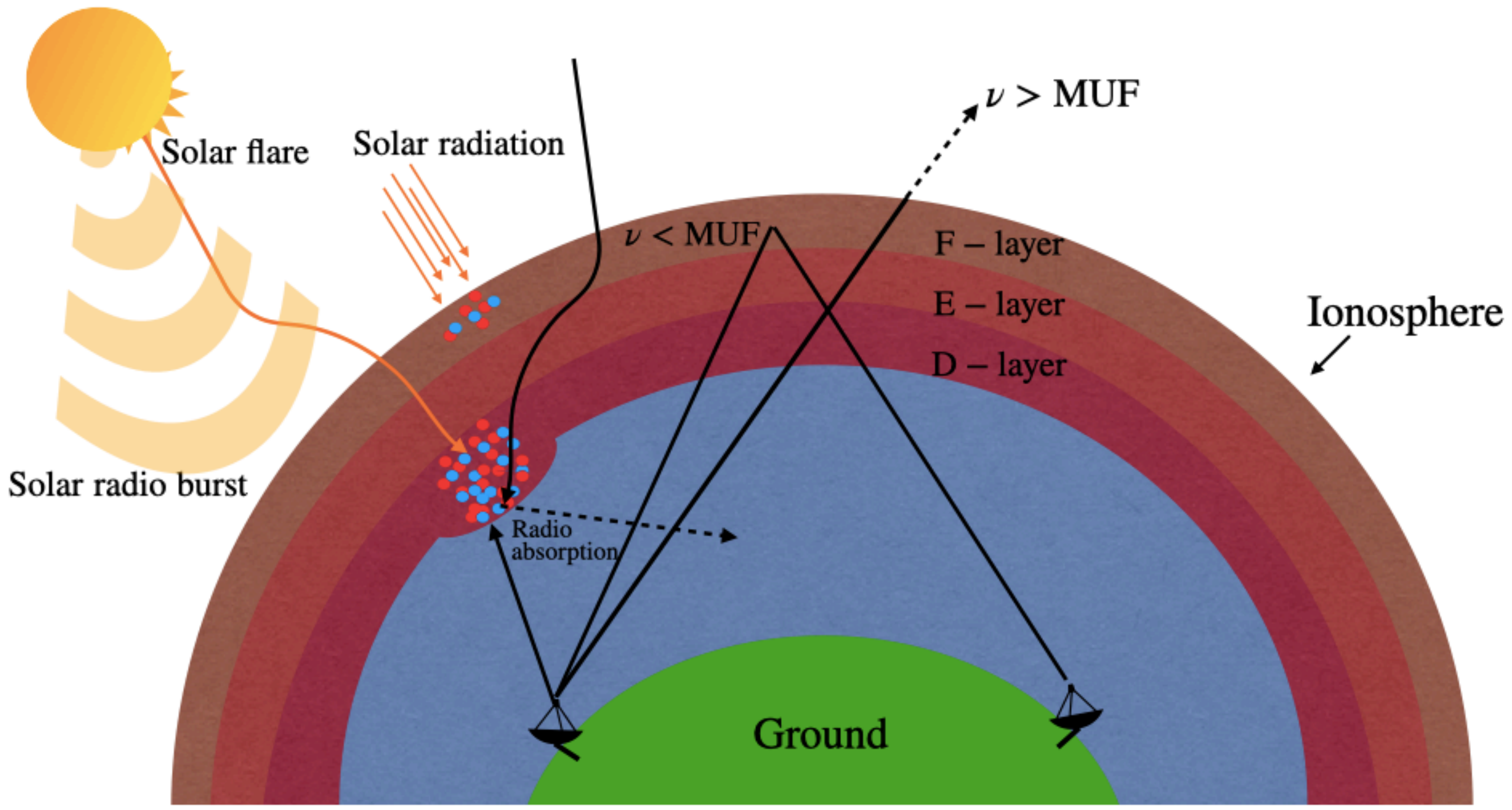


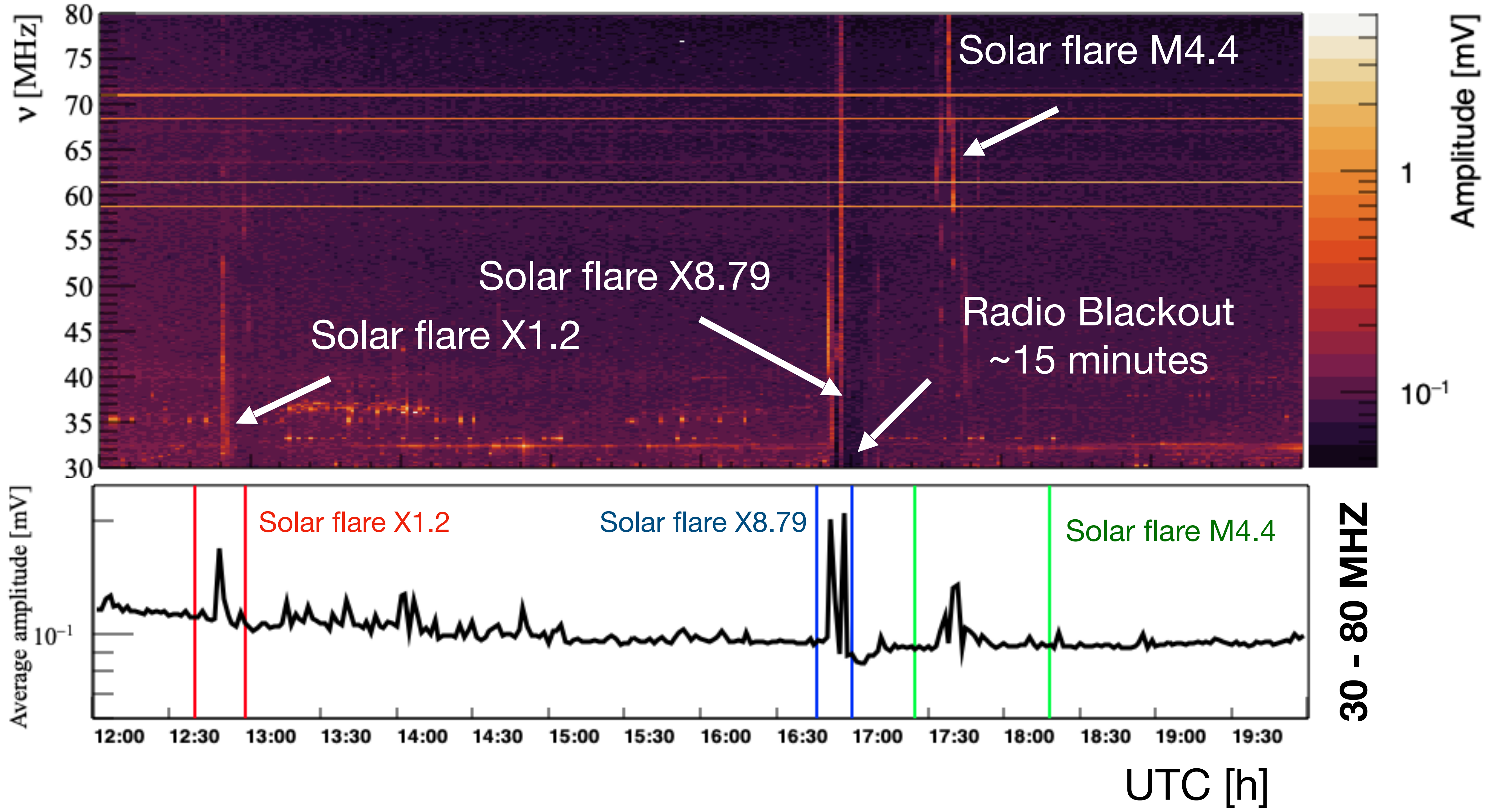




Conclusions

- Using approximately a decade of data, we observe a significant influence of solar activity on AERA data, highlighting the interplay between solar cycles and ionospheric ionization.
- Solar activity is correlated with increased broadband noise in the AERA's 30-40 MHz frequency range
- Solar activity's effect on the ionosphere results in the atmospheric reflection of distant terrestrial radio waves.
- 16 Solar Radio Bursts (SRBs) associated with moderate to strong radio blackouts have been detected in AERA data.

