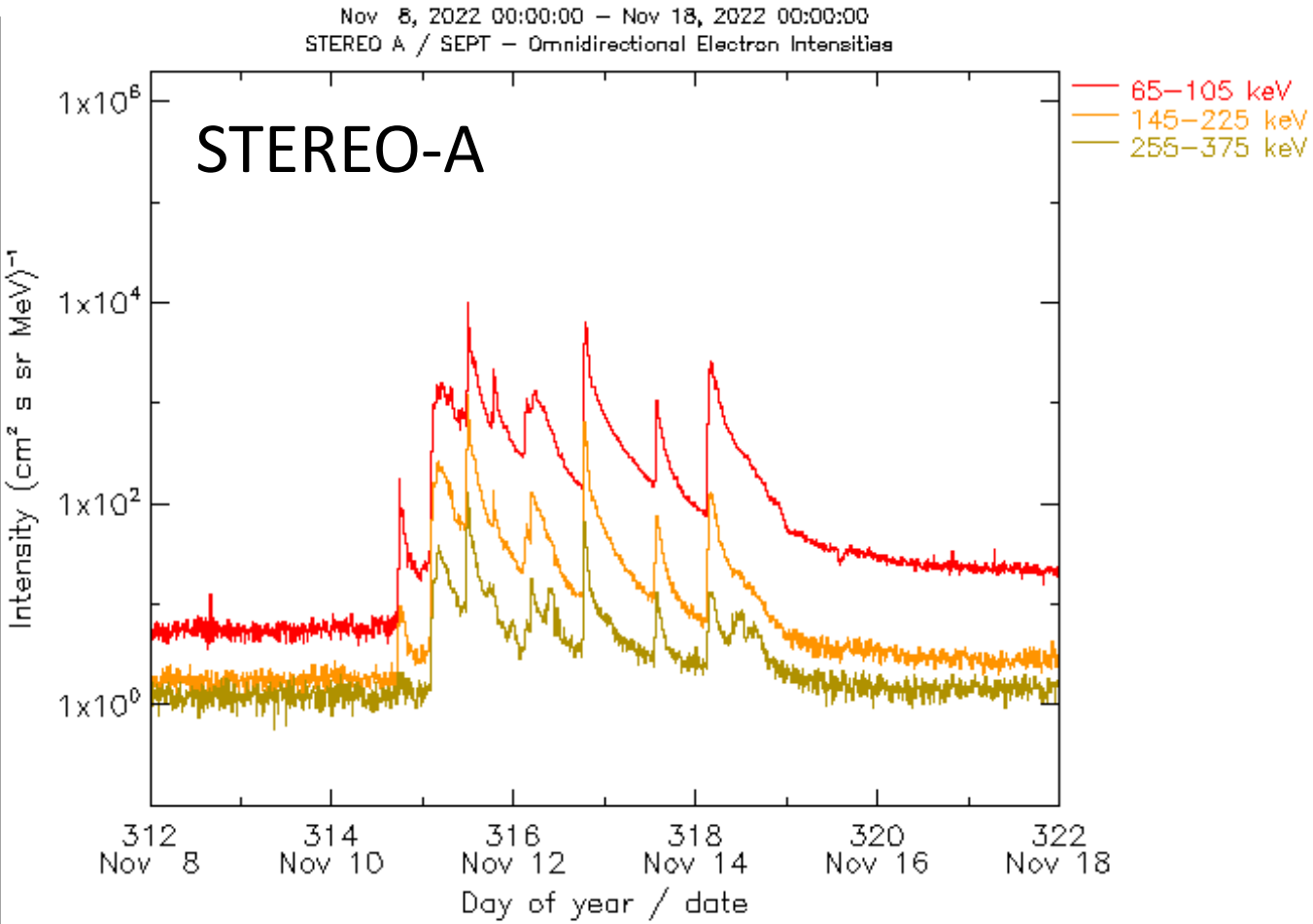
Rapid succession of SEP events associated with a series of EUV jets: Solar Orbiter, STEREO-A and near-Earth spacecraft observations

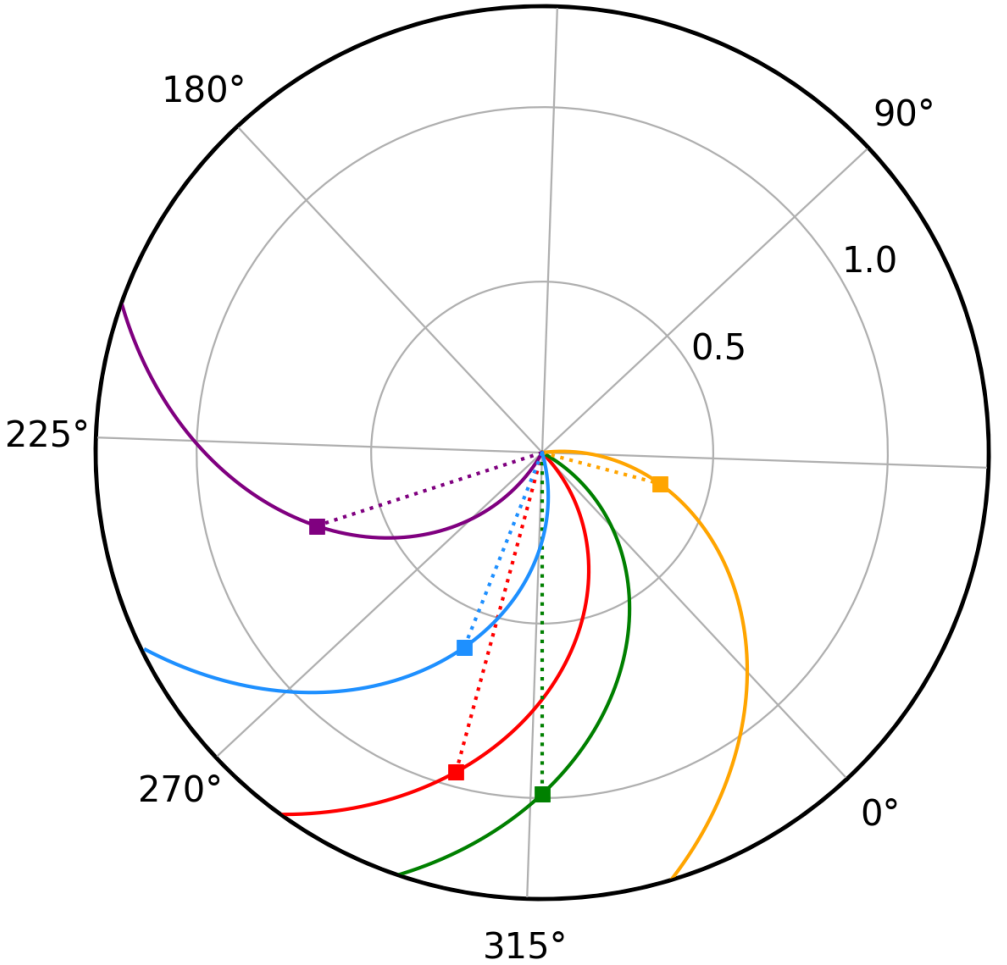
D. Lario[1], L. A. Balmaceda[1,2], R. Gomez-Herrero[3], G. M. Mason[4], V. Krupar[1, 5], J. Rodriguez-Pacheco[3], F. Carcaboso[1], I. G. Richardson[1,6], N. Wijsen[1,6], R. D. Strauss[7] , N. Dresing[8], I.C. Jebaraj[8], A. Kouloumvakos[4], R. Bučík[9], D. Pacheco[10], L. Rodriguez-Garcia[3], C. MacCormack[1,11], T. S. Horbury[12] ,L. Rodriguez[13], A.N. Zhukov[13]

(1) Heliophysics Science Division, NASA/GSFC
(2) George Mason University
(3) Universidad de Alcalá
(4) The Johns Hopkins University. Applied Physics Laboratory
(5) University of Maryland, Baltimore County
(6) University of Maryland, College Park
(7) North-West University, Potchefstroom
(8) University of Turku
(9) Southwest Research Institute
(10) Christian-Albrechts-Universität zu Kiel
(11) The Catholic University of America
(12) Imperial College London
(13) SIDC, Royal Observatory of Belgium



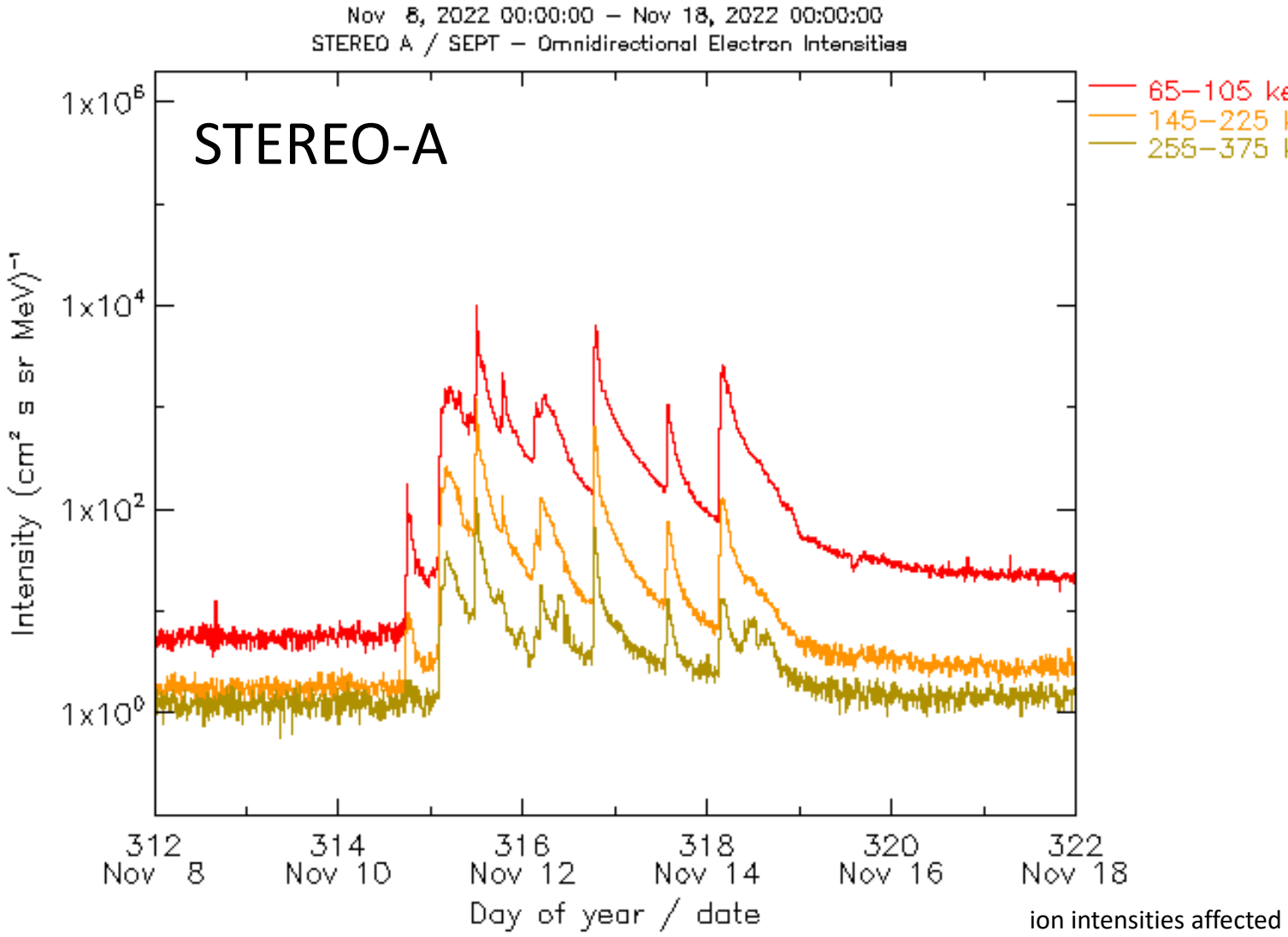
Outline

- Solar origin of these events
- The relationship between the multiple signatures of the parent solar eruptions (EUV jets, type III radio bursts, X-ray emissions, …)
- Ion composition signatures of these events.
- Multi-spacecraft observations. Interplanetary context affecting the particle transport and spacecraft magnetic connection



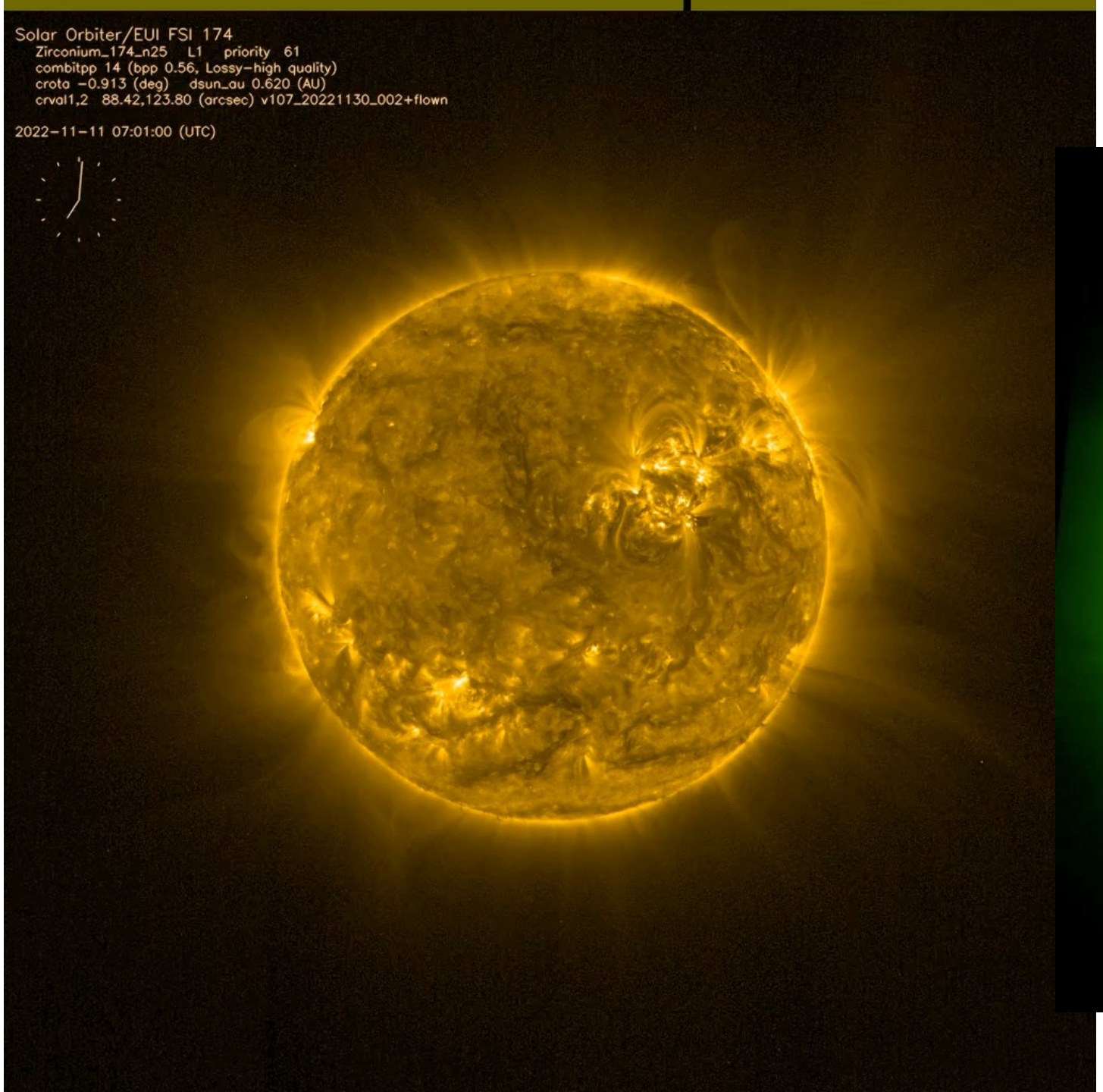
STEREO A
Earth
BepiColombo
Parker Solar Probe
Solar Orbiter

