Microwave observations and the nature of high-energy solar gamma-ray events and on predicting SEP spectrum

P. Zucca, K.-L. Klein, G. Trottet, G. Share, N. Vilmer, O. Malandraki,

M. Nunez, B. Heber, C. Hamadache, J. Kiener, V. Tatischeff, R. Vainio

Work under the HESPERIA –HORIZON 2020 project framework

OUTLINE

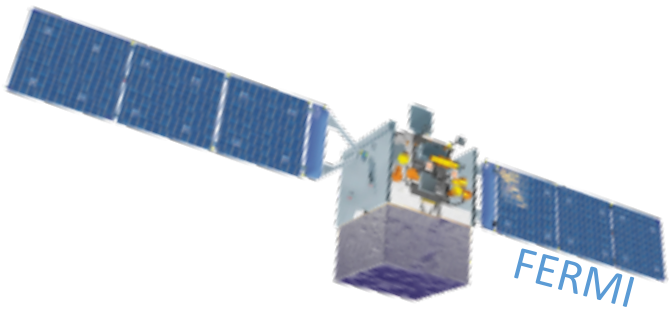
- Introduction, the HESPERIA project
- Microwave emission to study gamma ray emission
- Microwave emission to forecast energetic particles

HESPERIA

High Energy Solar Particle Events foRecastIng and *Analysis*.
It is an H2020 project, under PROTEC-1-2014: Space Weather.

- Establish the link between relativistic protons in the solar atmosphere and near Earth to elucidate under which conditions protons and nucleons are accelerated at the Sun.
- Constrain the relationship of gamma-ray emission with other electromagnetic signatures (RADIO, X-ray).
- Search for proxies of proton acceleration that can be used for forecasting purposes

HESPERIA Gamma-ray catalogue



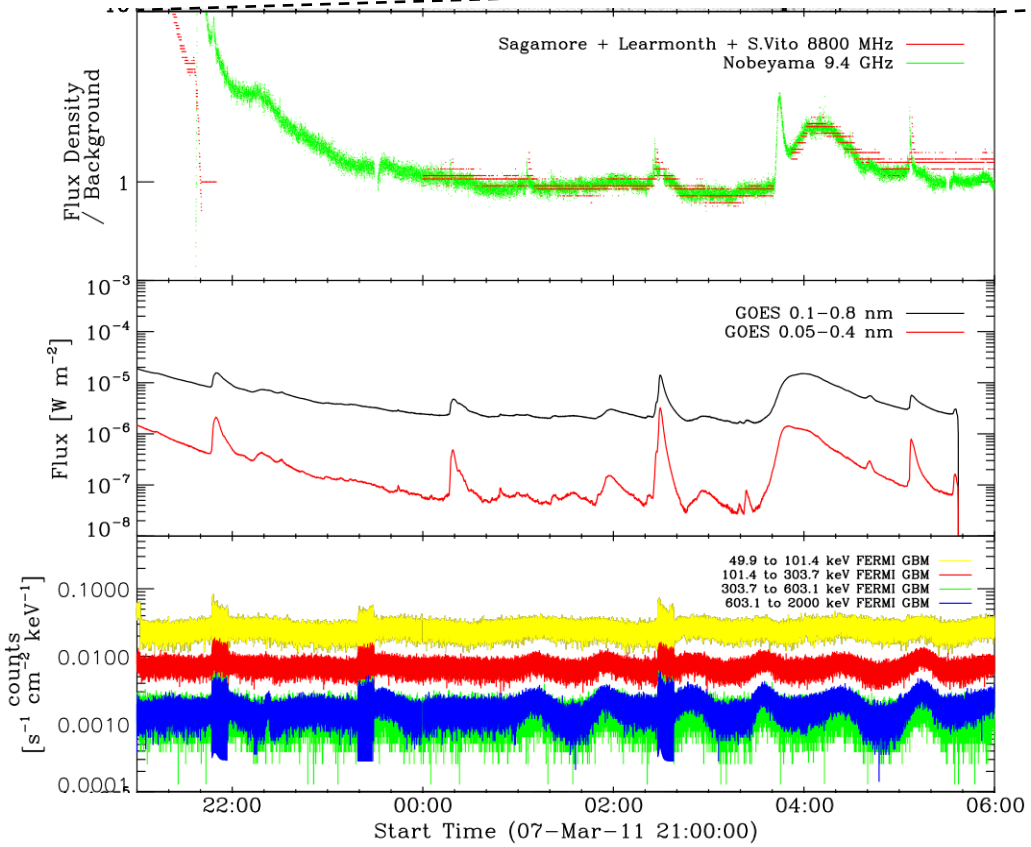
- With the launch of Fermi, it is now possible to detect >100 MeV γ-rays.
- Large number of solar events with γ-ray emission above photon energies of 100 MeV
- In some cases the emission persists over several hours.