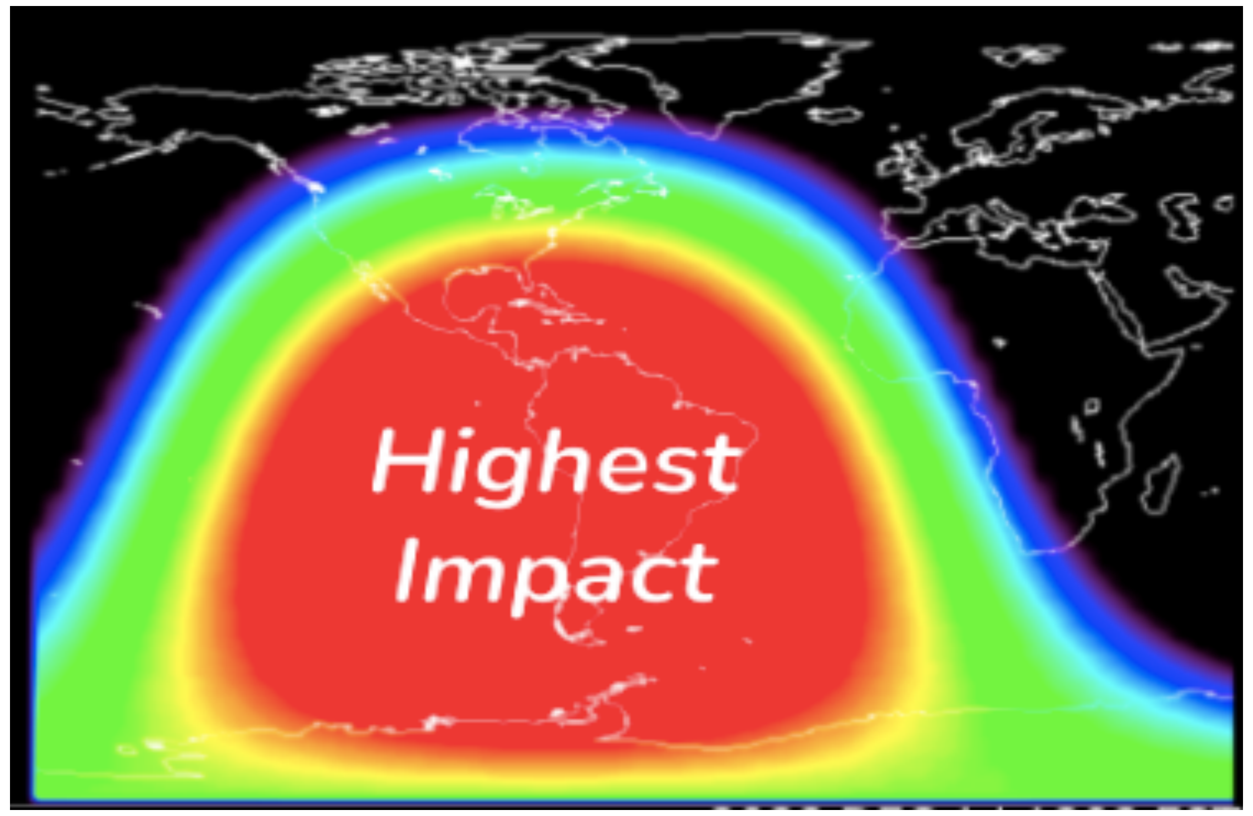


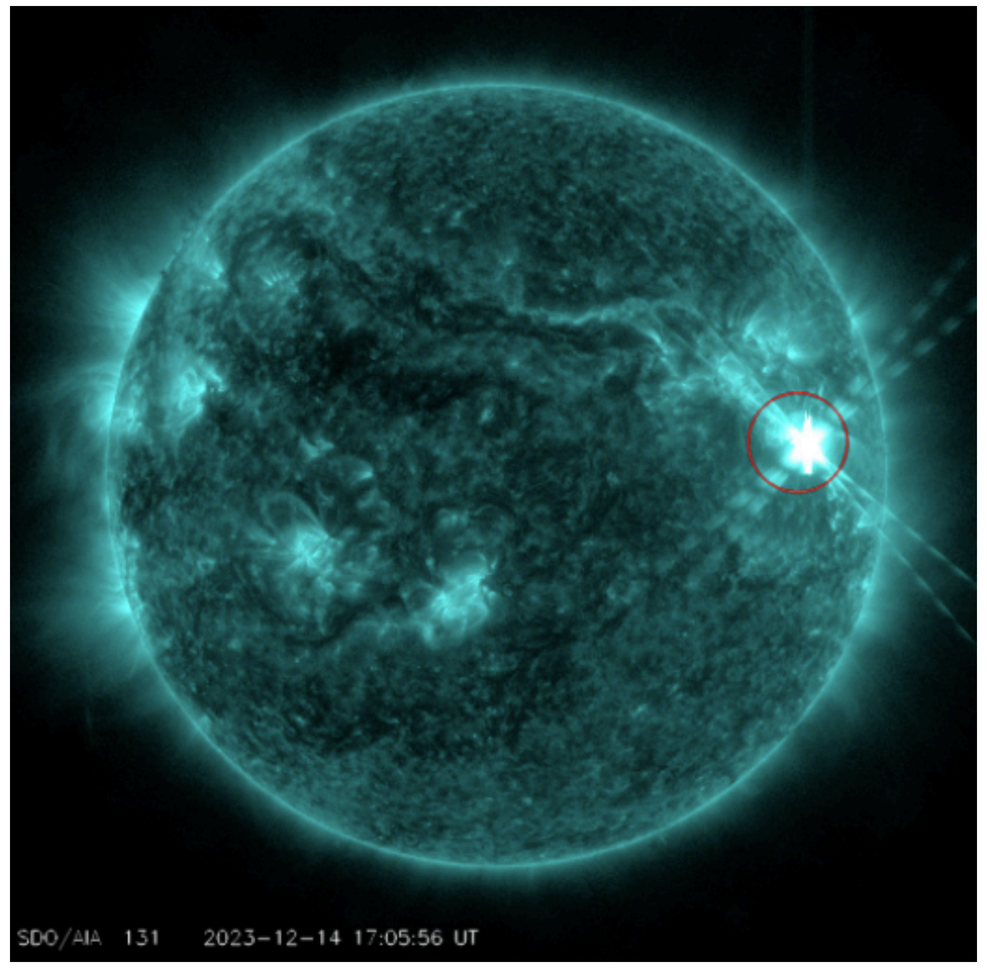


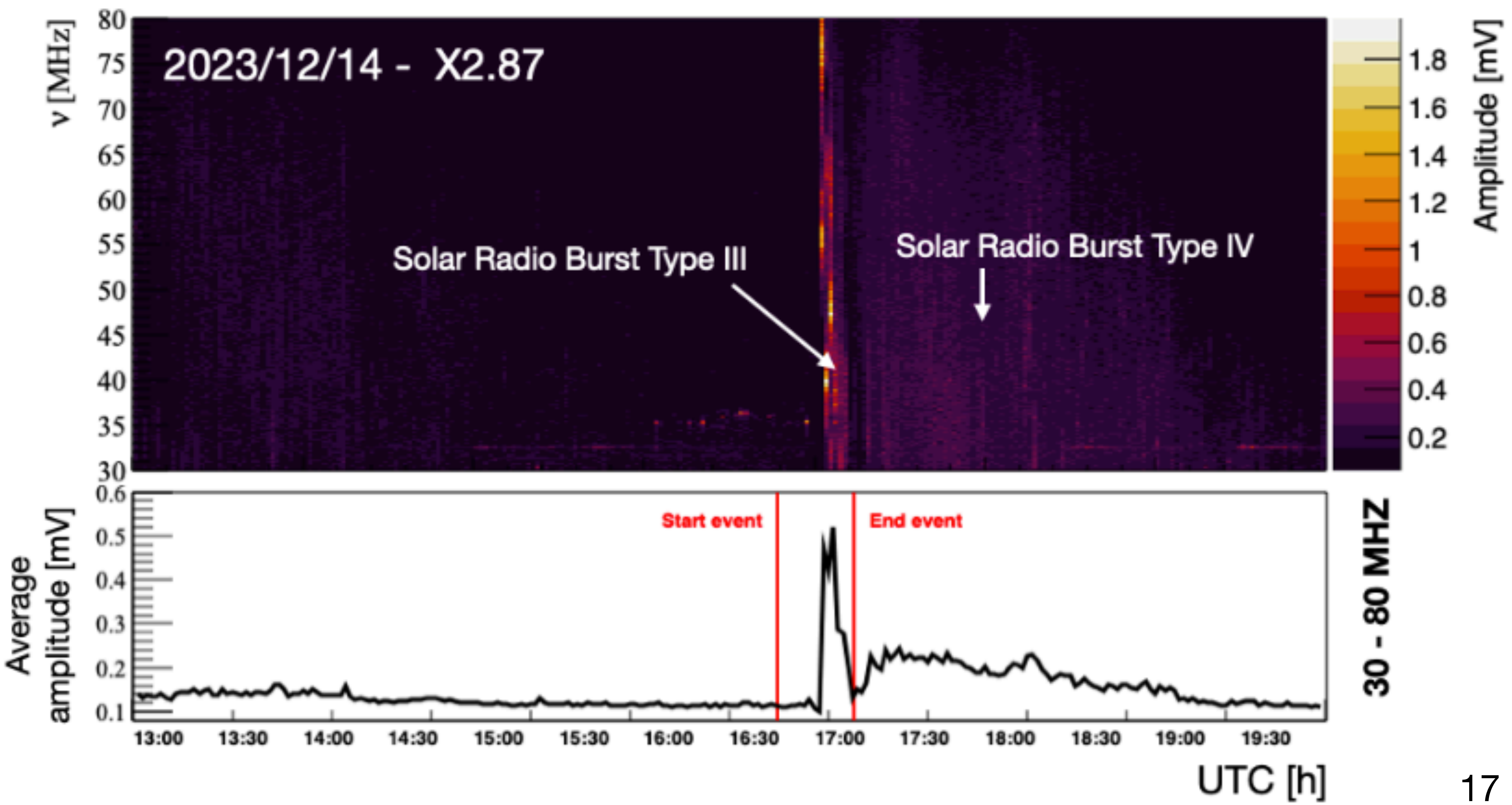
BACKUP

Remaining events

- Event Number 11, occurred on December 14, 2023 and was marked by the most potent solar flare ever recorded in Solar Cycle 25. According to NOAA, this event triggered severe radio blackouts below 30 MHz, impacting various terrestrial instruments used in telecommunications. Above 