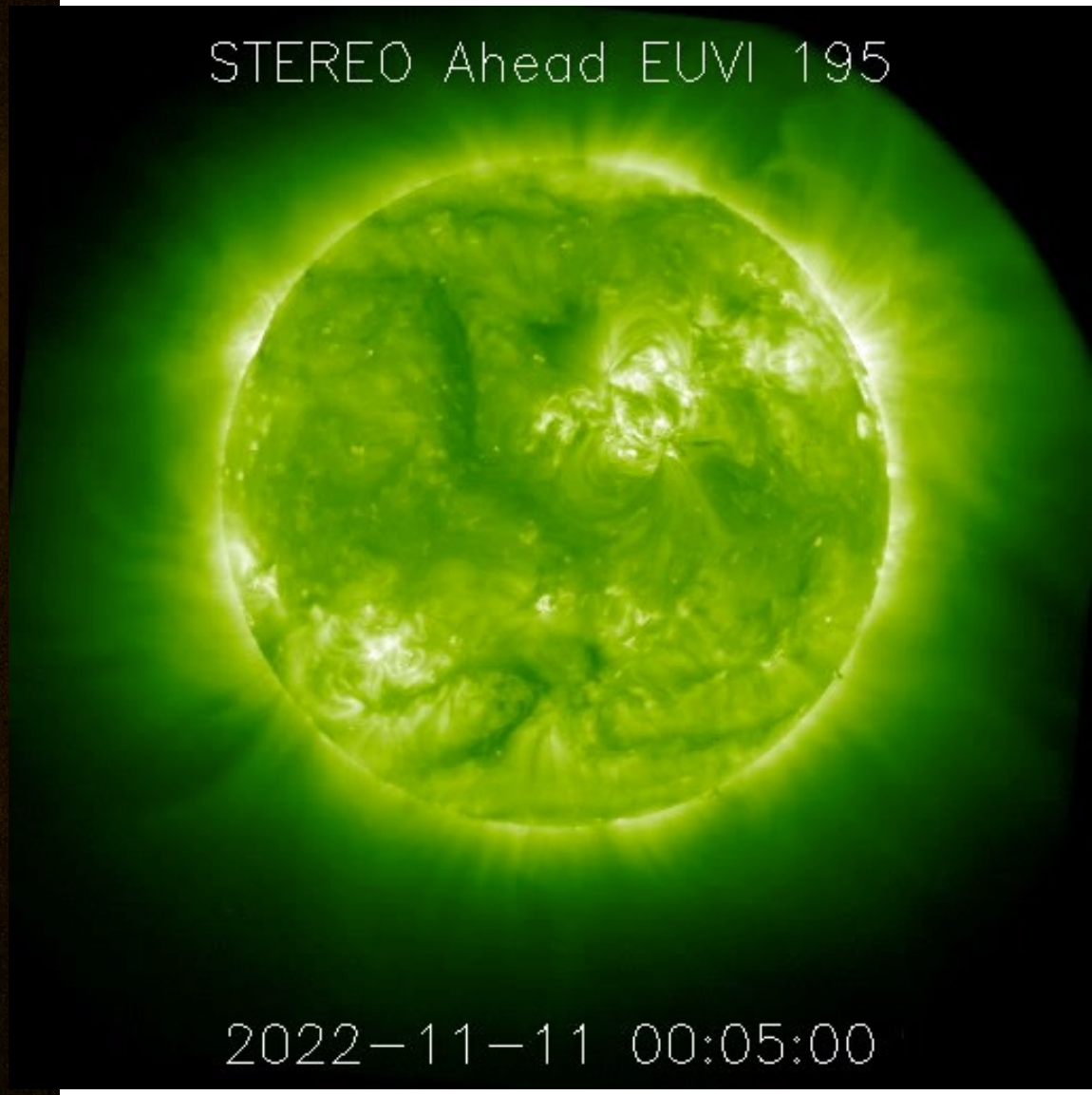
PSP ~0.69 AU -72 deg
SolO ~0.62 AU -21 deg Lat=7.89 deg
STA ~0.96 AU -15 deg Lat=4.91 deg
Earth ~0.99 AU 0 deg Lat=3.34deg

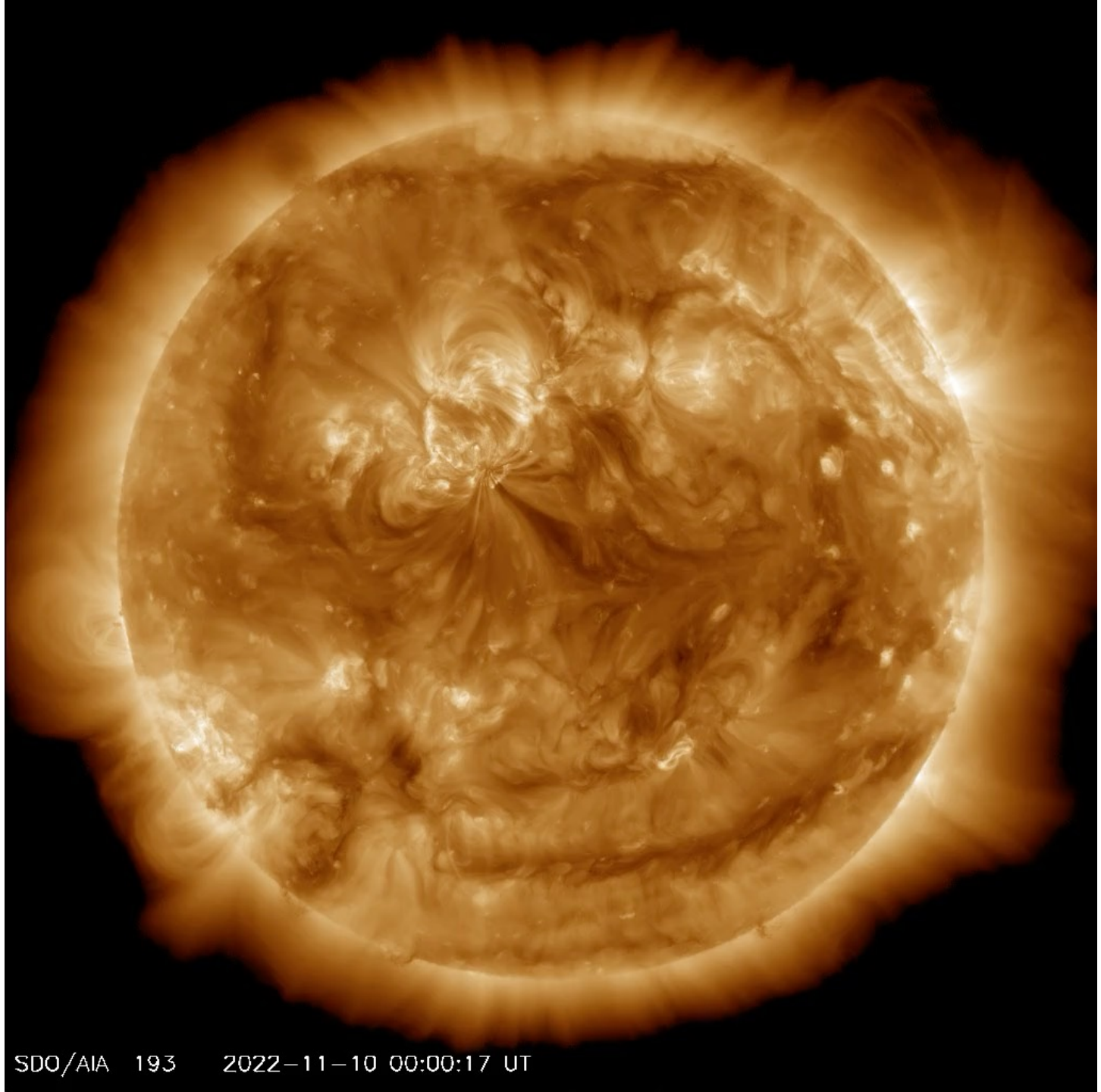


9-14 Nov 2022 sequence of events

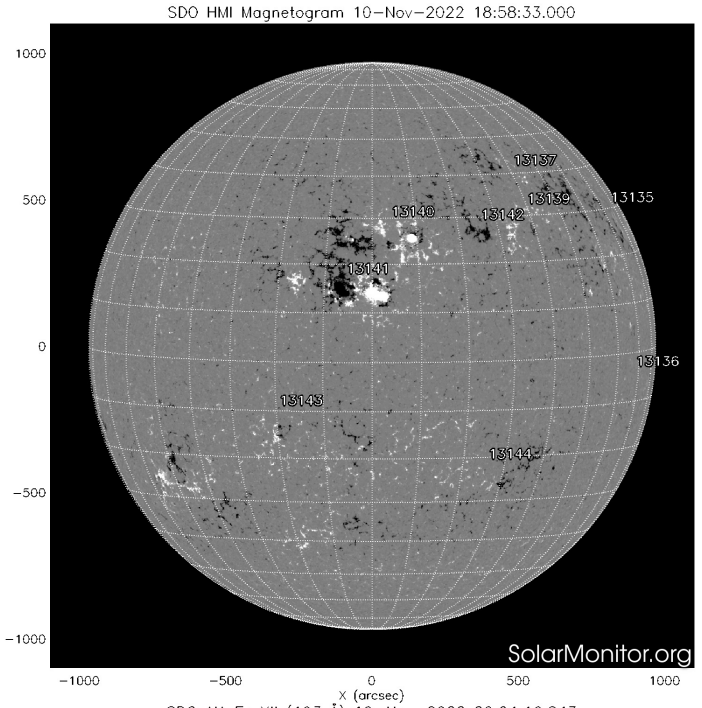
ion intensities affected

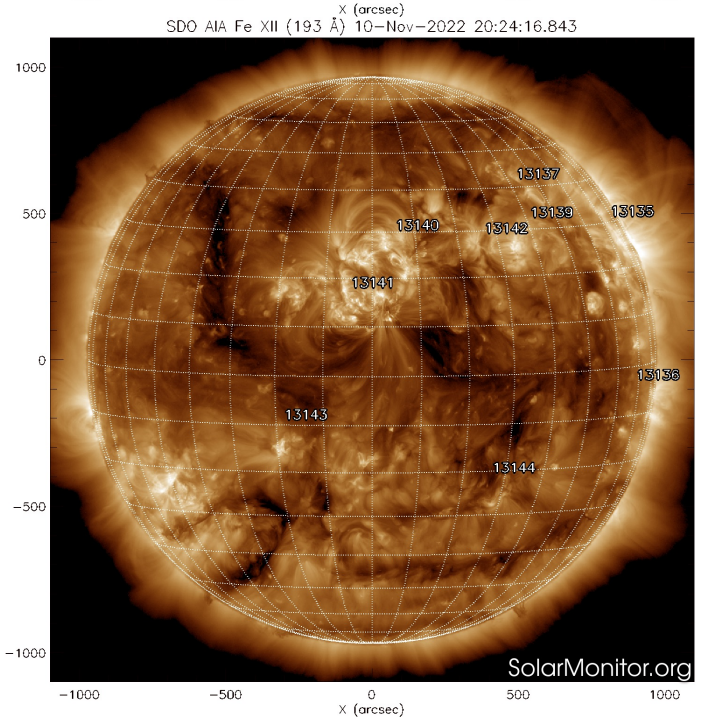

Solar Orbiter/EUI FSI 174
Zirconium_174_n25 L1 priority 61
combitpp 14 (bpp 0.56, Lossy-high quality)
crota -0.913 (deg) dsun_au 0.620 (AU)
crval1,2 88.42,123.80 (arcsec) v107_20221130_002+flown
2022-11-11 07:01:00 (UTC)