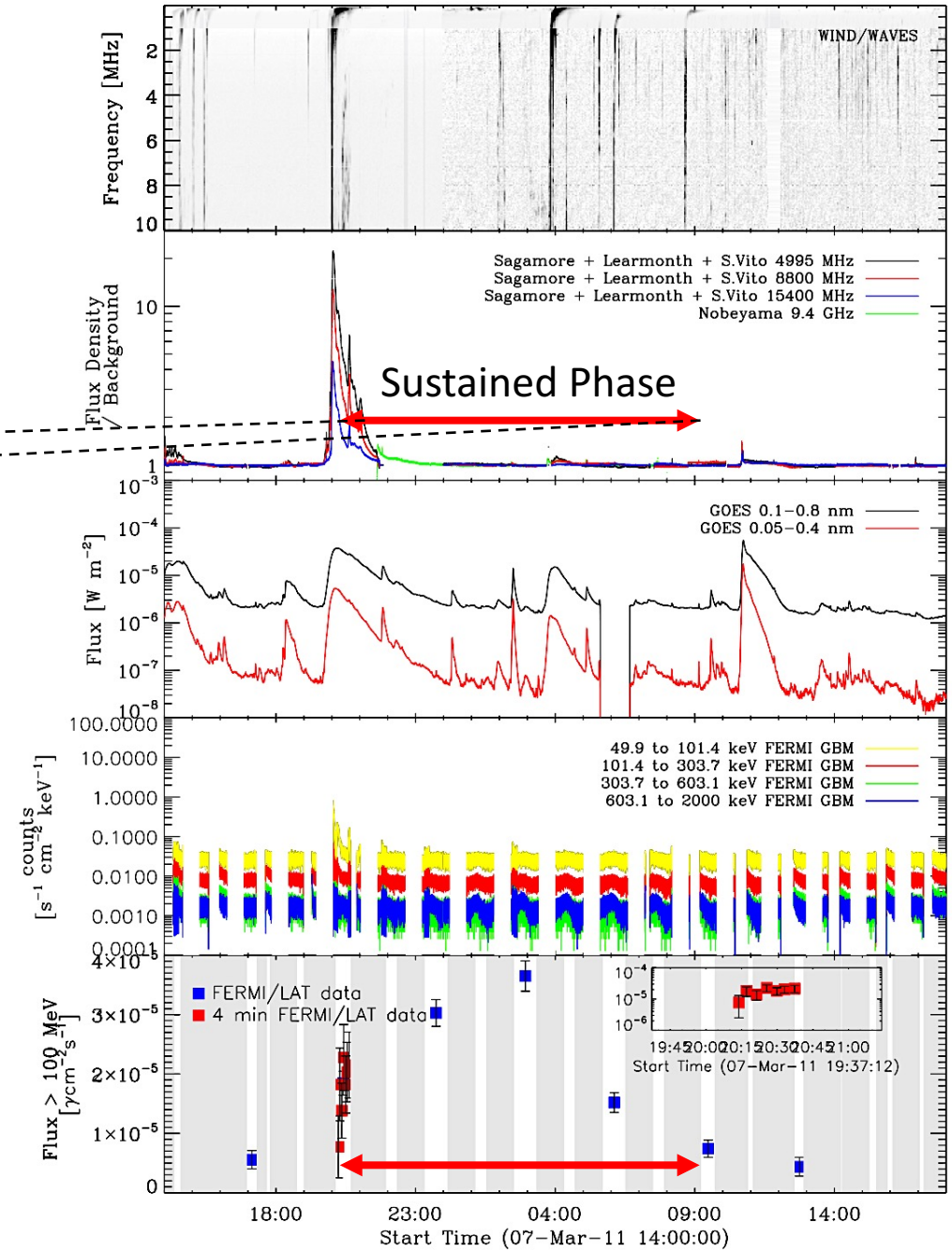
- Acceleration directly in the flare site or by shock-wave/CME ?
- How can the Sun accelerate particles above 300 MeV for several hours ?
- Hard X-ray and microwave signatures to see if long-duration gamma-ray are accompanied by signatures of long-duration electron acceleration