30 MHz, our observations in AERA data revealed a highly intense Type III SRB across the frequency range of 30 to 80 MHz. Besides, we can also observe the presence of a type IV SRB after the Type III SRB, lasting more than 2 hours.







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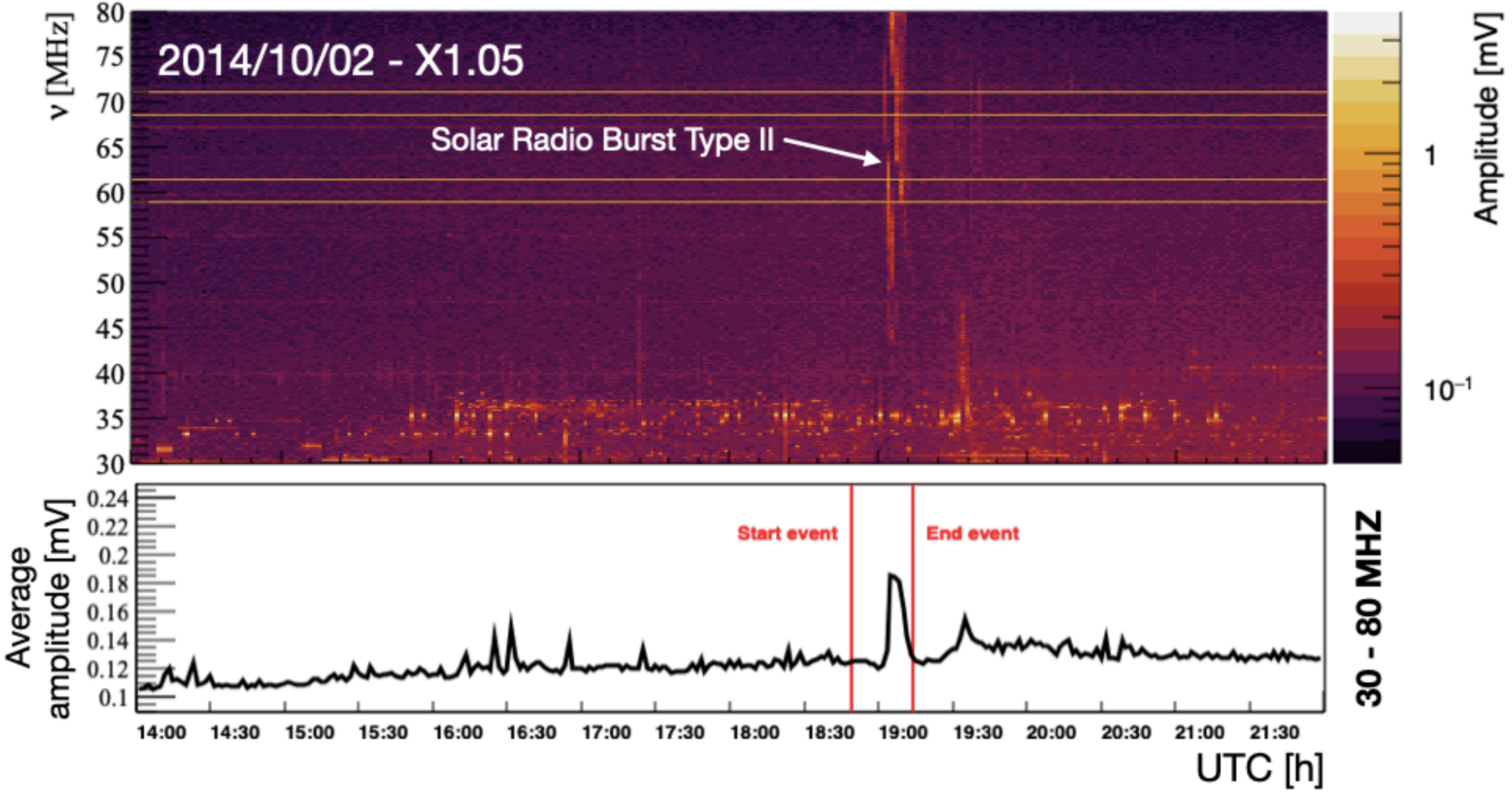

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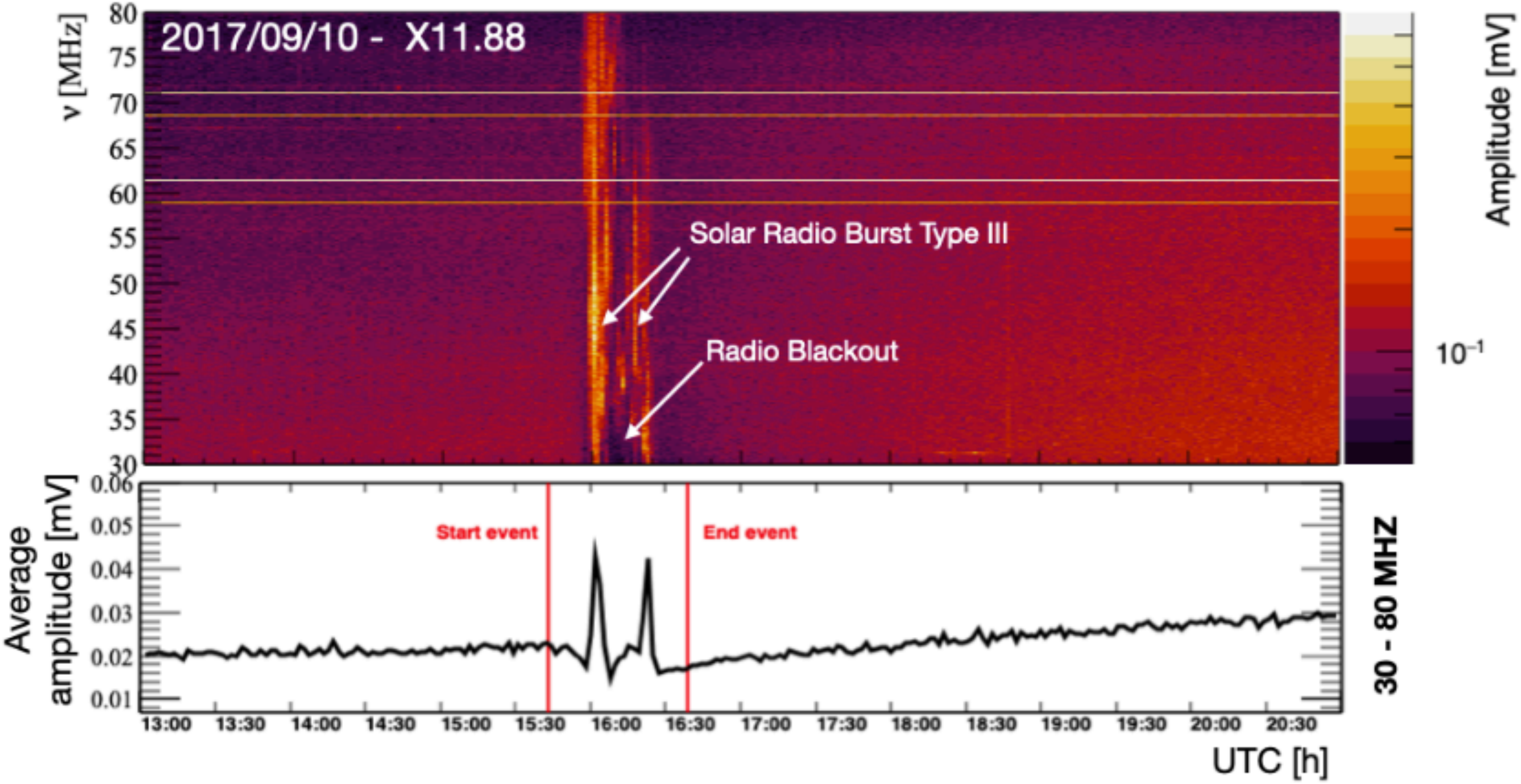