STEREO Ahead EUVI 195
2022-11-11 00:05:00

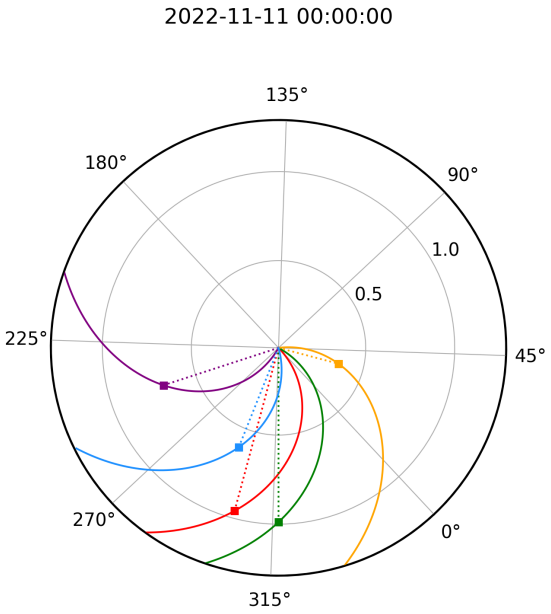


Multiple jets from AR 13141

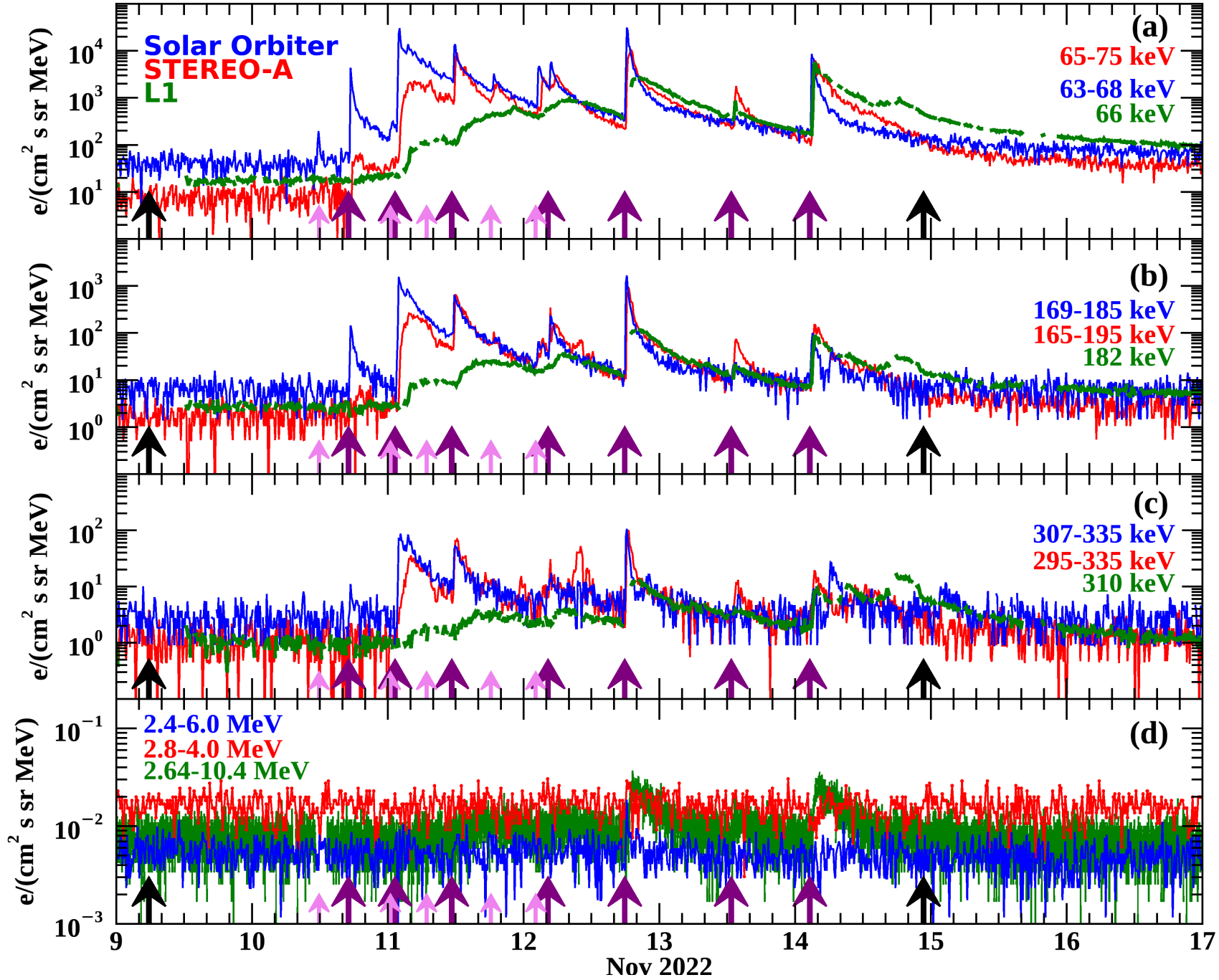




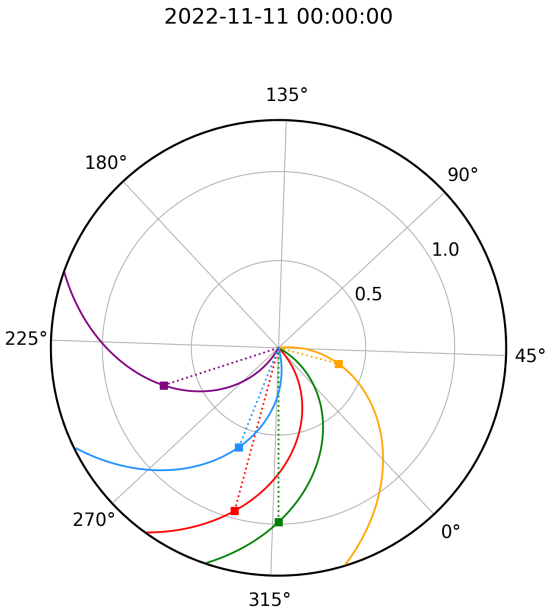
Electron observations



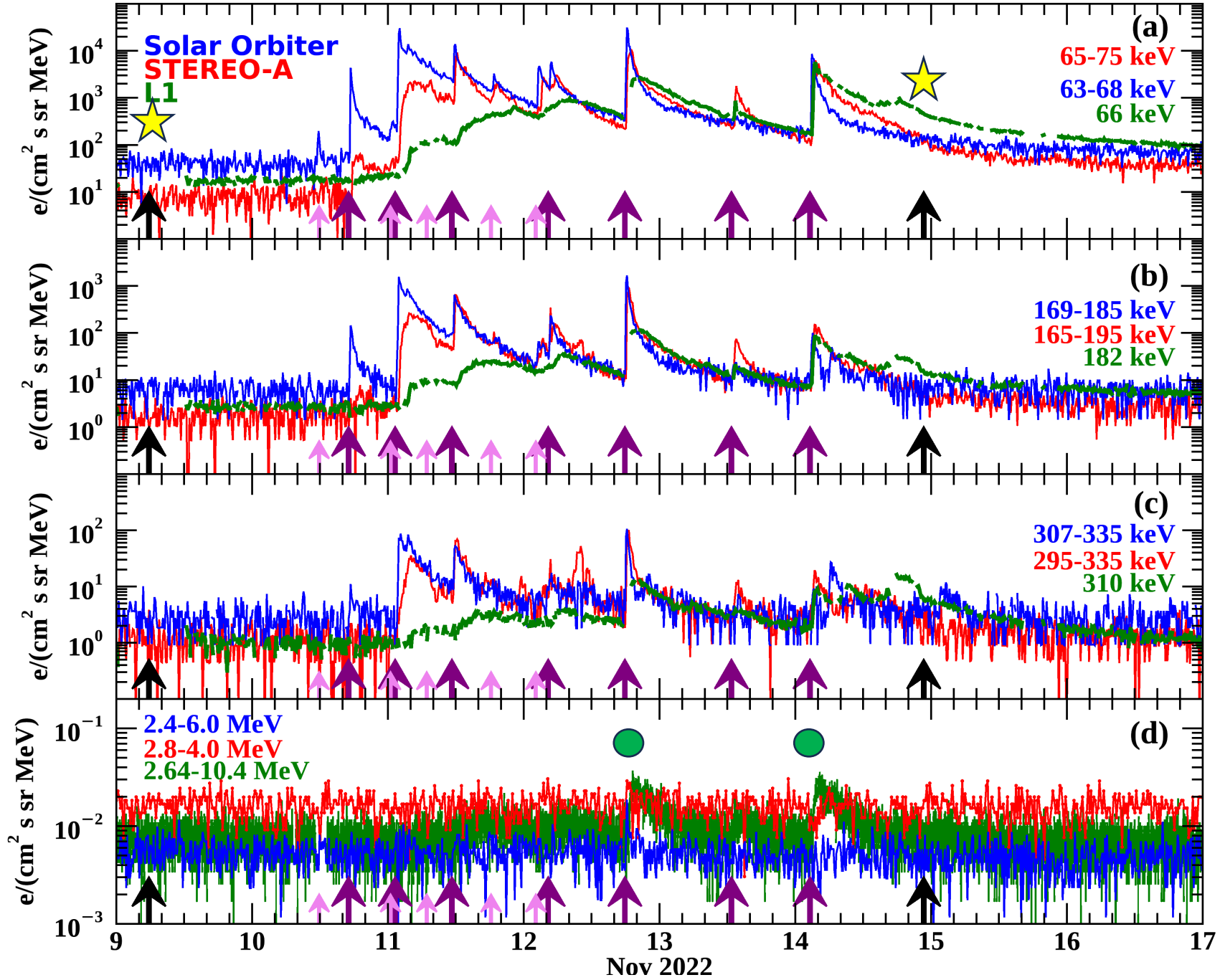
PSP ~0.69 AU -72 deg
SolO ~0.62 AU -21 deg
STA ~0.96 AU -15 deg
Earth ~1.02 AU 0 deg



Electron observations

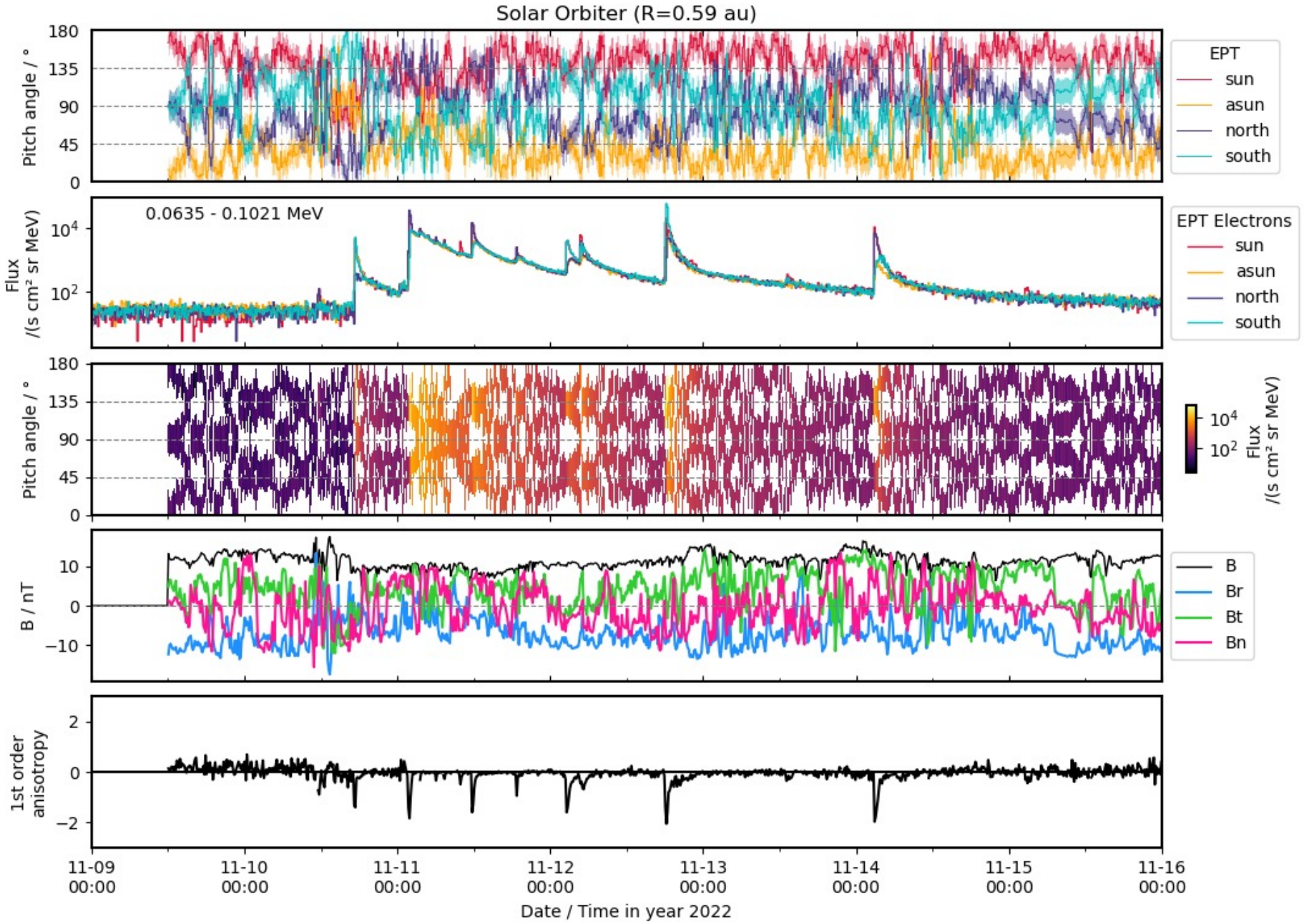


PSP ~0.69 AU -72 deg
SolO ~0.62 AU -21 deg
STA ~0.96 AU -15 deg
Earth ~1.02 AU 0 deg

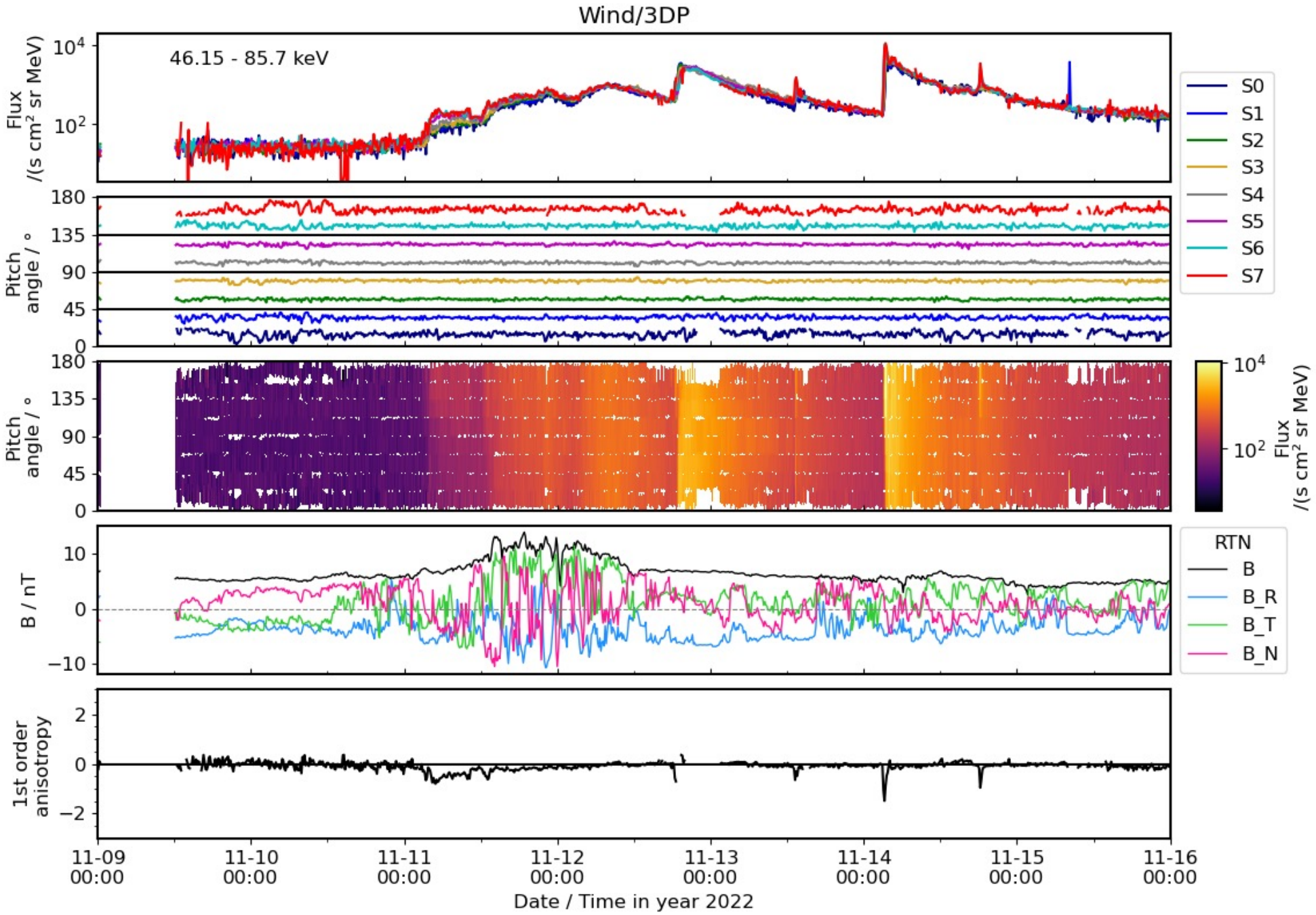


Solar Orbiter Anisotropy Information

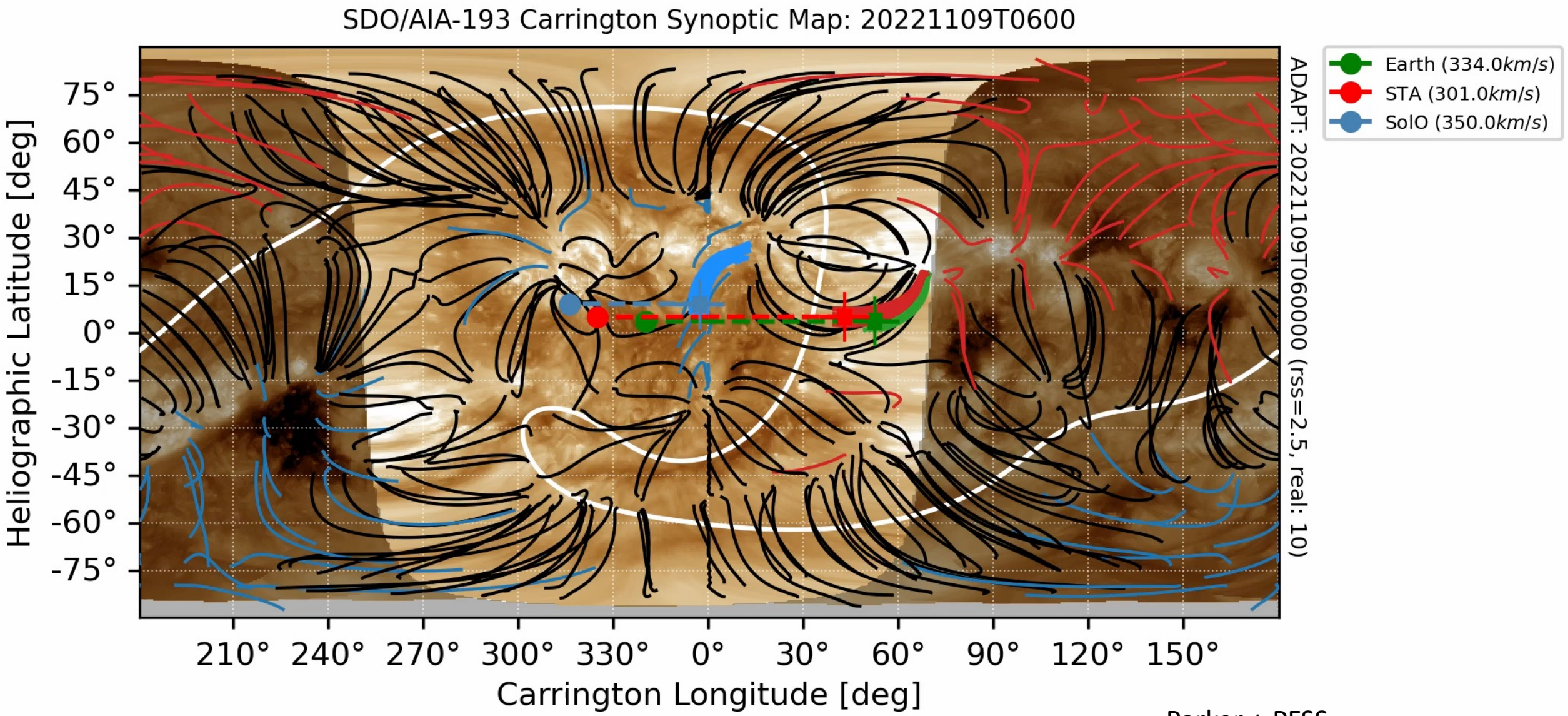
$$A = \frac{3\int_{-1}^{+1} I(\mu)\,\mu\,d\mu}{\int_{-1}^{+1} I(\mu)\,d\mu}$$



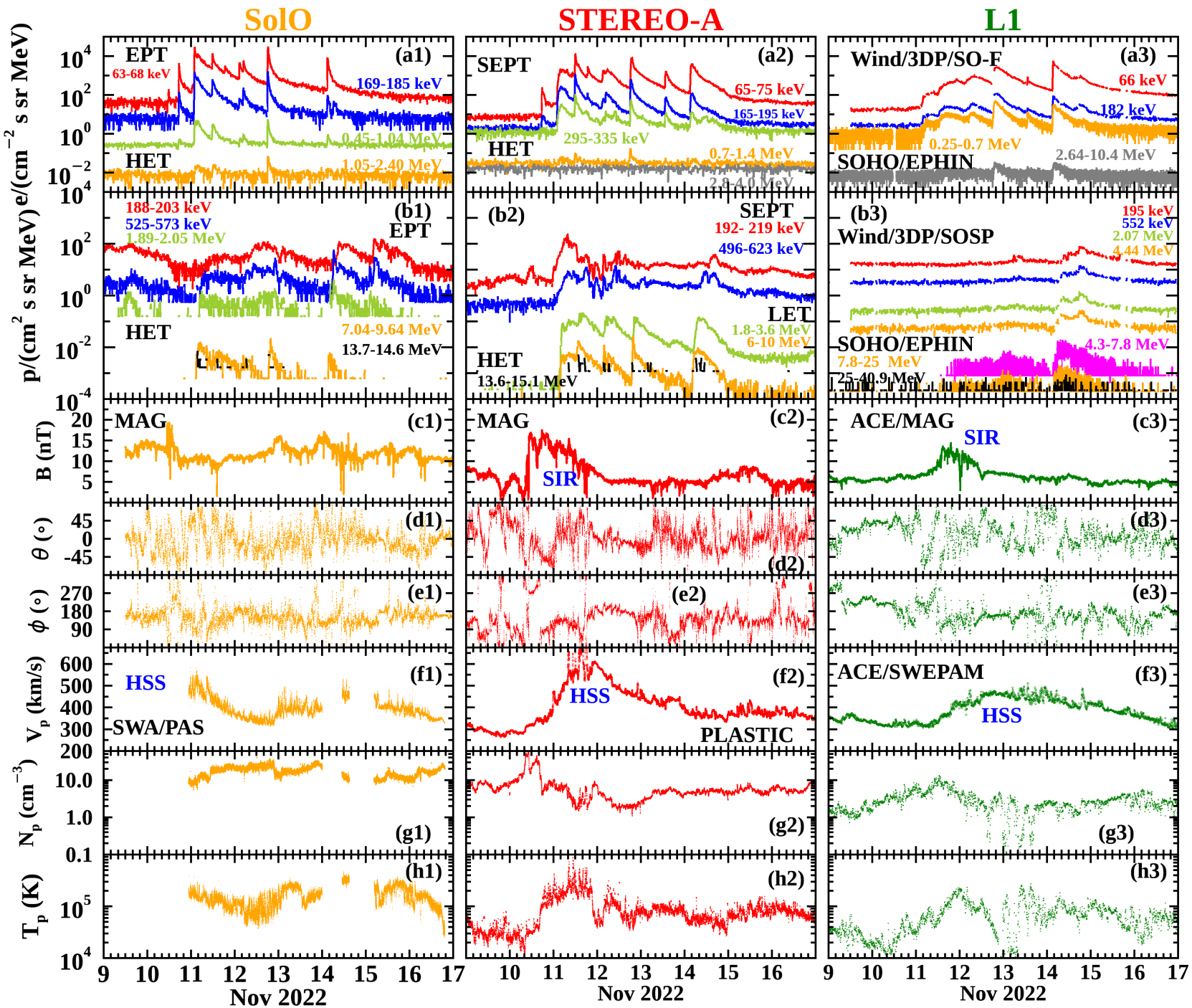
Wind/3DP Anisotropy Information

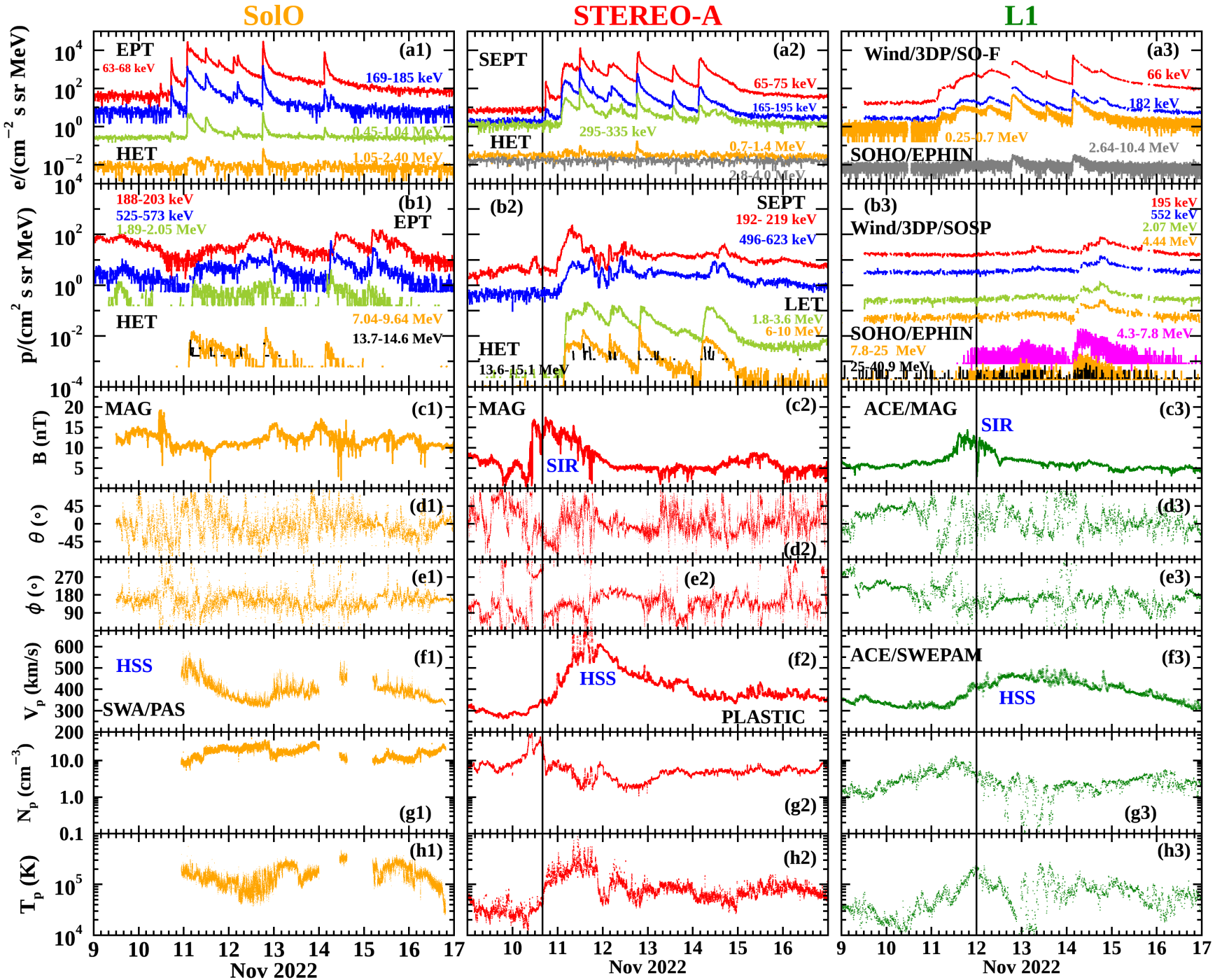


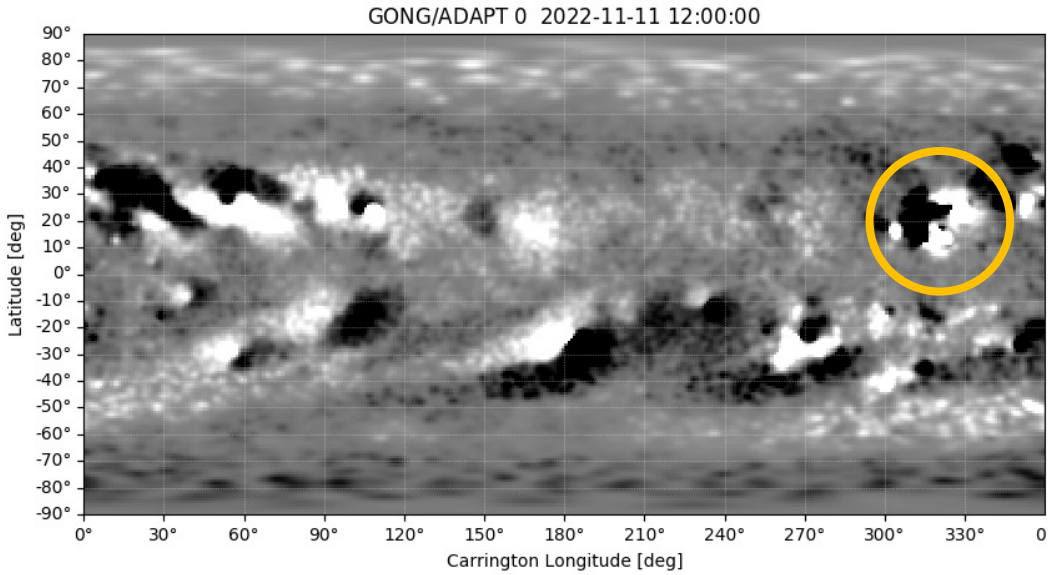
$$A = \frac{3\int_{-1}^{+1} I(\mu)\,\mu\,d\mu}{\int_{-1}^{+1} I(\mu)\,d\mu}$$

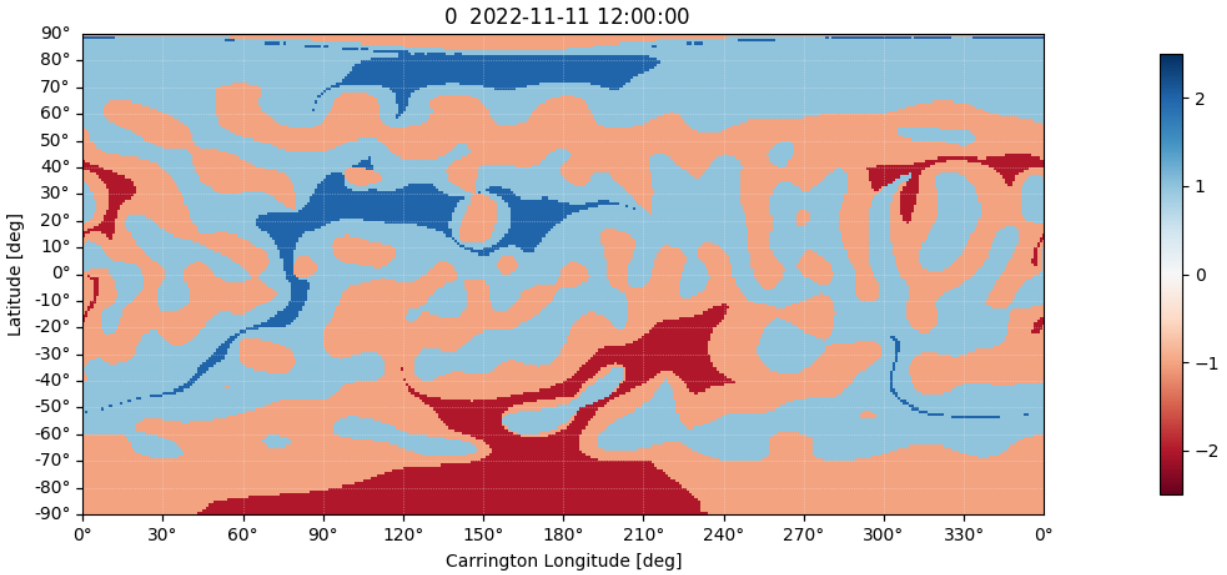

SDO/AIA-193 Carrington Synoptic Map: 20221109T0600
Heliographic Latitude [deg]
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
210°
240°
270°
300°
330°
0°
30°
60°
90°
120°
150°
Carrington Longitude [deg]
Earth (334.0km/s)
STA (301.0km/s)
SolO (350.0km/s)
ADAPT: 20221109T060000 (rss=2.5, real: 10)

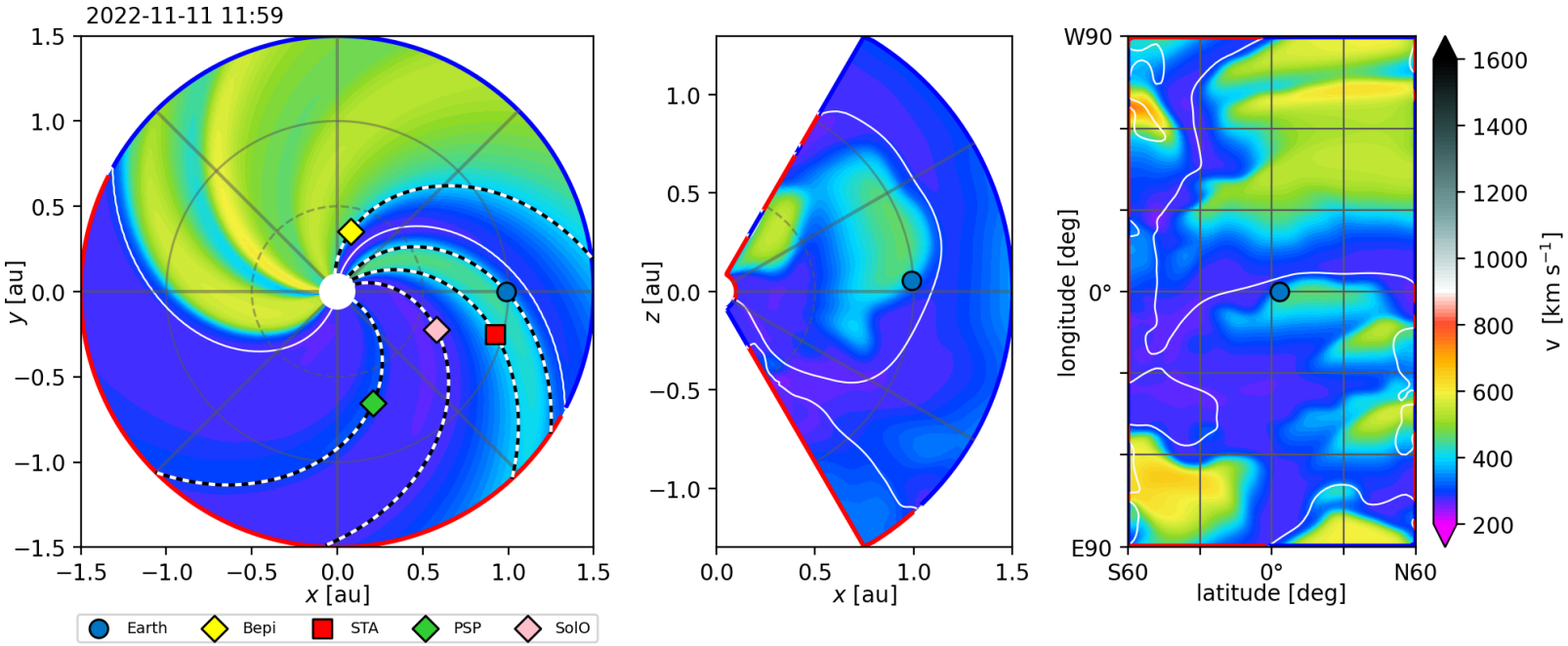
Parker + PFSS


SolO
STEREO-A
L1
EPT
63-68 keV
169-185 keV
0.45-1.04 MeV
HET
1.05-2.40 MeV
(a1)
SEPT
65-75 keV
165-195 keV
295-335 keV
HET
0.7-1.4 MeV
2.8-4.0 MeV
(a2)
Wind/3DP/SO-F
66 keV
182 keV
0.25-0.7 MeV
SOHO/EPHIN
2.64-10.4 MeV
(a3)
p/(cm^2 s sr MeV) e/(cm^{-2} s sr MeV)
188-203 keV
525-573 keV
1.89-2.05 MeV
EPT
HET
7.04-9.64 MeV
13.7-14.6 MeV
(b1)
(b2)
SEPT
192- 219 keV
496-623 keV
LET
1.8-3.6 MeV
6-10 MeV
HET
13.6-15.1 MeV
(b3)
Wind/3DP/SOSP
195 keV
552 keV
2.07 MeV
4.44 MeV
SOHO/EPHIN
4.3-7.8 MeV
7.8-25 MeV
25-40.9 MeV
B (nT)
MAG
(c1)
MAG
SIR
(c2)
ACE/MAG
SIR
(c3)
θ (°)
(d1)
(d2)
(d3)
ϕ (°)
(e1)
(e2)
(e3)
V$_p$ (km/s)
HSS
SWA/PAS
(f1)
HSS
PLASTIC
(f2)
ACE/SWEPAM
HSS
(f3)
N$_p$ (cm^{-3})
(g1)
(g2)
(g3)
T$_p$ (K)
(h1)
(h2)
(h3)
9 10 11 12 13 14 15 16 17
Nov 2022
10 11 12 13 14 15 16
Nov 2022
9 10 11 12 13 14 15 16 17
Nov 2022