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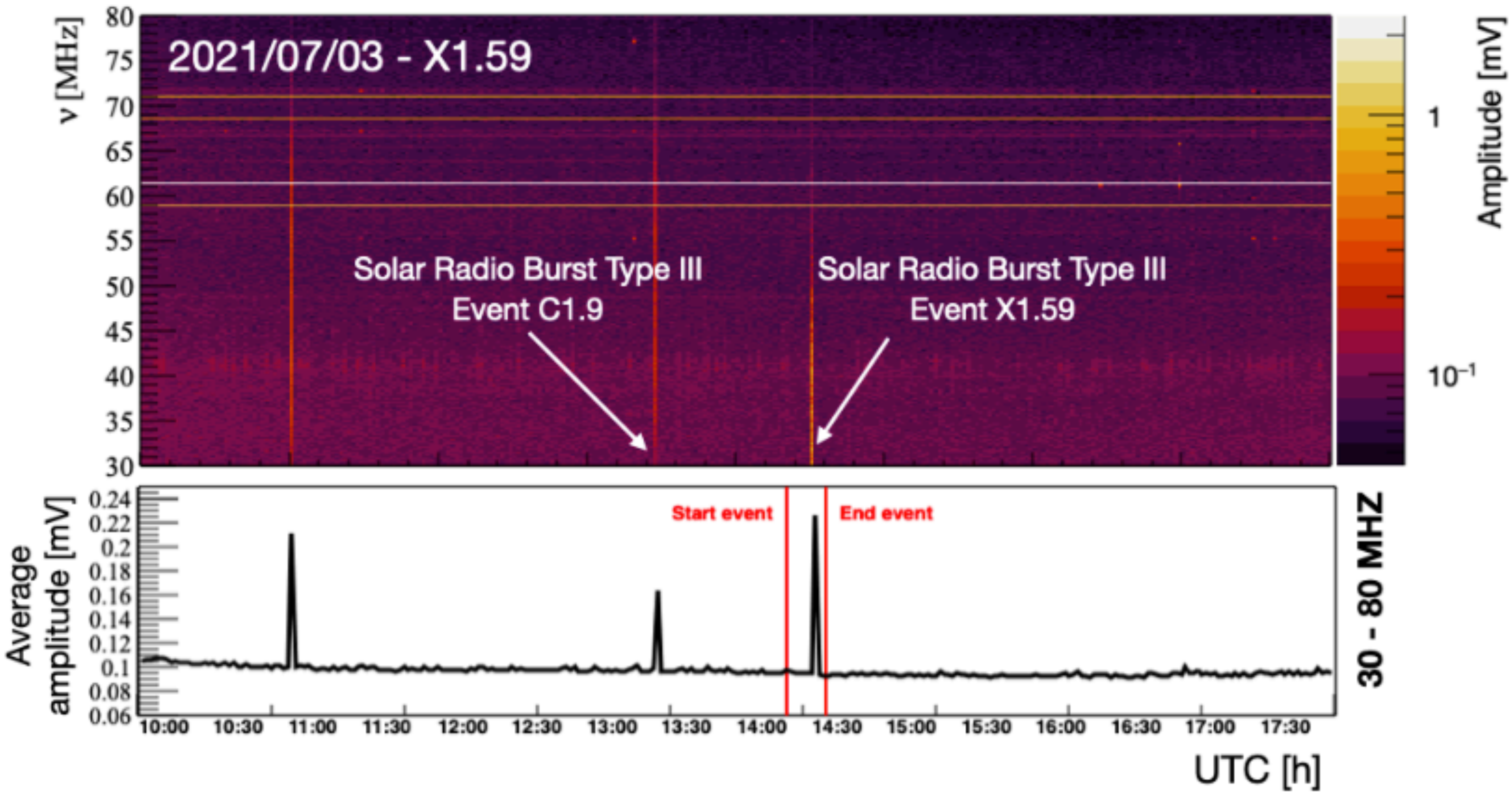

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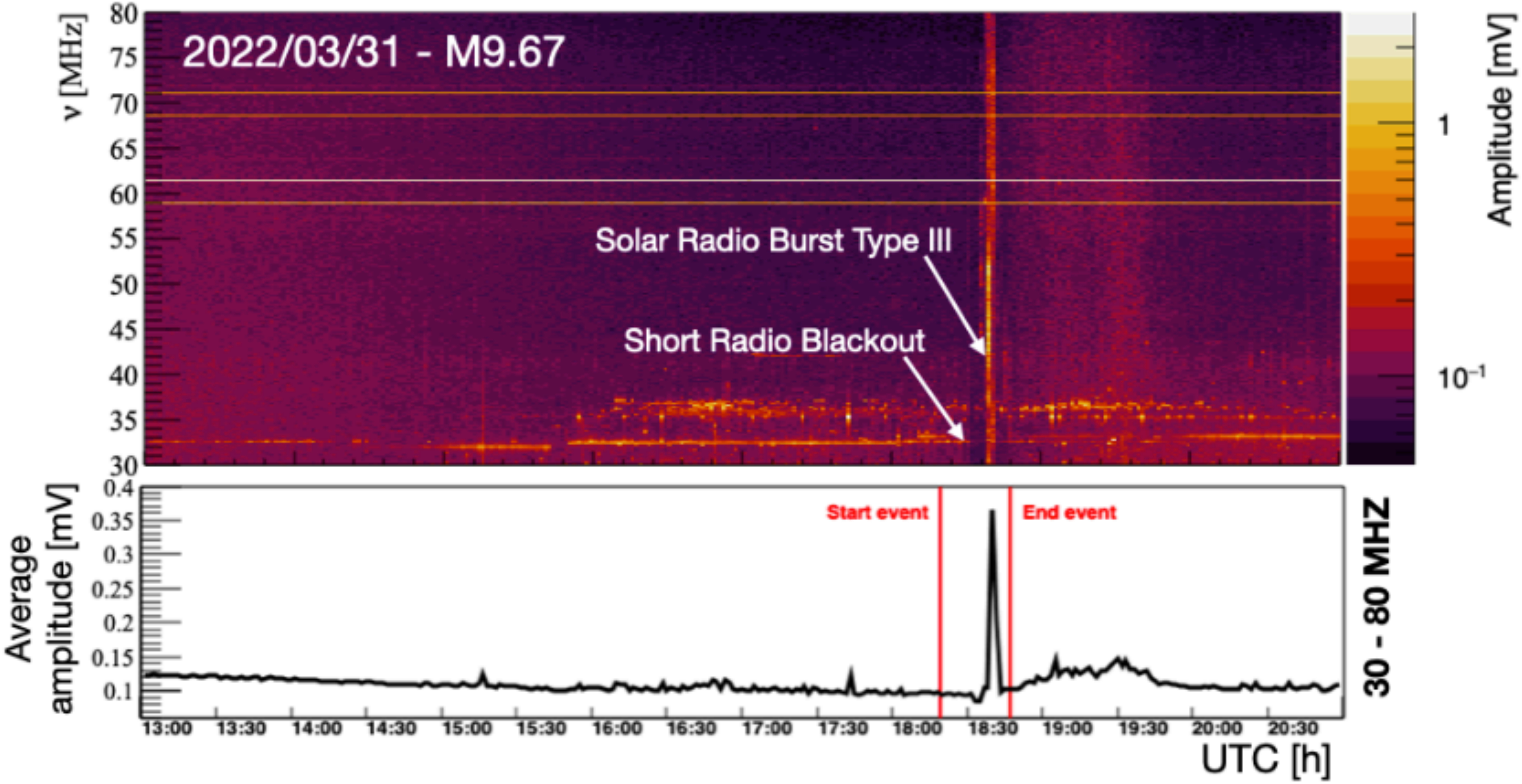

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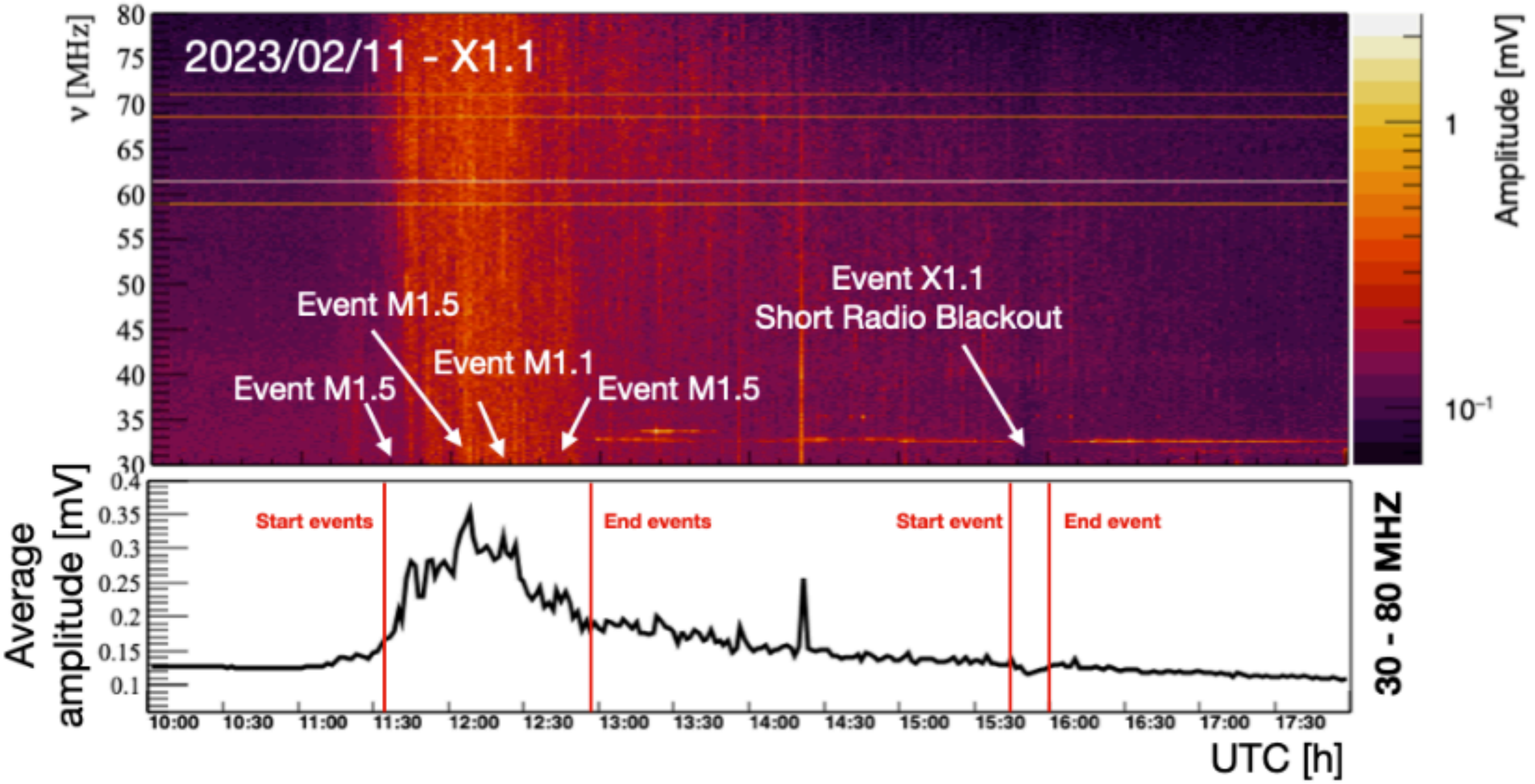

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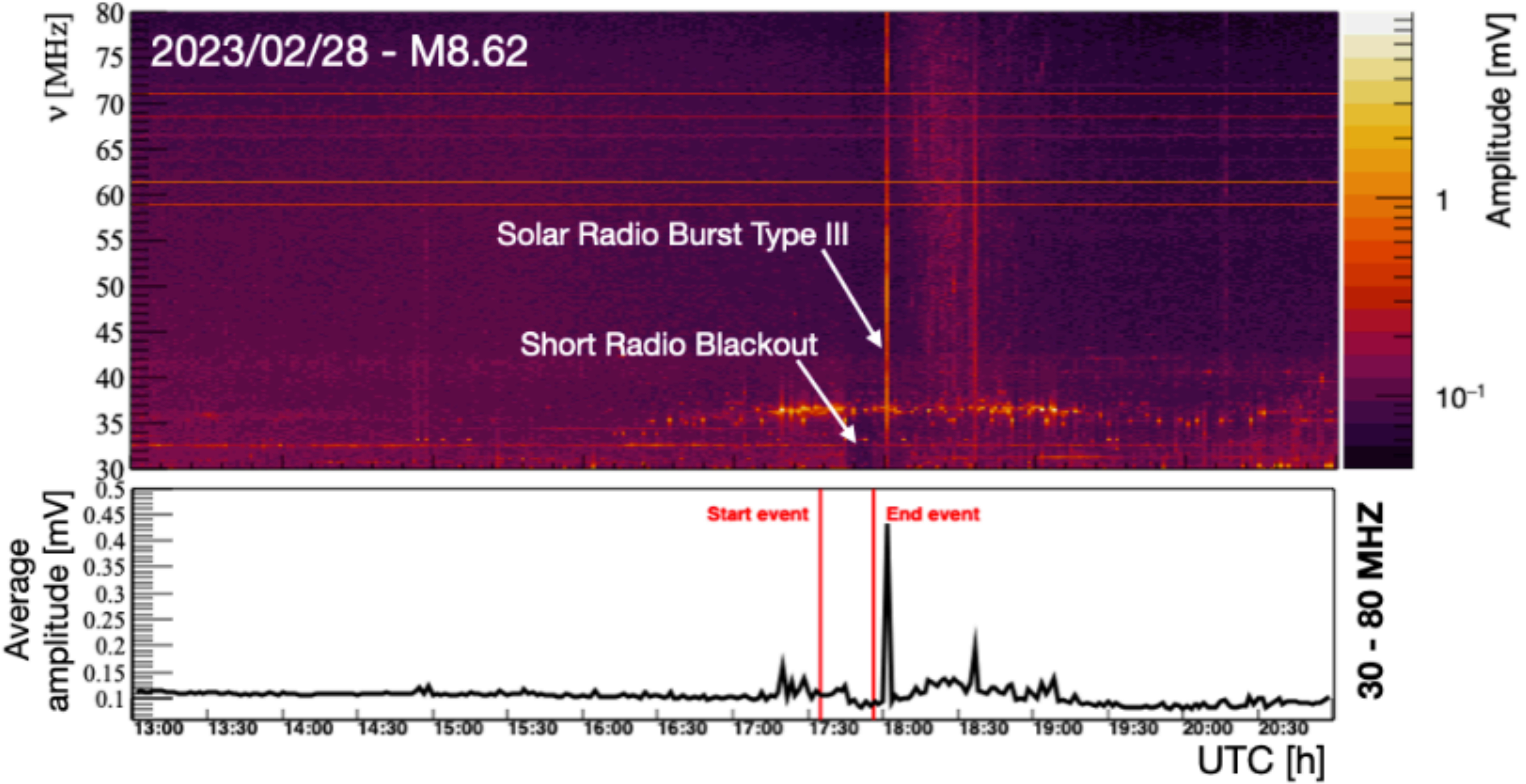