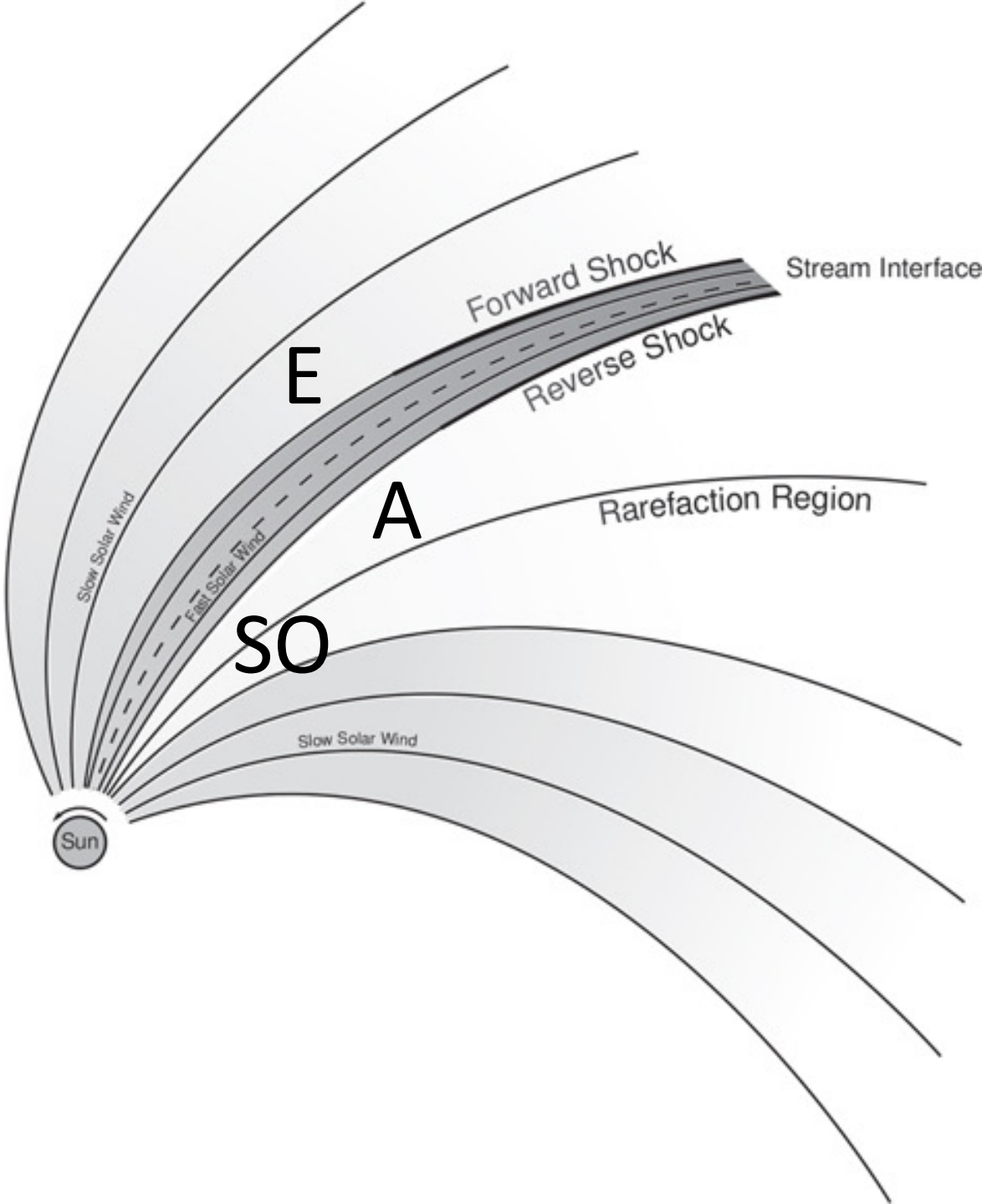

SolO
STEREO-A
L1
EPT
63-68 keV
169-185 keV
0.45-1.04 MeV
HET
1.05-2.40 MeV
(a1)
SEPT
65-75 keV
165-195 keV
295-335 keV
HET
0.7-1.4 MeV
2.8-4.0 MeV
(a2)
Wind/3DP/SO-F
66 keV
182 keV
0.25-0.7 MeV
SOHO/EPHIN
2.64-10.4 MeV
(a3)
e/(cm^{-2} s sr MeV)
188-203 keV
525-573 keV
1.89-2.05 MeV
EPT
HET
7.04-9.64 MeV
13.7-14.6 MeV
(b1)
(b2)
SEPT
192- 219 keV
496-623 keV
LET
1.8-3.6 MeV
6-10 MeV
HET
13.6-15.1 MeV
(b3)
Wind/3DP/SOSP
195 keV
552 keV
2.07 MeV
4.44 MeV
SOHO/EPHIN
4.3-7.8 MeV
7.8-25 MeV
25-40.9 MeV
p/(cm^2 s sr MeV)
MAG
(c1)
MAG
SIR
(c2)
ACE/MAG
SIR
(c3)
B (nT)
θ (°)
(d1)
(d2)
(d3)
ϕ (°)
(e1)
(e2)
(e3)
HSS
SWA/PAS
(f1)
HSS
PLASTIC
(f2)
ACE/SWEPAM
HSS
(f3)
V$_p$ (km/s)
N$_p$ (cm^{-3})
(g1)
(g2)
(g3)
T$_p$ (K)
(h1)
(h2)
(h3)
Nov 2022
Nov 2022
Nov 2022

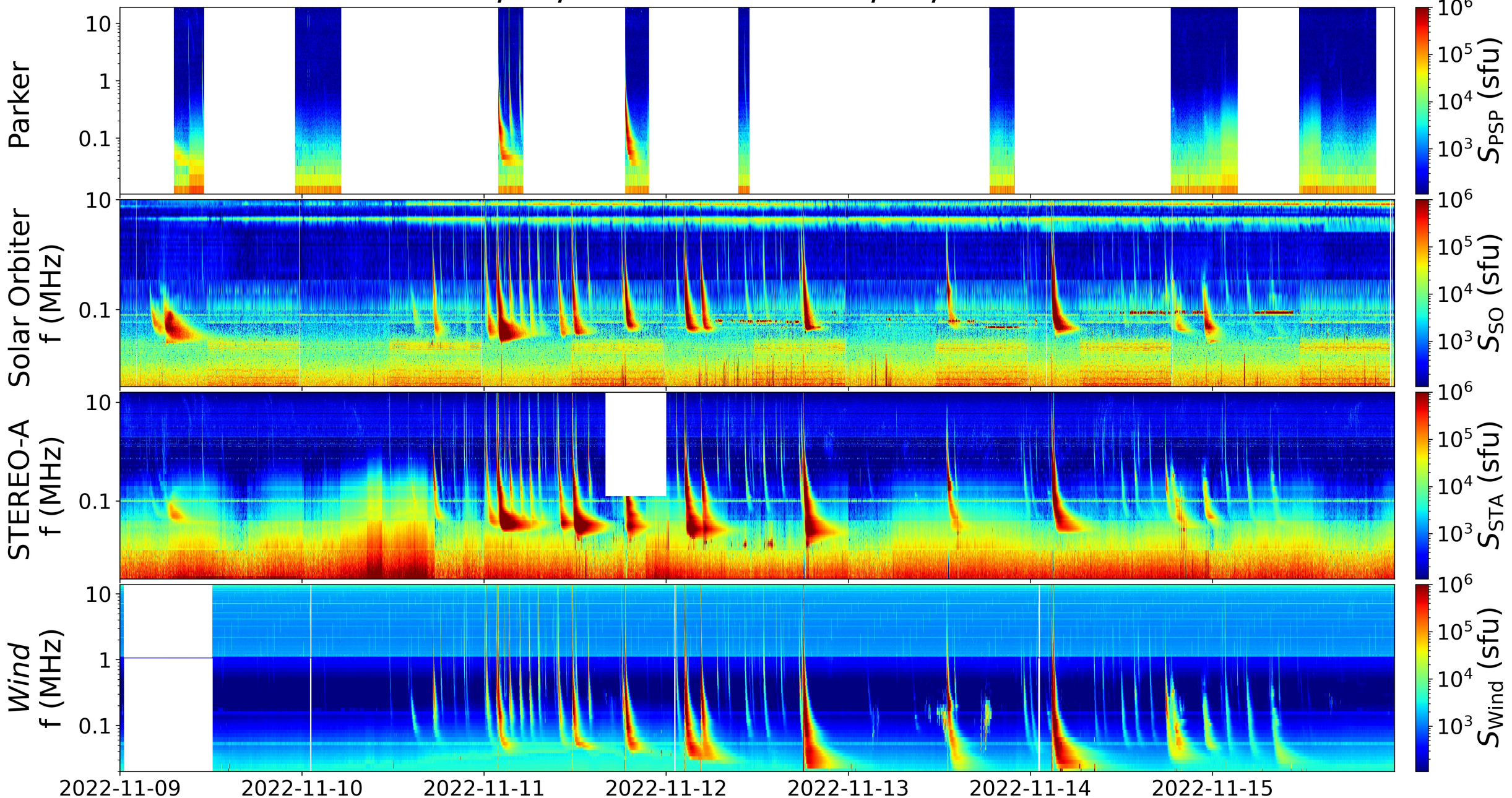






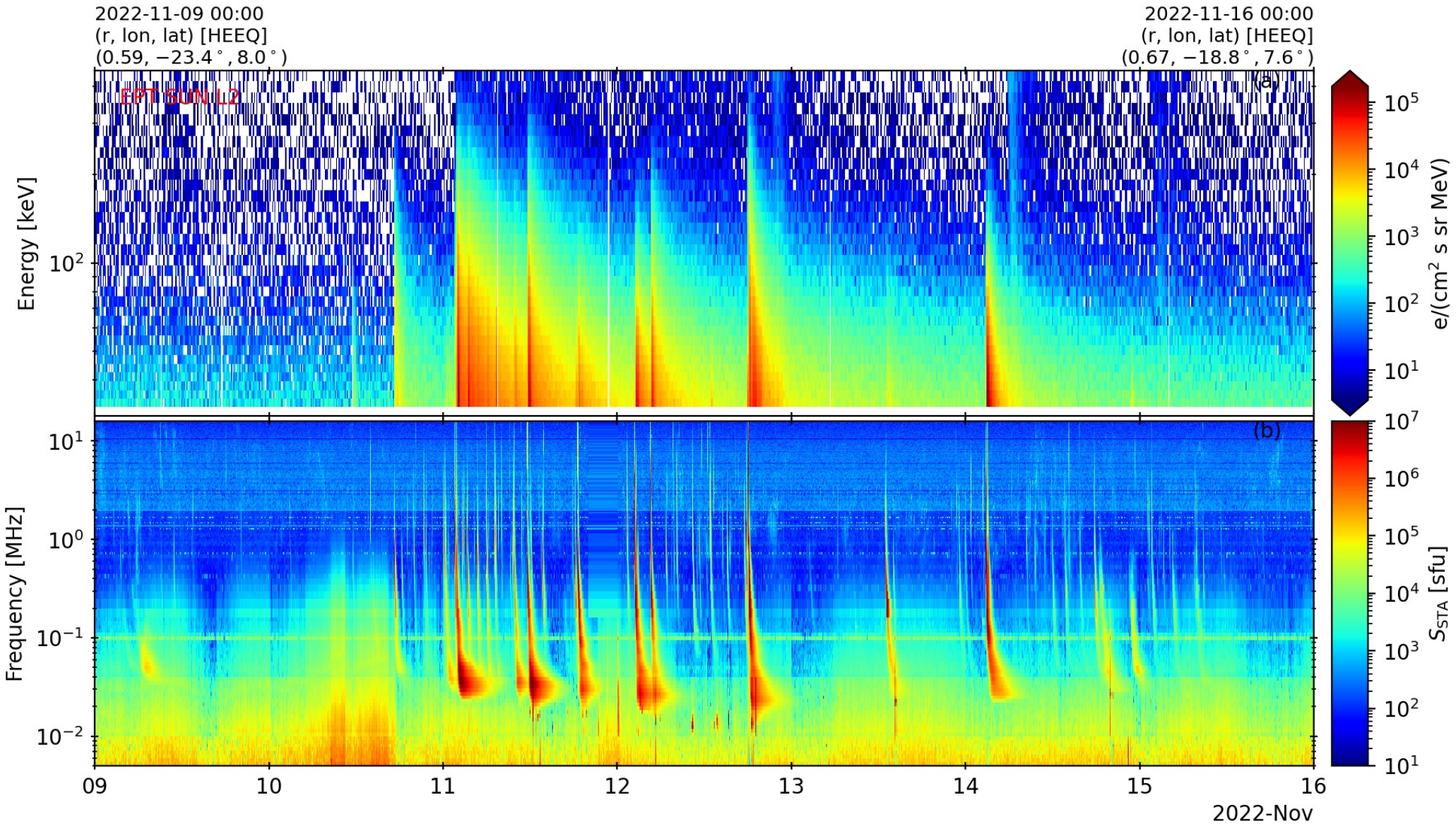
EUHFORIA results


Forward Shock
Stream Interface
Reverse Shock
E
A
SO
Rarefaction Region
Slow Solar Wind
Fast Solar Wind
Slow Solar Wind
Sun


2022/11/09 00:00 - 2022/11/15 23:59
Parker
Solar Orbiter
f (MHz)
STEREO-A
f (MHz)
Wind
f (MHz)
10
1
0.1
S_{PSP} (sfu)
S_{SO} (sfu)
S_{STA} (sfu)
S_{Wind} (sfu)
10^6
10^5
10^4
10^3
2022-11-09
2022-11-10
2022-11-11
2022-11-12
2022-11-13
2022-11-14
2022-11-15
V. Krupar