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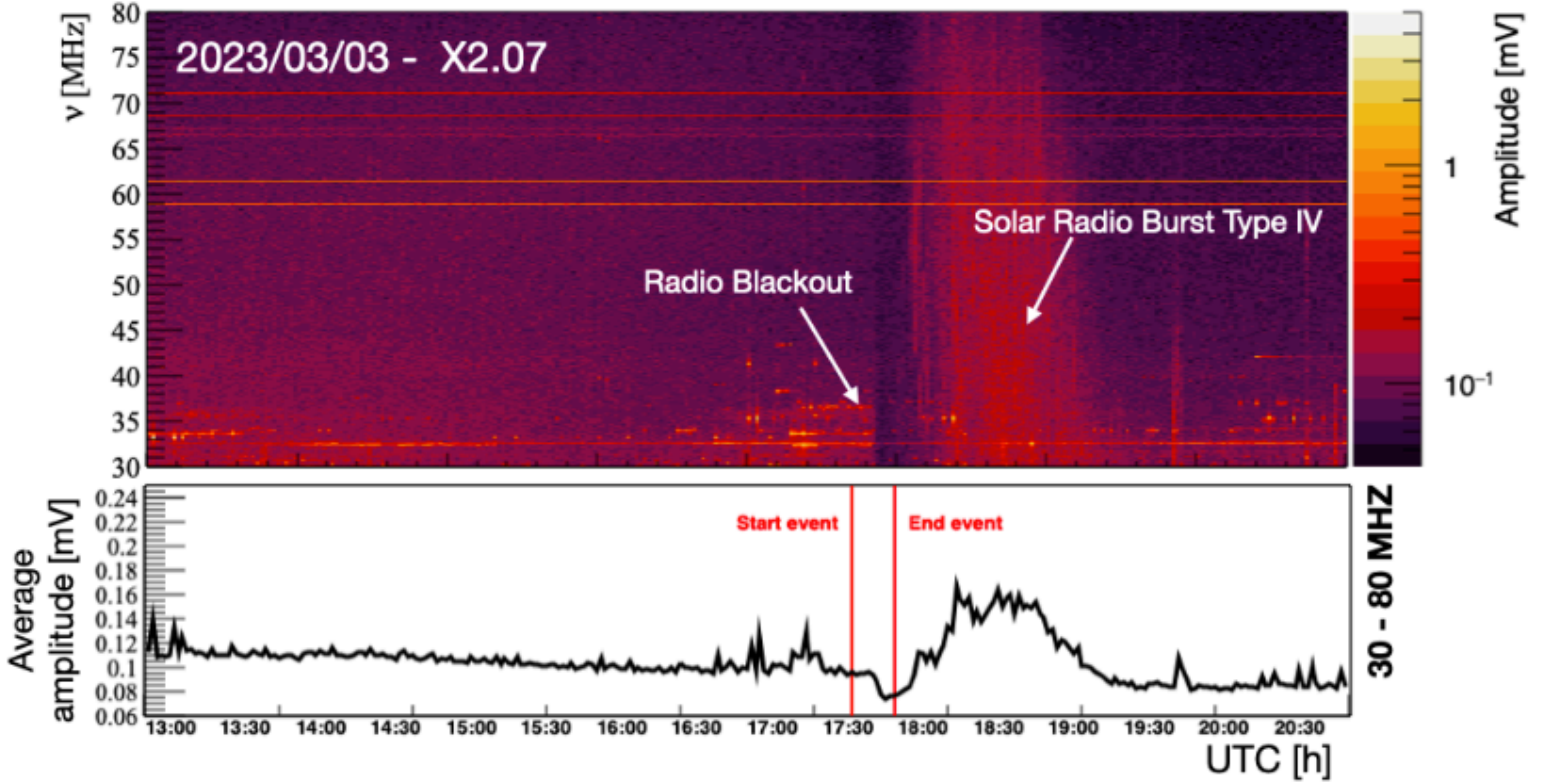

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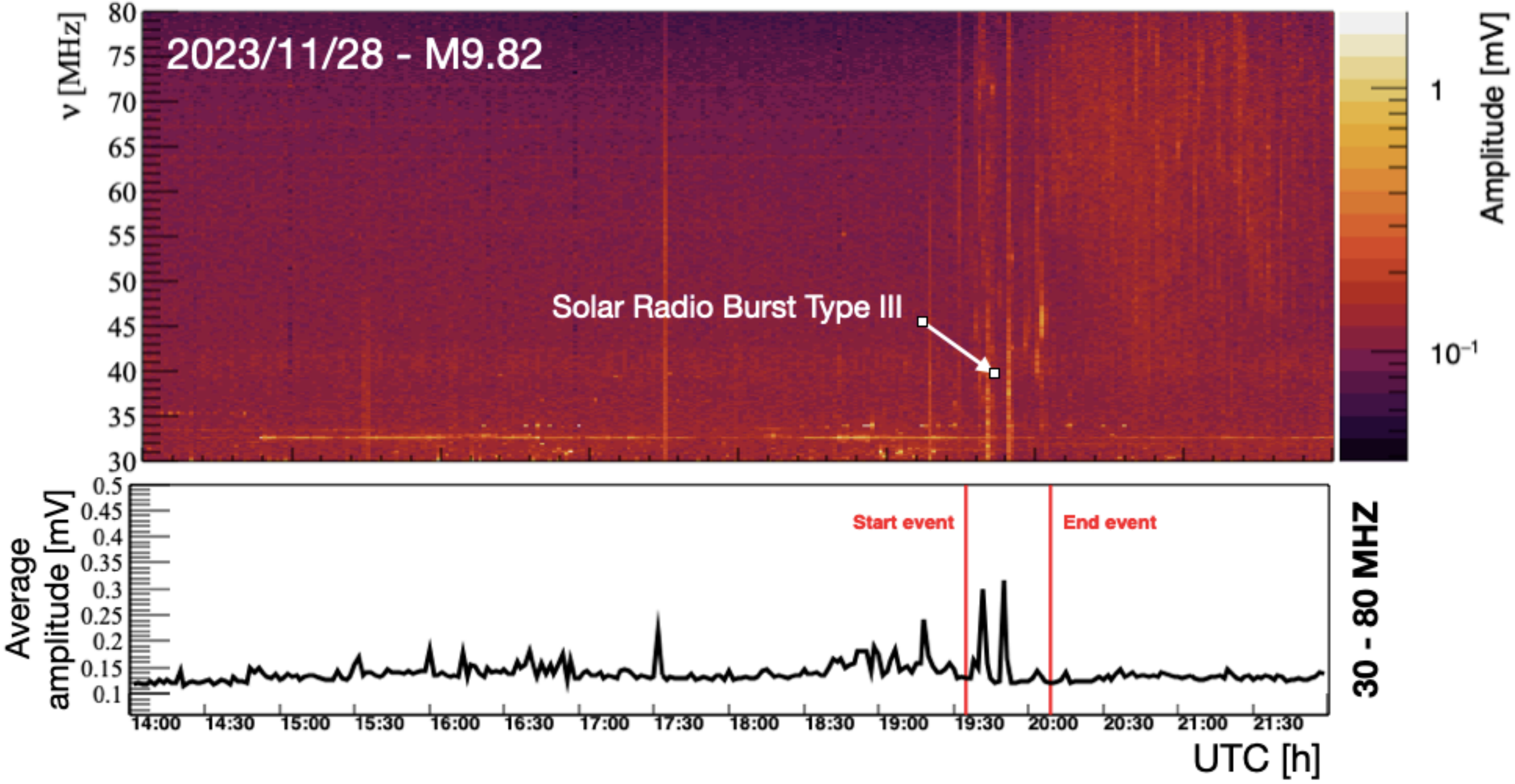

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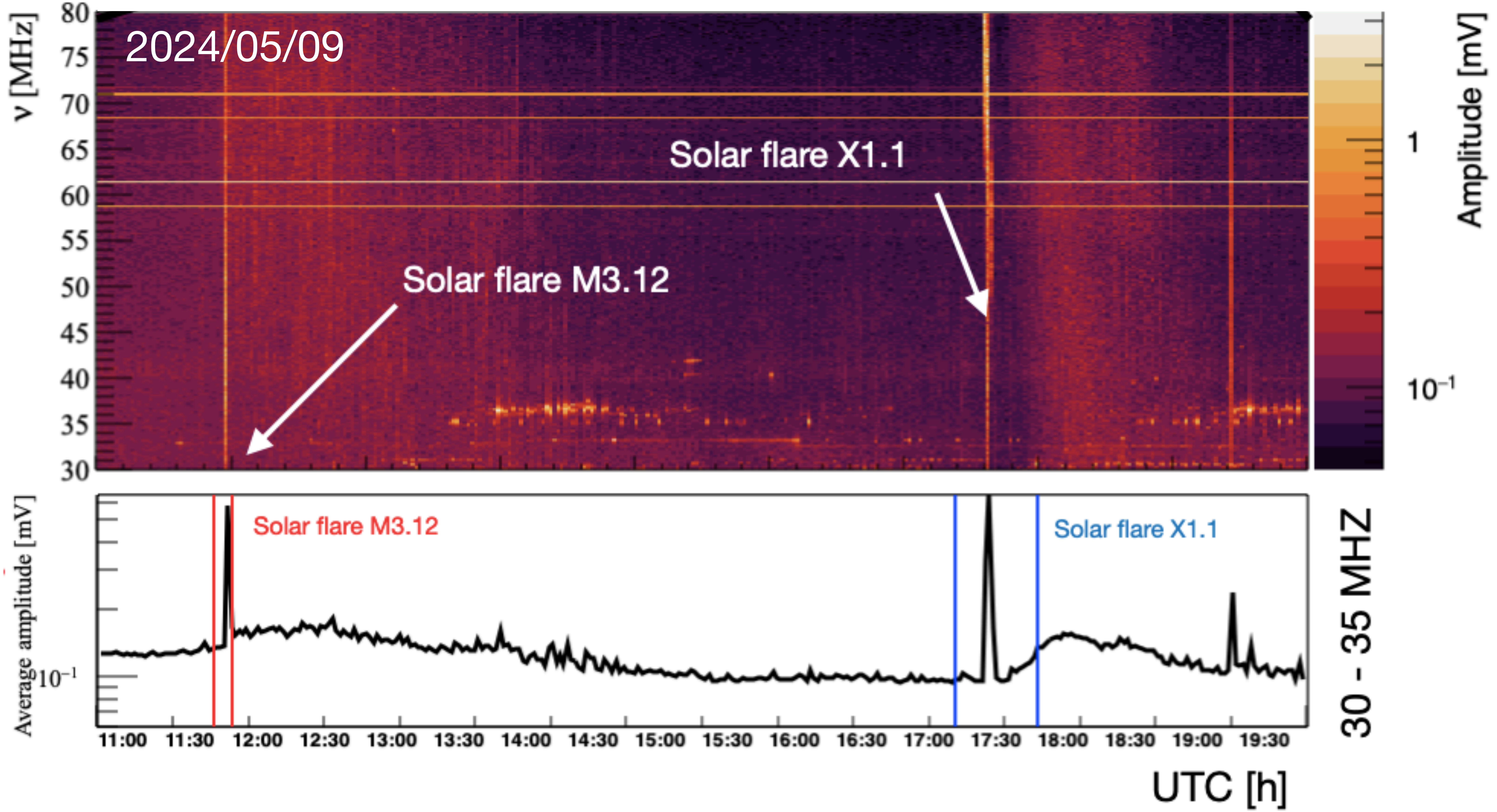

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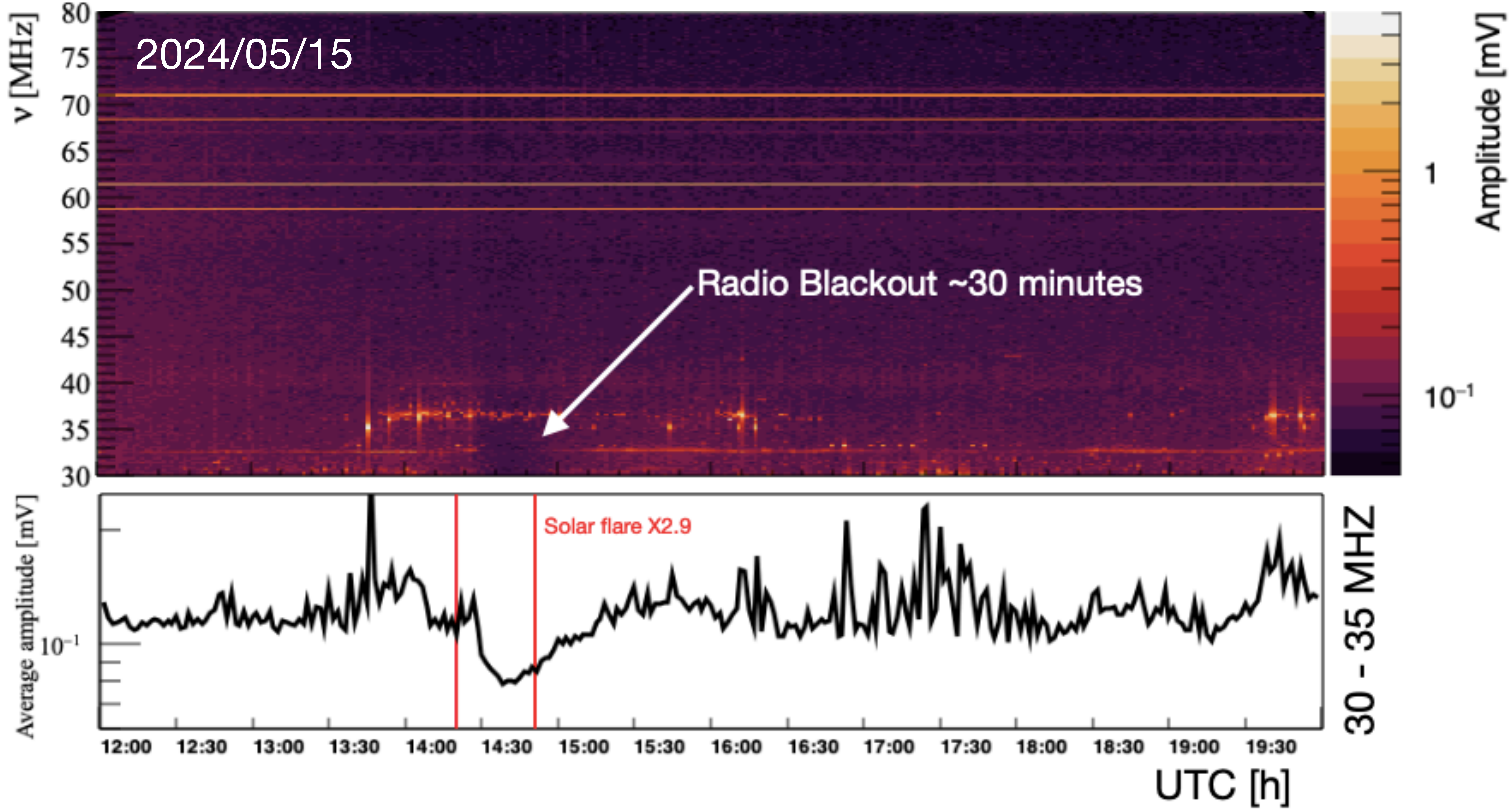
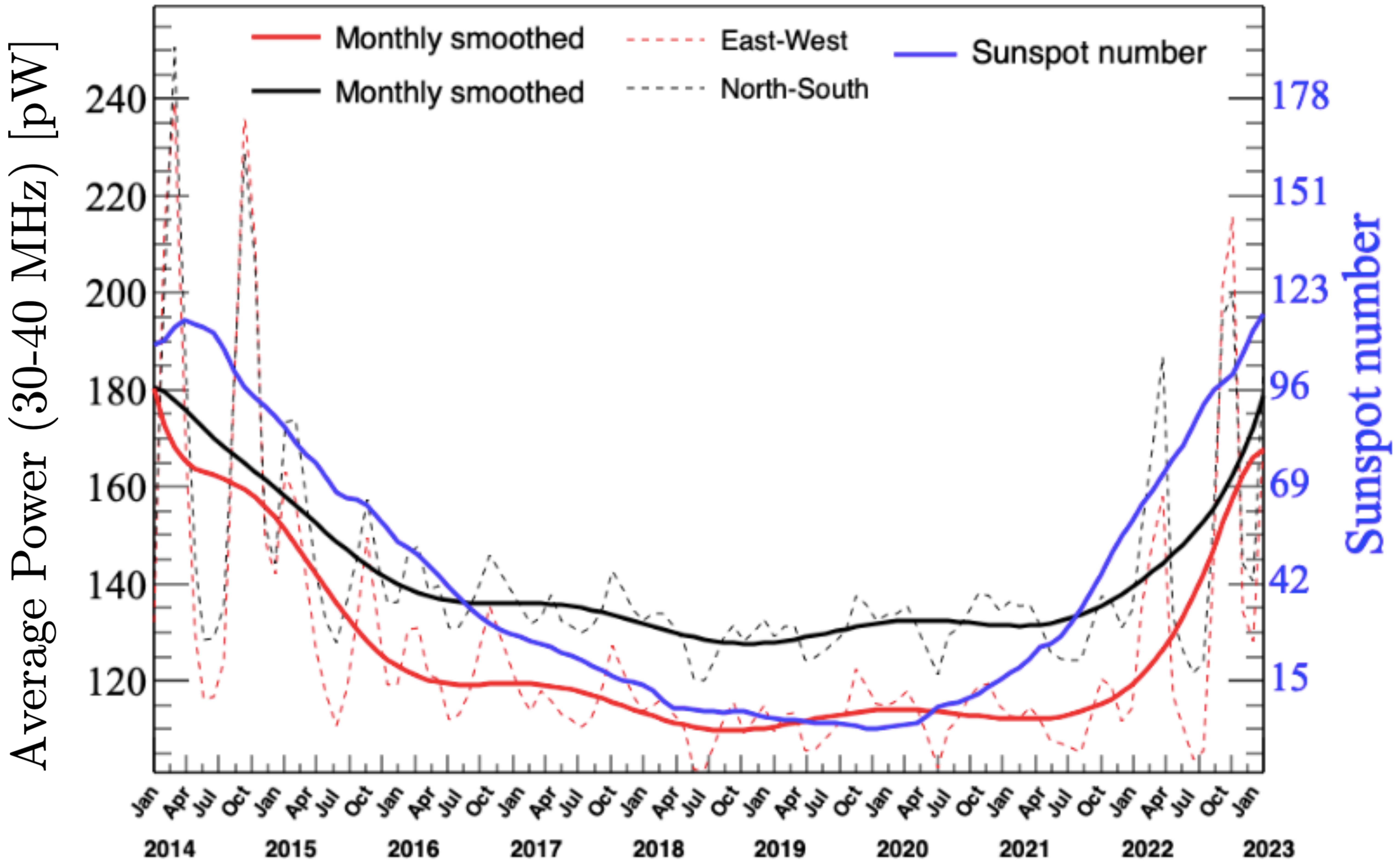