Solar Orbiter
EPT electrons
31-435 keV

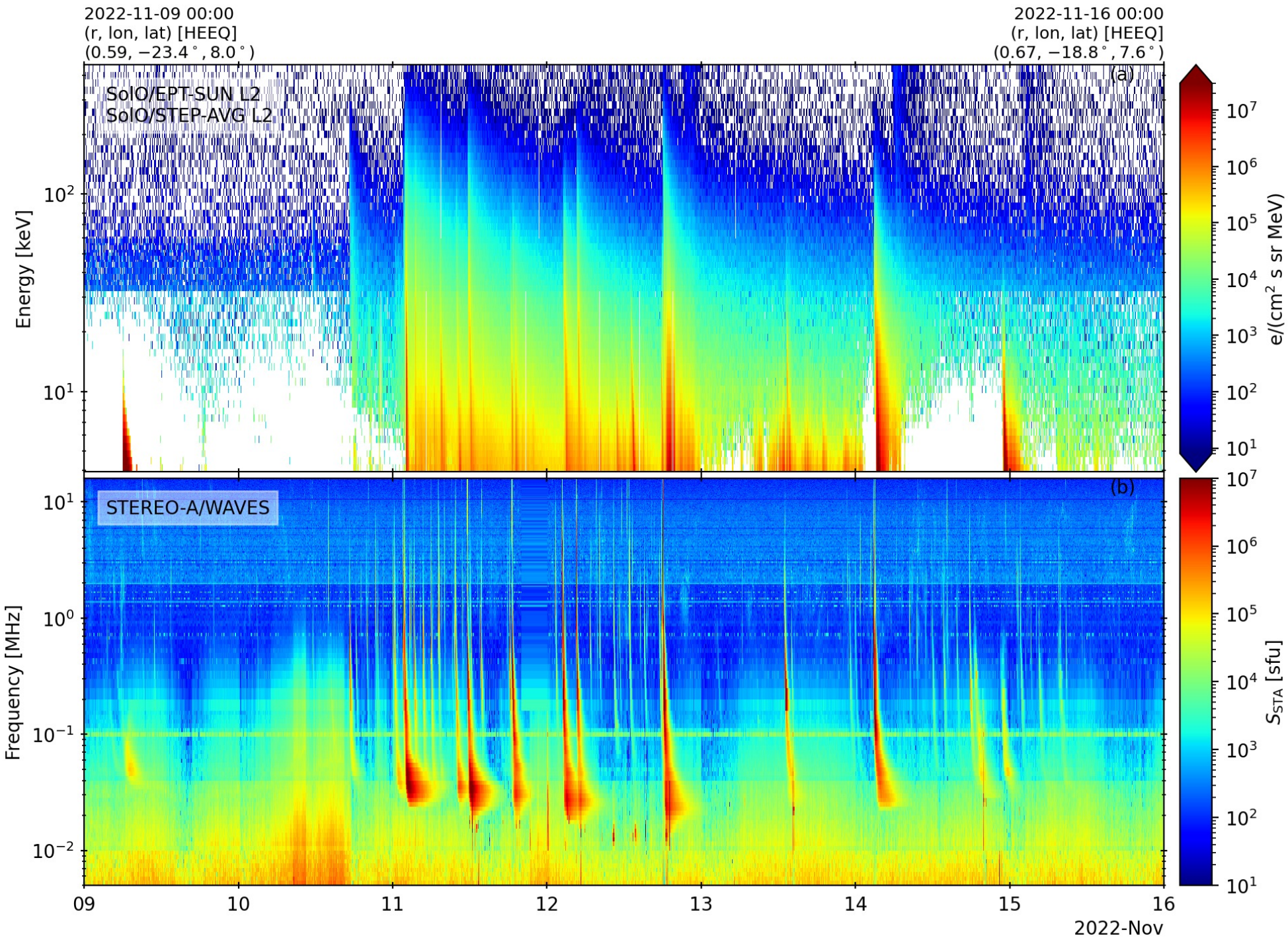
STEREO-A
Multiple Type III
Radio bursts

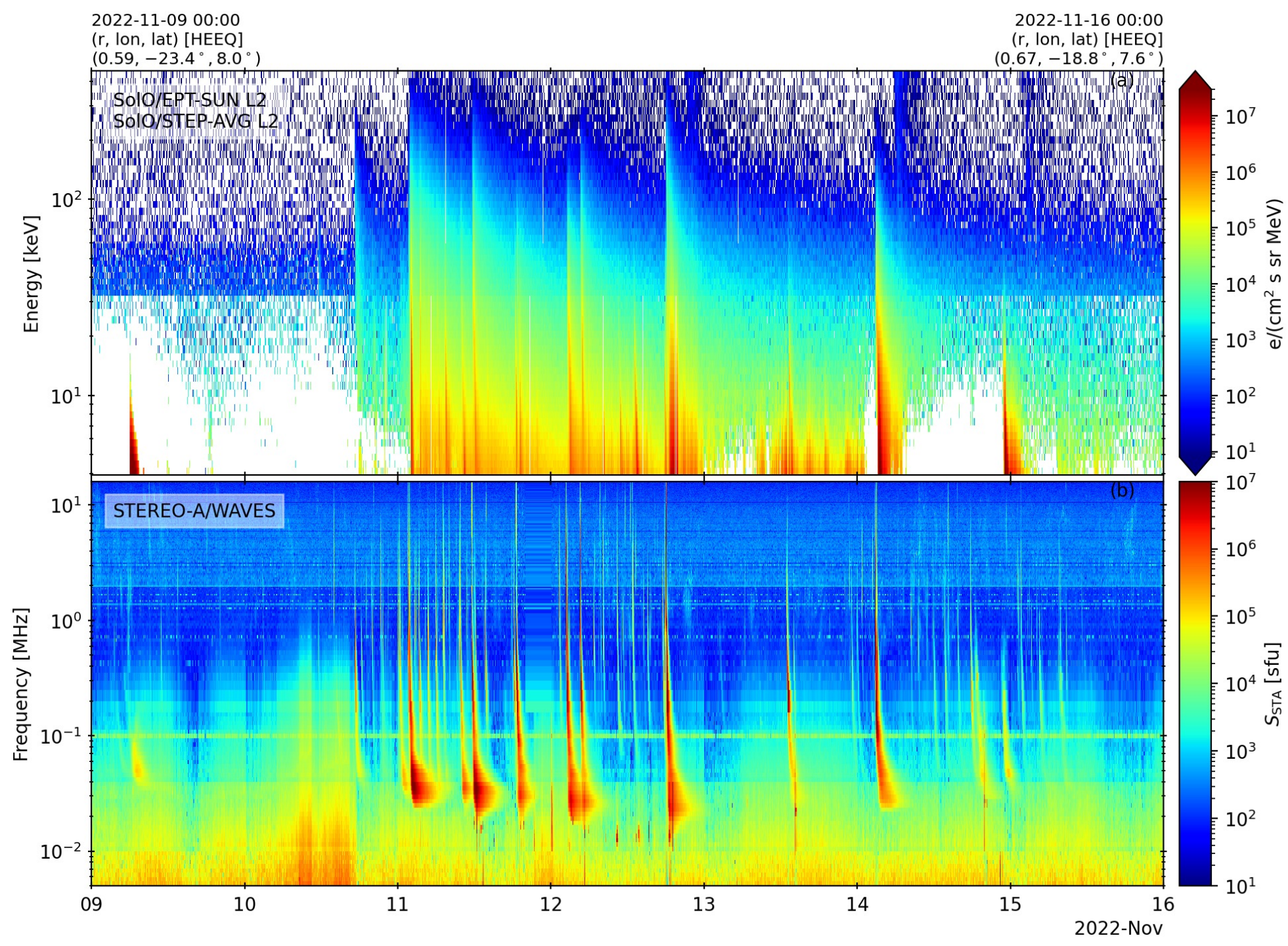


Solar Orbiter
EPT electrons
31-435 keV

STEP electrons
4-31 keV

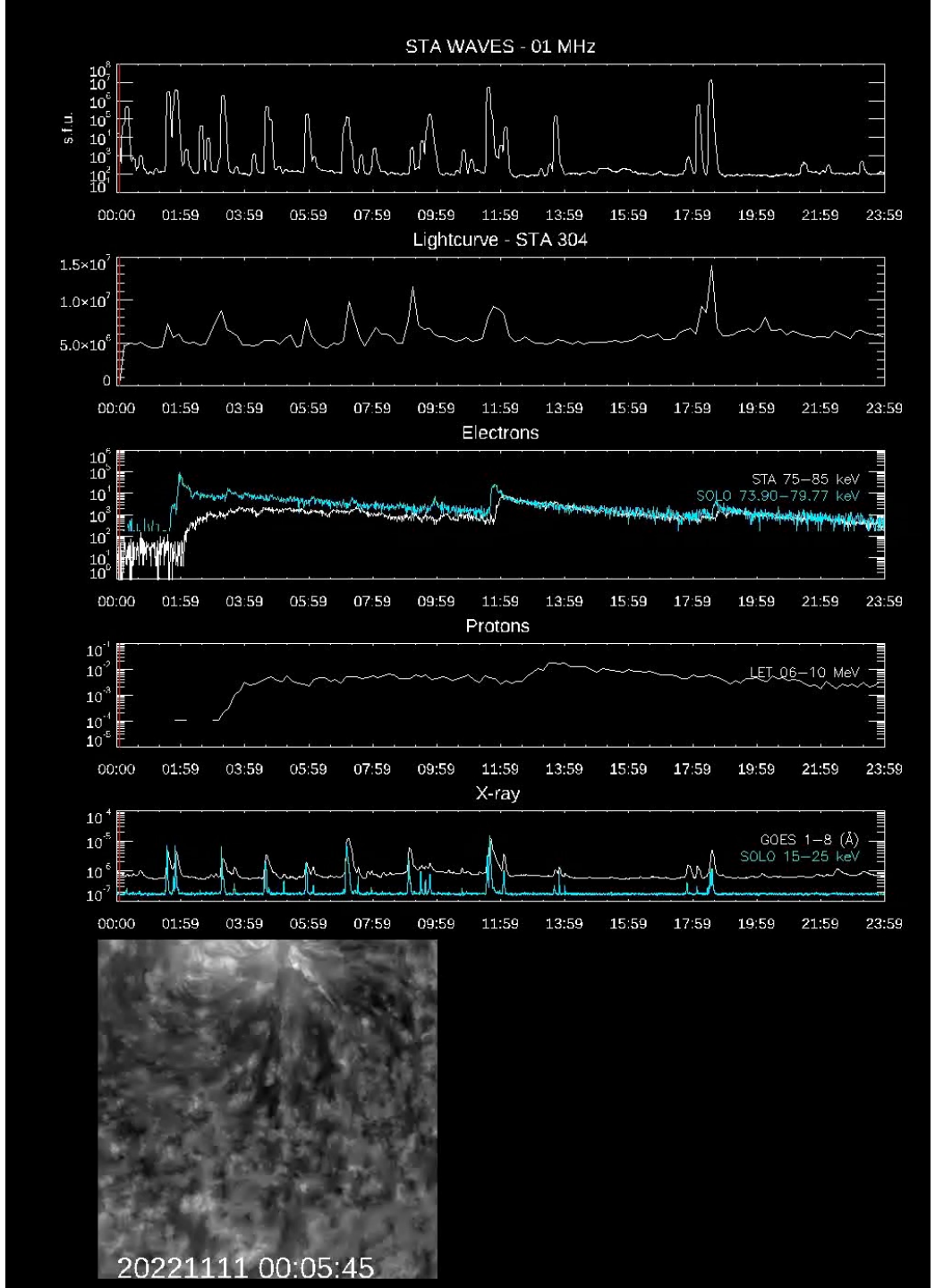
STEREO-A
Multiple Type III
Radio bursts

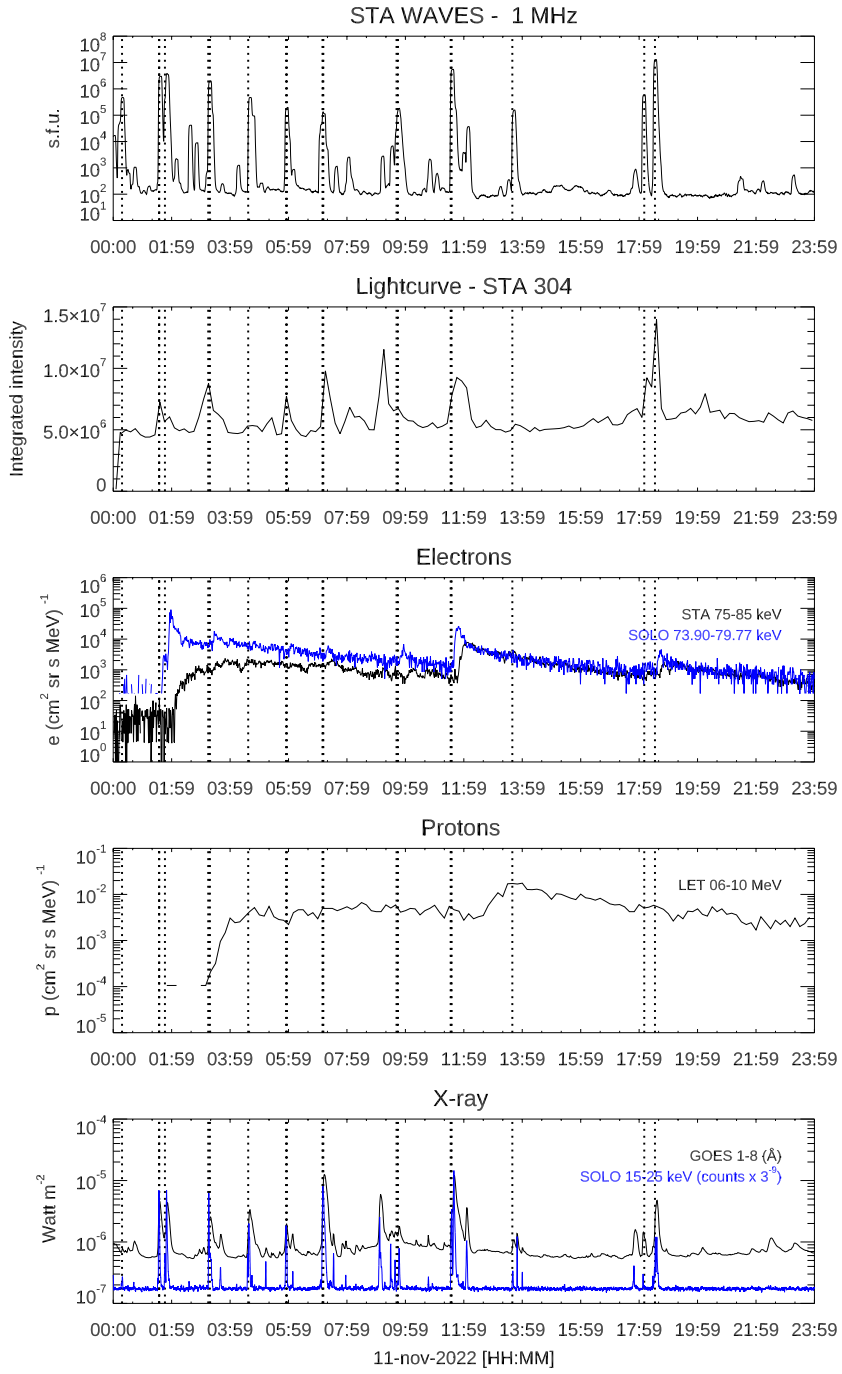


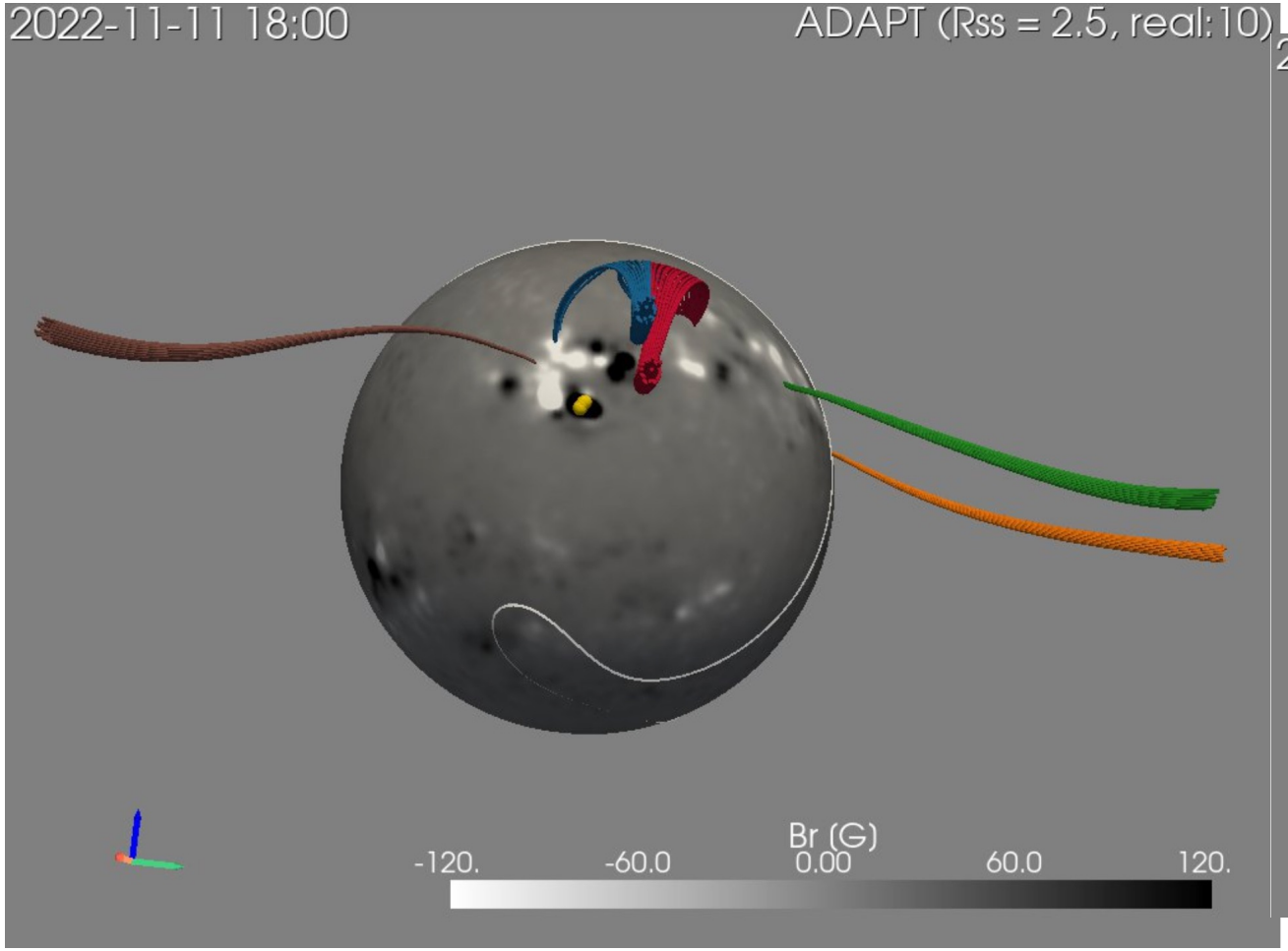


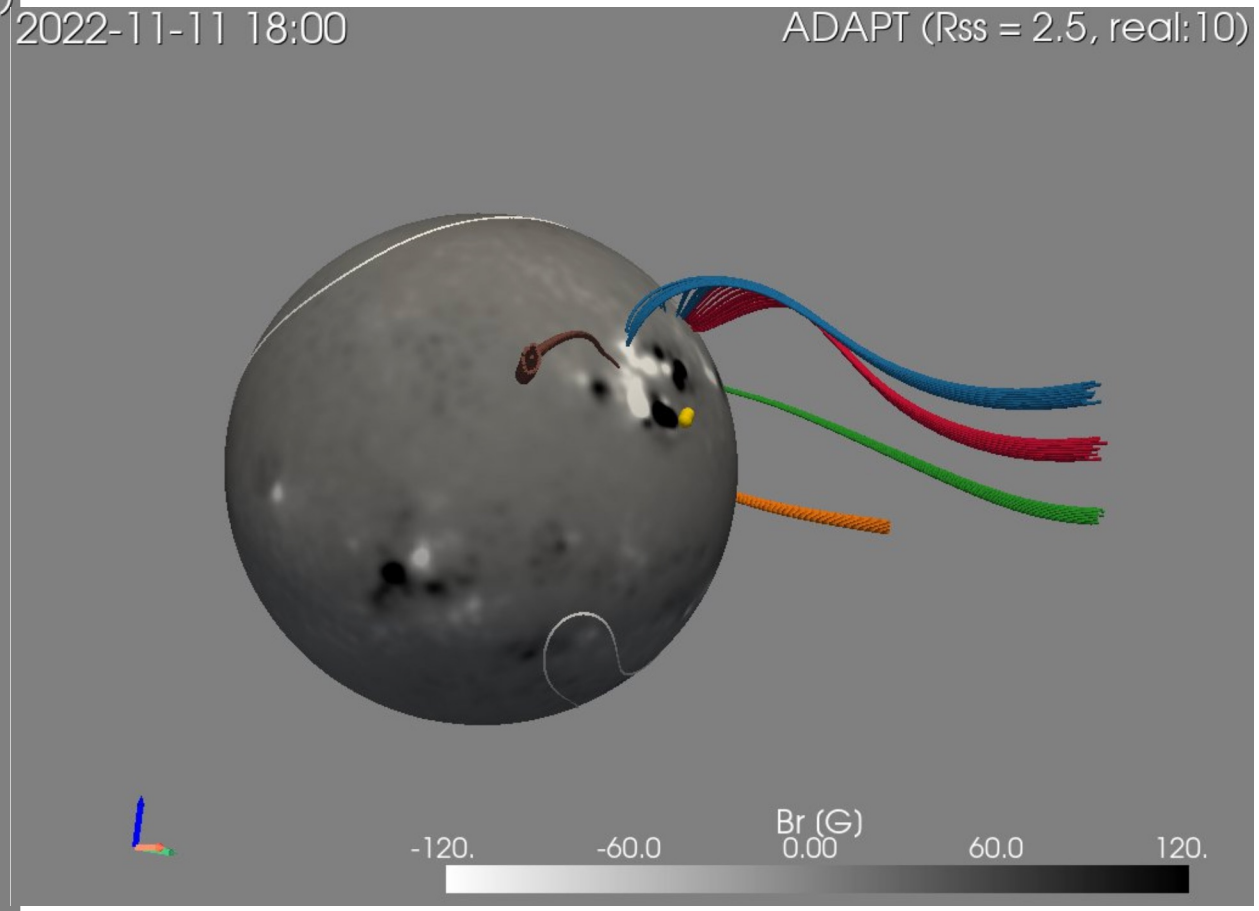
e- Release Times (Raúl)

09 Nov 313/05:52:16 i
10 Nov 314/11:30:16
10 Nov 314/17:10:43
11 Nov 315/00:18:10
11 Nov 315/01:34:10 p
01:34:32(V)
11 Nov 315/01:46:10
11 Nov 315/03:15:44
03:18:37(V)
11 Nov 315/04:37:09
11 Nov 315/05:55:07
05:56:31(V)
11 Nov 315/07:09:47
07:11:31(V)
11 Nov 315/09:41:51
09:44:50(V)
11 Nov 315/11:32:58 p
11:35:00(V)
11 Nov 315/13:39:38
11 Nov 315/18:10:31
11 Nov 315/18:32:30
12 Nov 316/02:21:16 p
02:24:17(V)
12 Nov 316/04:33:13
04:34:47(V)
12 Nov 316/12:51:29
12 Nov 316/17:47:55 p
13 Nov 317/13:05:04
14 Nov 318/02:42:03 p
02:45:04(V)
14 Nov 318/22:36:53 i
22:31:37(V)

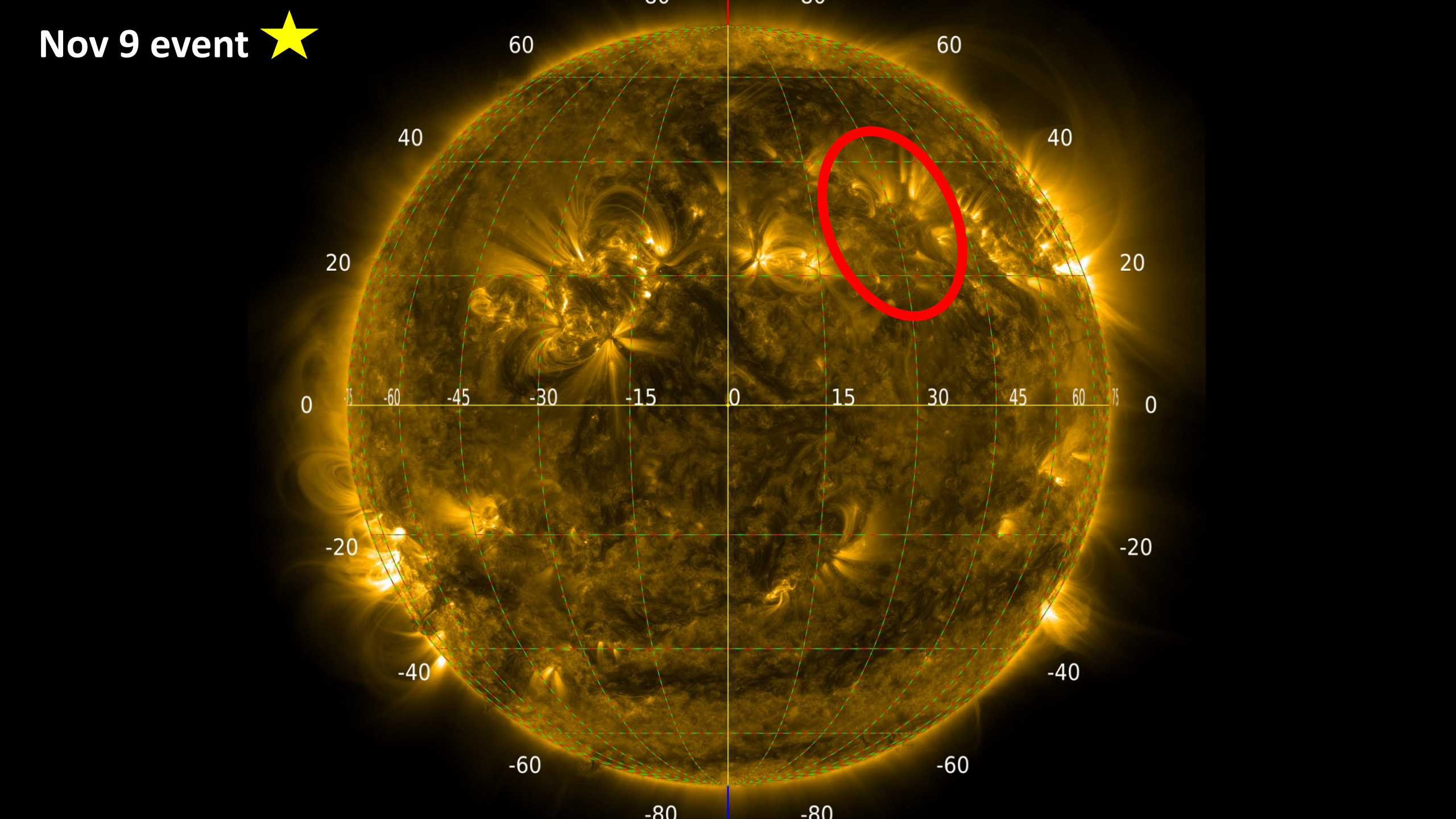

STA WAVES - 01 MHz
s.f.u.
00:00 01:59 03:59 05:59 07:59 09:59 11:59 13:59 15:59 17:59 19:59 21:59 23:59
Lightcurve - STA 304
1.5×10^7
1.0×10^7
5.0×10^6
0
Electrons
STA 75–85 keV
SOLO 73.90–79.77 keV
Protons
LET 06–10 MeV
X-ray
GOES 1–8 (Å)
SOLO 15–25 keV
20221111 00:05:45

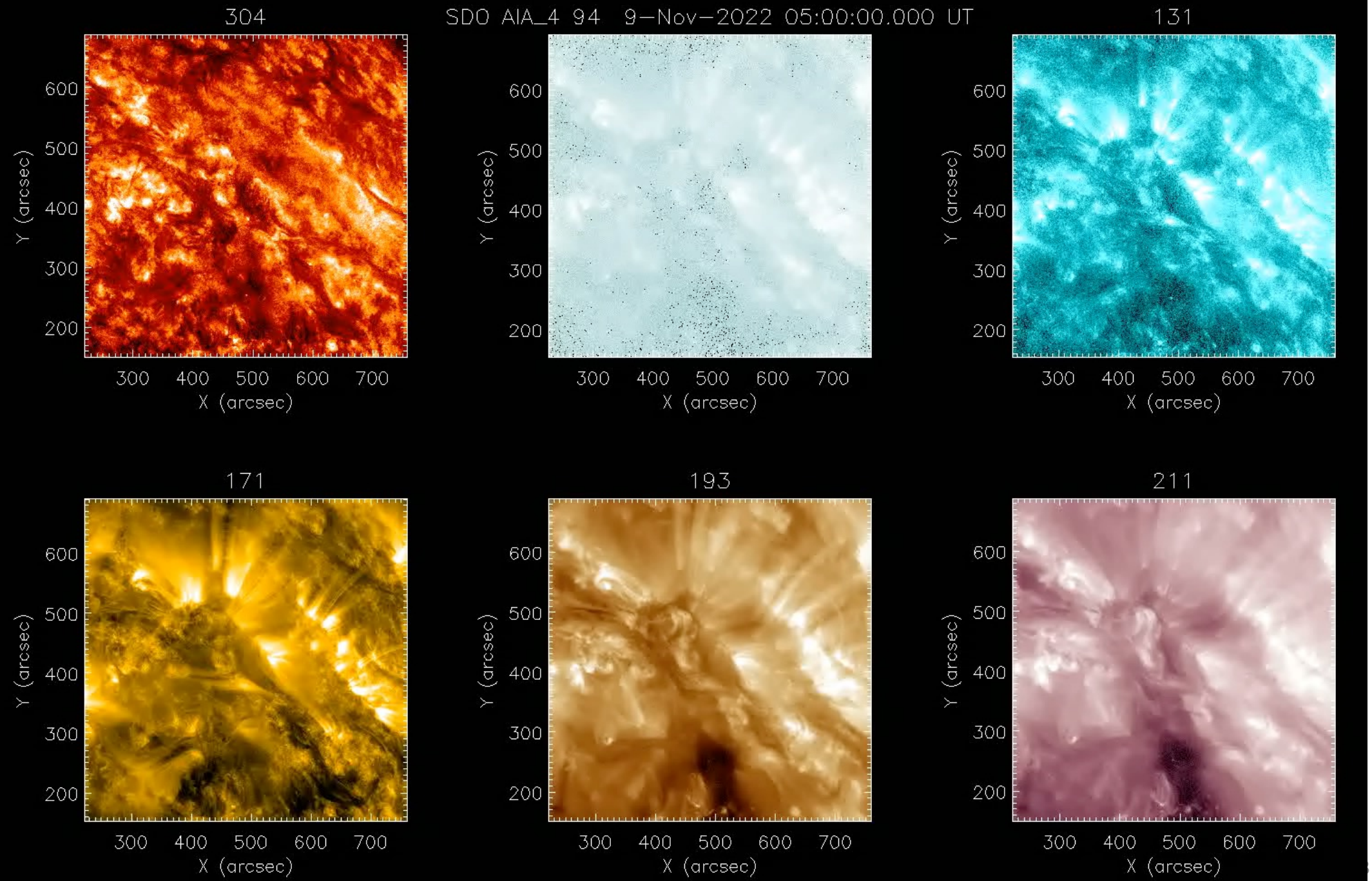

STA WAVES - 1 MHz
s.f.u.
00:00 01:59 03:59 05:59 07:59 09:59 11:59 13:59 15:59 17:59 19:59 21:59 23:59
Lightcurve - STA 304
Integrated intensity
Electrons
e (cm2 sr s MeV)-1
STA 75-85 keV
SOLO 73.90-79.77 keV
Protons
p (cm2 sr s MeV)-1
LET 06-10 MeV
X-ray
Watt m-2
GOES 1-8 (Å)
SOLO 15-25 keV (counts x 3-6)
11-nov-2022 [HH:MM]

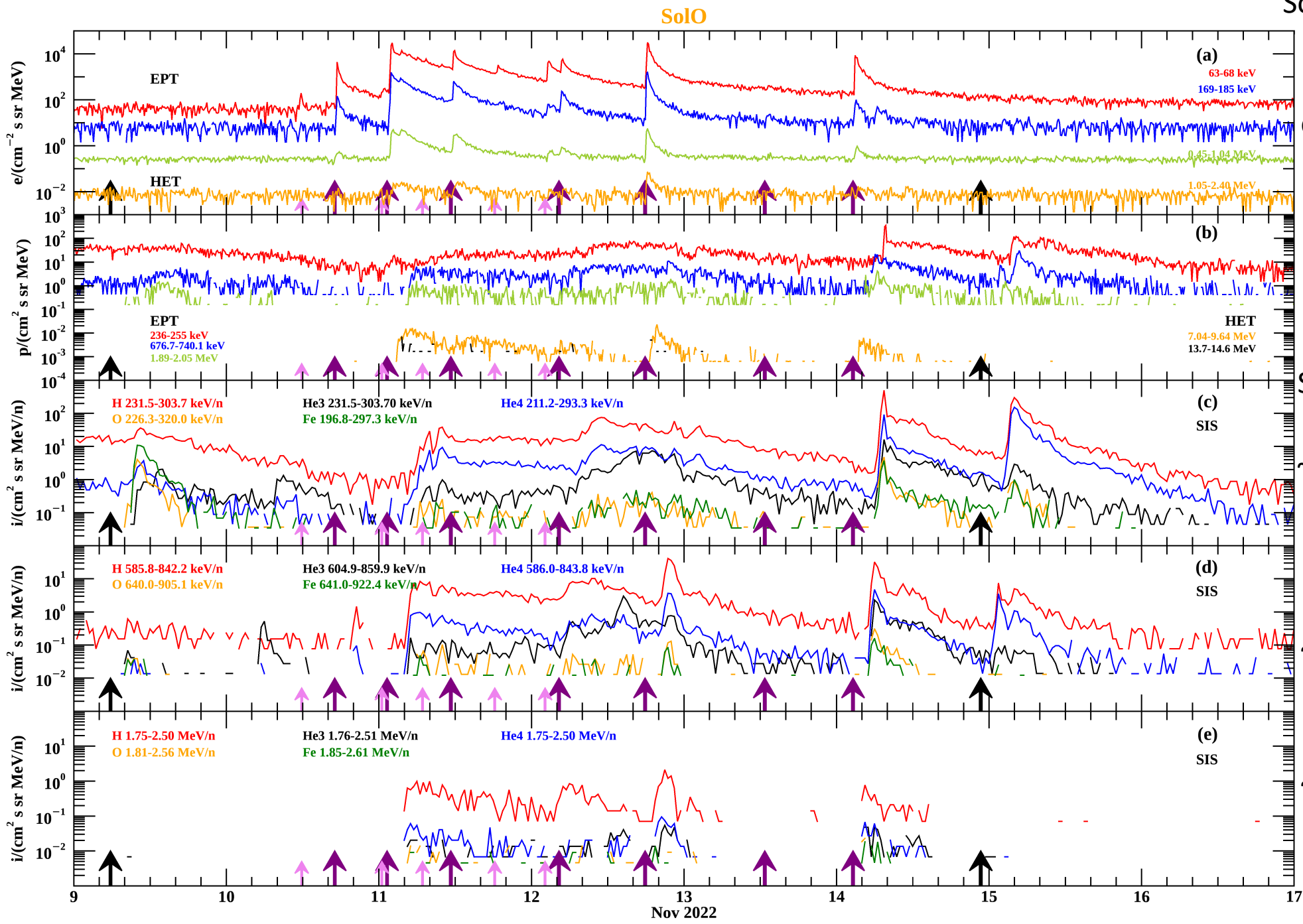

2022-11-11 18:00
ADAPT (Rss = 2.5, real:10)
Br (G)
-120.
-60.0
0.00
60.0
120.


2022-11-11 18:00
ADAPT (Rss = 2.5, real:10)
Br (G)
-120.
-60.0
0.00
60.0
120.