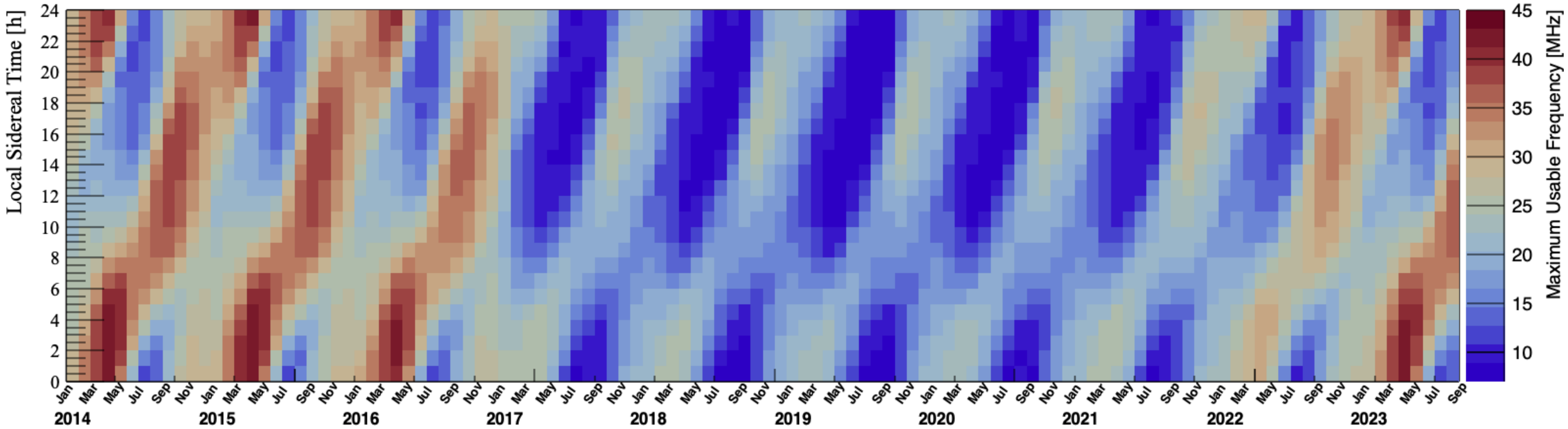
Correlation between MUF and broadband noise measured by AERA within the 30-40 MHz frequency range

- Examining the temporal evolution over almost a decade of these broadband noises in the 30-40 MHz range, we observe that the increase/decrease in power is correlated with the increase/decrease in the number of sunspots, indicative of solar cycle variations



Maximum Usable Frequency as a function of months

- High MUF coincides with the cycle of solar activity.



- To compare the MUF with the data, we use the monthly average power for each hour in LST of all antennas as a function of months between the frequency range 30-40 MHz.

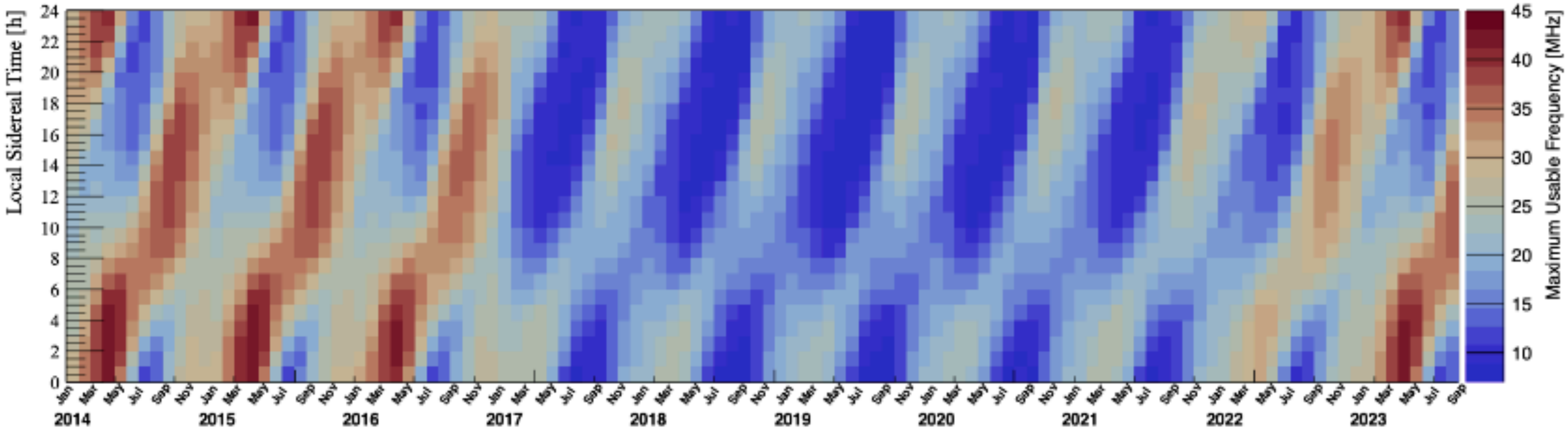
$$\bar{P}_{\text{data}}(t) = \frac{1}{n_\nu + n_{\text{antenns}}} \sum_{i=1}^{n_{\text{antennas}}} \sum_{\nu=30MHz}^{40MHz} P_i(t,\nu)$$

- To remove galactic modulation present in the data, we calculated the average signal power for each LST hour during 2018. This period was used because it did not present much noise in any of the frequency bands.

$$\bar{P}_{\text{background}}(t) = \frac{1}{n_\nu + n_{\text{antenns}} + n_{\text{months}}} \sum_{j=\text{jan2018}}^{\text{dez2018}} \sum_{i=1}^{n_{\text{antennas}}} \sum_{\nu=30MHz}^{40MHz} P_{i,j}(t,\nu)$$

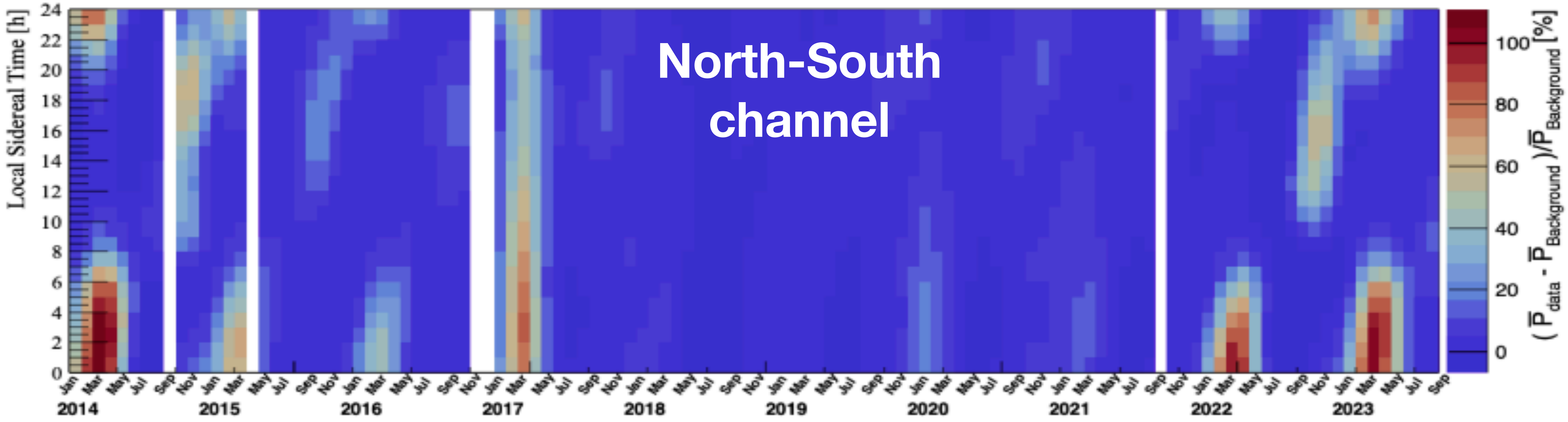
- We compute the percentage difference between $\bar{P}_{\text{data}}$ and $\bar{P}_{\text{background}}$: $\frac{\bar{P}_{\text{data}} - \bar{P}_{\text{background}}}{\bar{P}_{\text{background}}}$

Correlation between MUF and broadband noise measured by AERA within the 30-40 MHz frequency range



Maximum usable frequency

MUF



AERA data (30 - 40 MHz)

$$\frac{\bar{P}_{\mathrm{data}} - \bar{P}_{\mathrm{background}}}{\bar{P}_{\mathrm{background}}}$$