Parker + PFSS


Nov 9 event
60
40
20
0
-20
-40
-60
-80
-75
-60
-45
-30
-15
0
15
30
45
60
75


SDO AIA_4 94 9-Nov-2022 05:00:00.000 UT
304
131
171
193
211
Y (arcsec)
X (arcsec)
200
300
400
500
600
700



Solar Orbiter/EPD

electrons

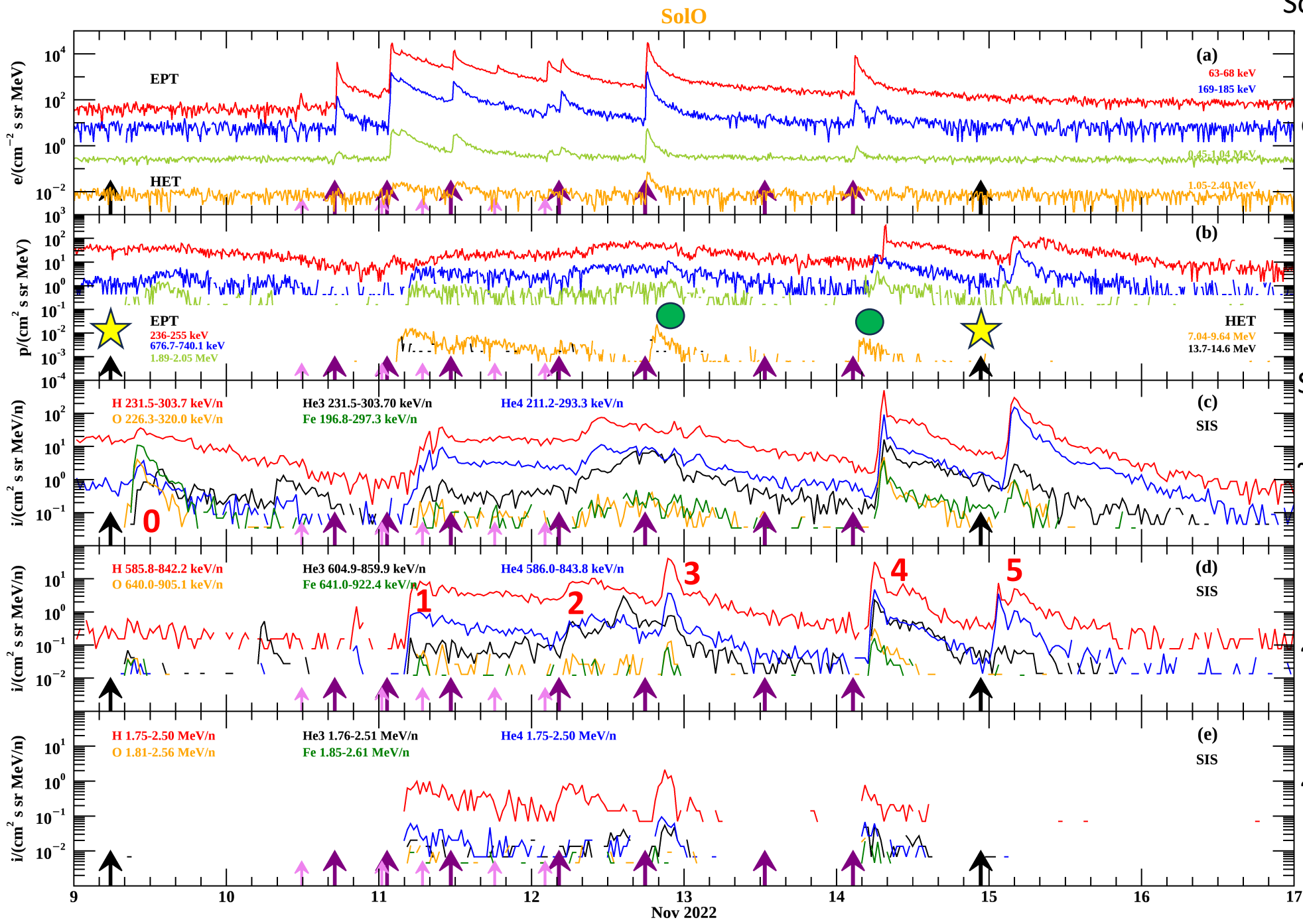
ions

Solar Orbiter/SIS

~200 keV/n

~600 keV/n

~1.7 MeV/n

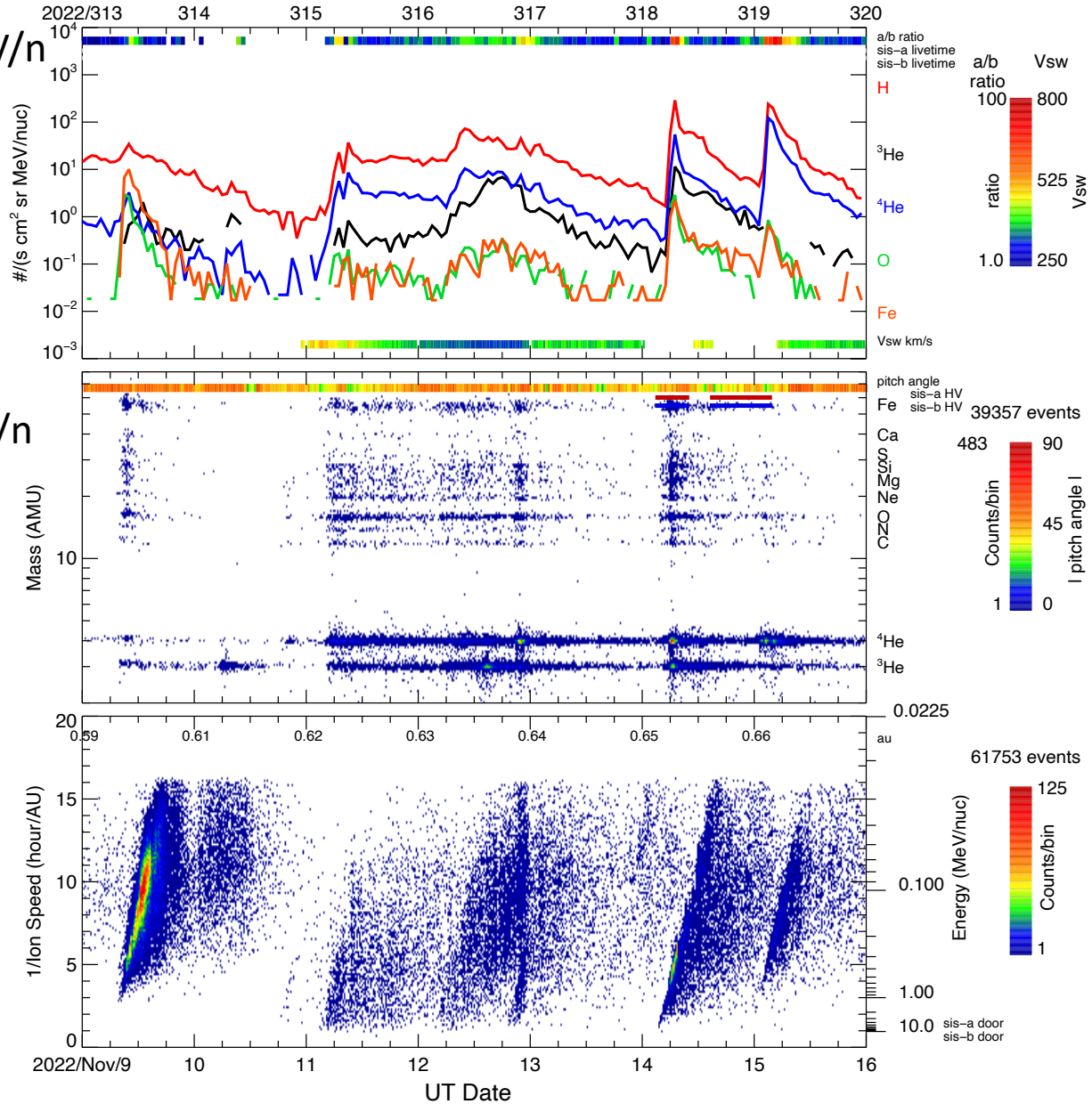

SolO
Solar Orbiter/EPD
(a)
EPT
63-68 keV
169-185 keV
0.45-1.04 MeV
HET
1.05-2.40 MeV
e/(cm^{-2} s sr MeV)
electrons
(b)
EPT
236-255 keV
676.7-740.1 keV
1.89-2.05 MeV
HET
7.04-9.64 MeV
13.7-14.6 MeV
p/(cm^2 s sr MeV)
ions
Solar Orbiter/SIS
H 231.5-303.7 keV/n
O 226.3-320.0 keV/n
He3 231.5-303.70 keV/n
Fe 196.8-297.3 keV/n
He4 211.2-293.3 keV/n
(c)
SIS
i/(cm^2 s sr MeV/n)
~200 keV/n
0
H 585.8-842.2 keV/n
O 640.0-905.1 keV/n
He3 604.9-859.9 keV/n
Fe 641.0-922.4 keV/n
He4 586.0-843.8 keV/n
(d)
SIS
1
2
3
4
5
~600 keV/n
H 1.75-2.50 MeV/n
O 1.81-2.56 MeV/n
He3 1.76-2.51 MeV/n
Fe 1.85-2.61 MeV/n
He4 1.75-2.50 MeV/n
(e)
SIS
~1.7 MeV/n
9
10
11
12
13
14
15
16
17
Nov 2022

Solar Orbiter/SIS

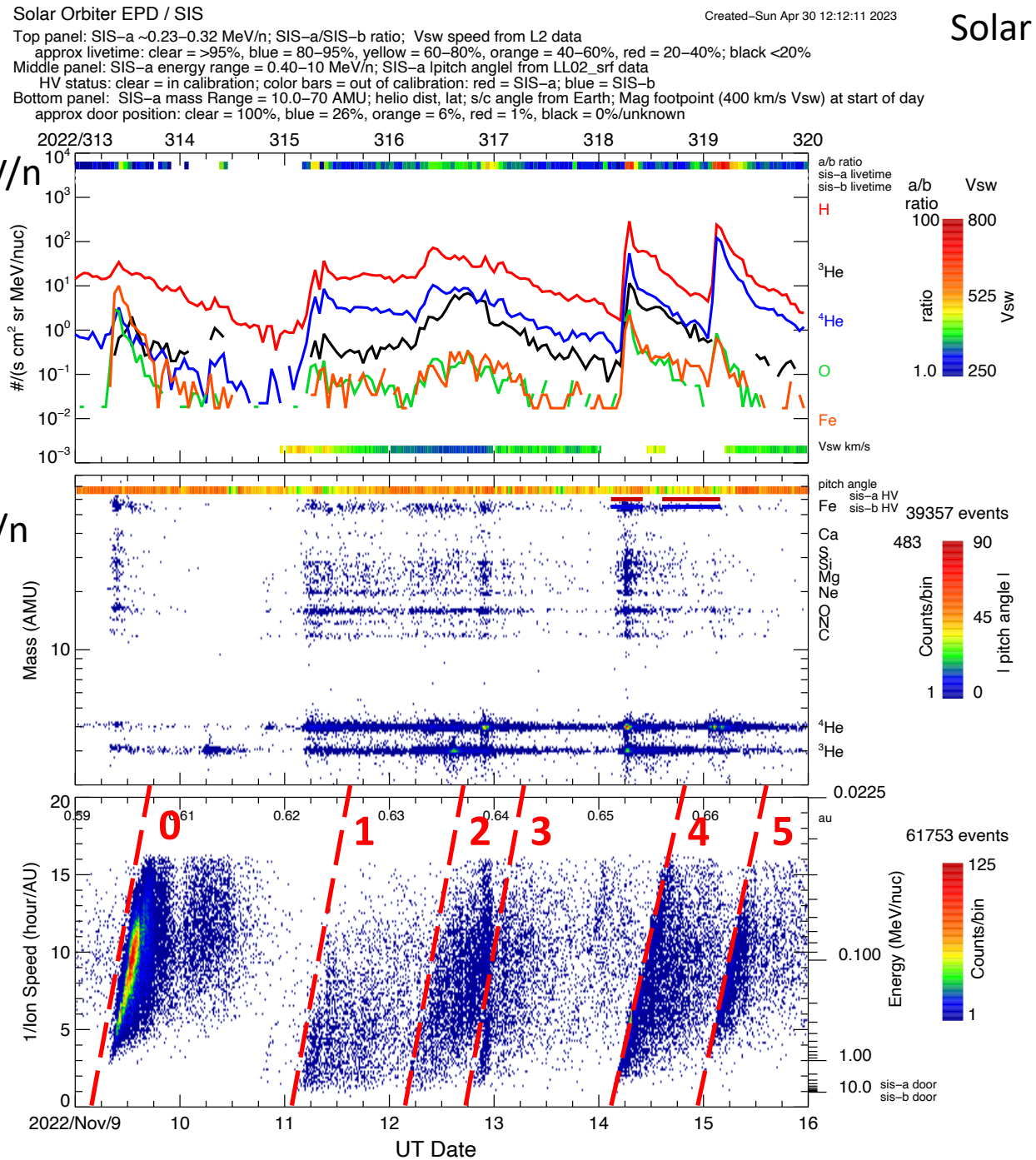
230-320 keV/n

0.4-10 MeV/n

10-70 AMU

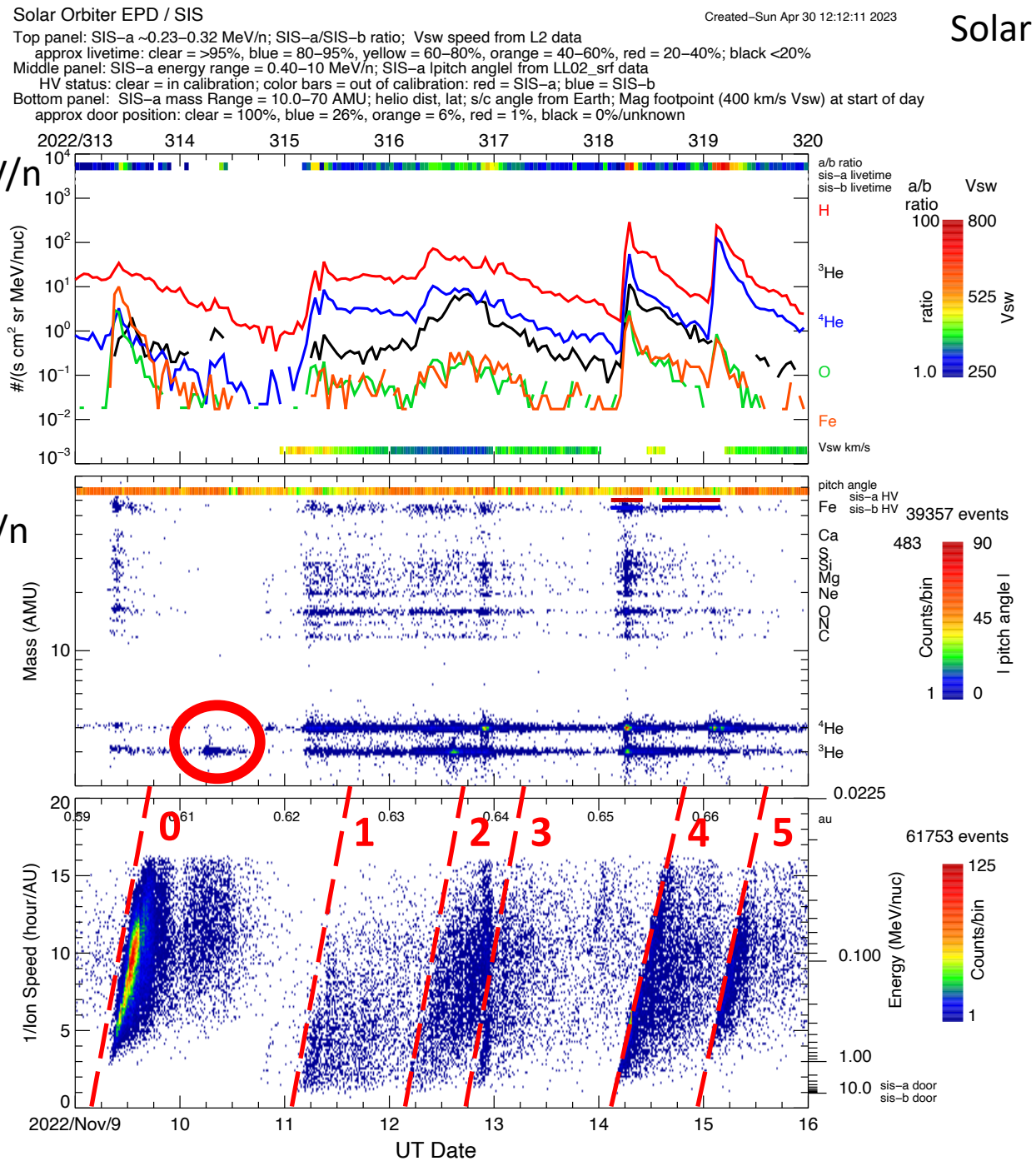


Solar Orbiter/SIS



	3He/4He (0.5-2.0 MeV/n)	Fe/O (0.32-0.45 MeV/n)
Event #0	2.19±0.52	2.66±0.20
Event #1	0.22±0.01	0.62±0.10
Event #2	1.25±0.03	0.92±0.13
Event #3	0.36±0.02	0.93±0.24
Event #4	0.84±0.02	1.04±0.10
Event #5	0.12±0.01	1.00±0.26

Solar Orbiter/SIS



	3He/4He (0.5-2.0 MeV/n)	Fe/O (0.32-0.45 MeV/n)
Event #0	2.19±0.52	2.66±0.20
Event #1	0.22±0.01	0.62±0.10
Event #2	1.25±0.03	0.92±0.13
Event #3	0.36±0.02	0.93±0.24
Event #4	0.84±0.02	1.04±0.10
Event #5	0.12±0.01	1.00±0.26
O	24.33±9.12	--

Ho et al. (2019, Solar Phys. 294:33)

Conclusions

1- Statistics of the occurrence rate of impulsive events:

For 0.1-300 keV electron events, Wang et al. (2012) estimated ~190 events/yr at solar maximum (~0.5 events/day)
~ 12 events/yr at solar minimum (~1 event/month).

At an energy of ~40 keV, Wang et al. (2012) estimated over the whole Sun ~10^4 events/yr at solar maximum (~27 events/day);
~35 events/yr at solar minimum (<3 events/month)

For 1.3-1.6 MeV/n 3He-rich events the quoted occurrence rate ~1000 3He-rich events/yr in the visible solar disk at maximum
(2.7 events/day) (Reames et al. 1994)

In our case we have the record of 12 electron events on 11 November 2022 (five 3He-rich events at ~600 keV/n in 5 days)

2- Almost one-to-one coincidence of Type III radio, X-ray flares, and EUV jets at the origin of these events
Interesting enough the events on 9 Nov and late on 14 Nov rich in heavy ions at low energies (<1 MeV/n) and lacking near-relativistic (>30 keV) electrons did not show
clear EUV jets, significant X-ray emission, and the Type III radio burst started at low frequencies (<1 MHz)

3- CMEs (not the clearest CMEs in the world) able to generate significant ~2 MeV electron intensity increases (at least at Earth)

4- The complicated IP context medium, with a HSS and a SIR, does not prevent the arrival of particles at the 3 locations (especially at L1, although with more isotropic electron intensities)