HESPERIA Gamma-ray catalogue

Sample of 26 gamma-ray events

Gamma ray emission lasting >13 hours





HESPERIA Gamma-ray catalogue

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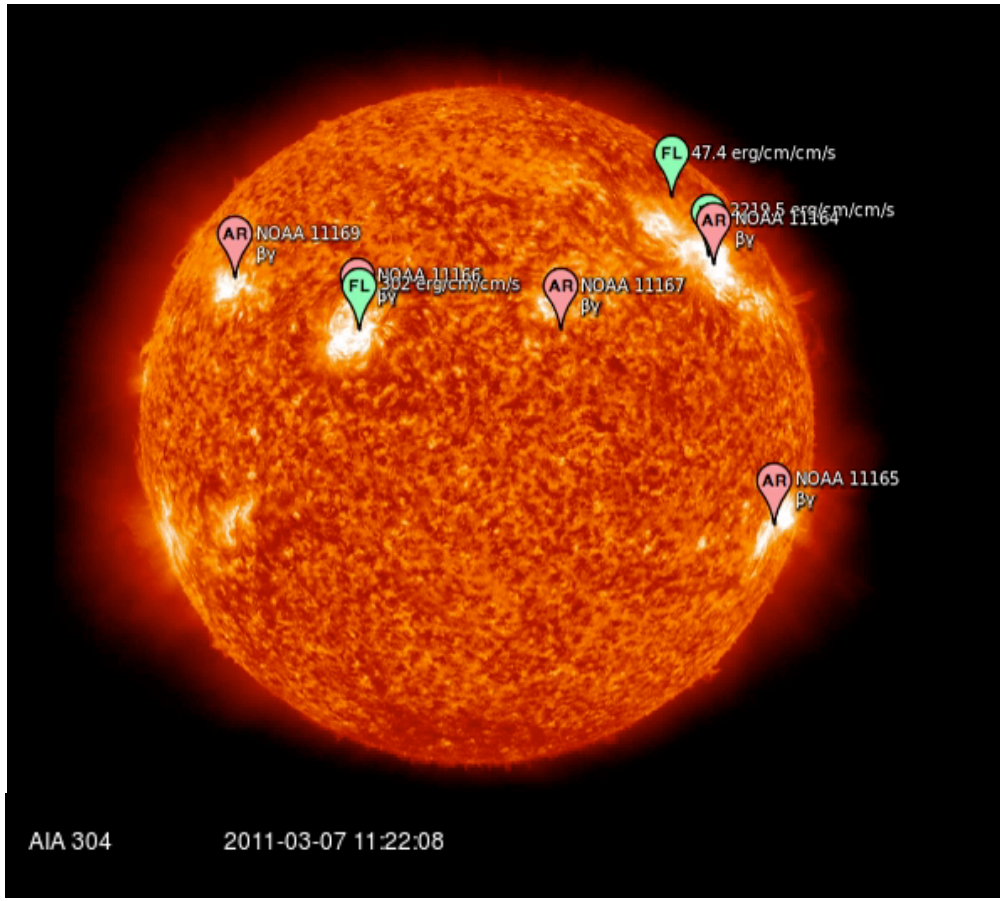
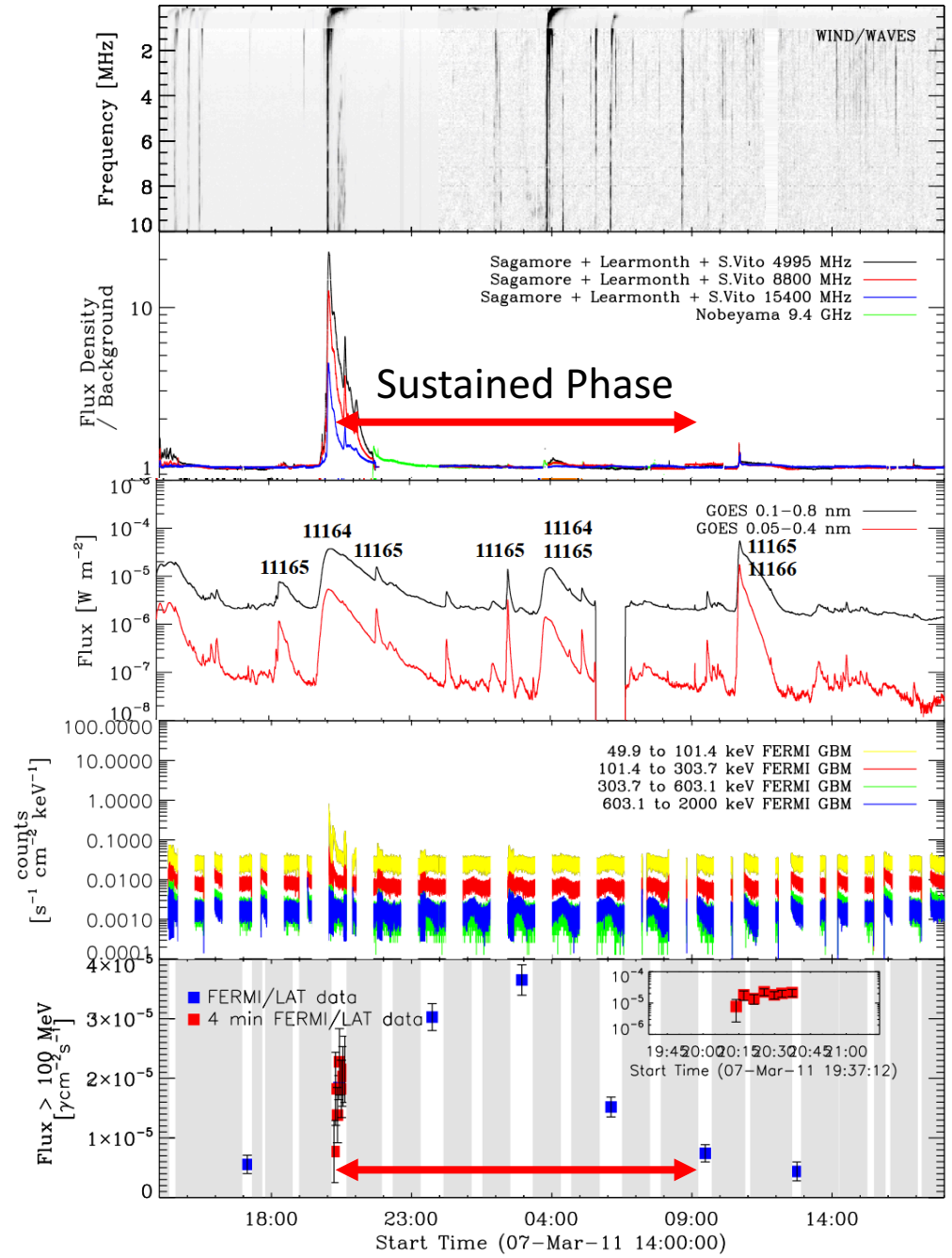
Gamma ray emission lasting >13 hours

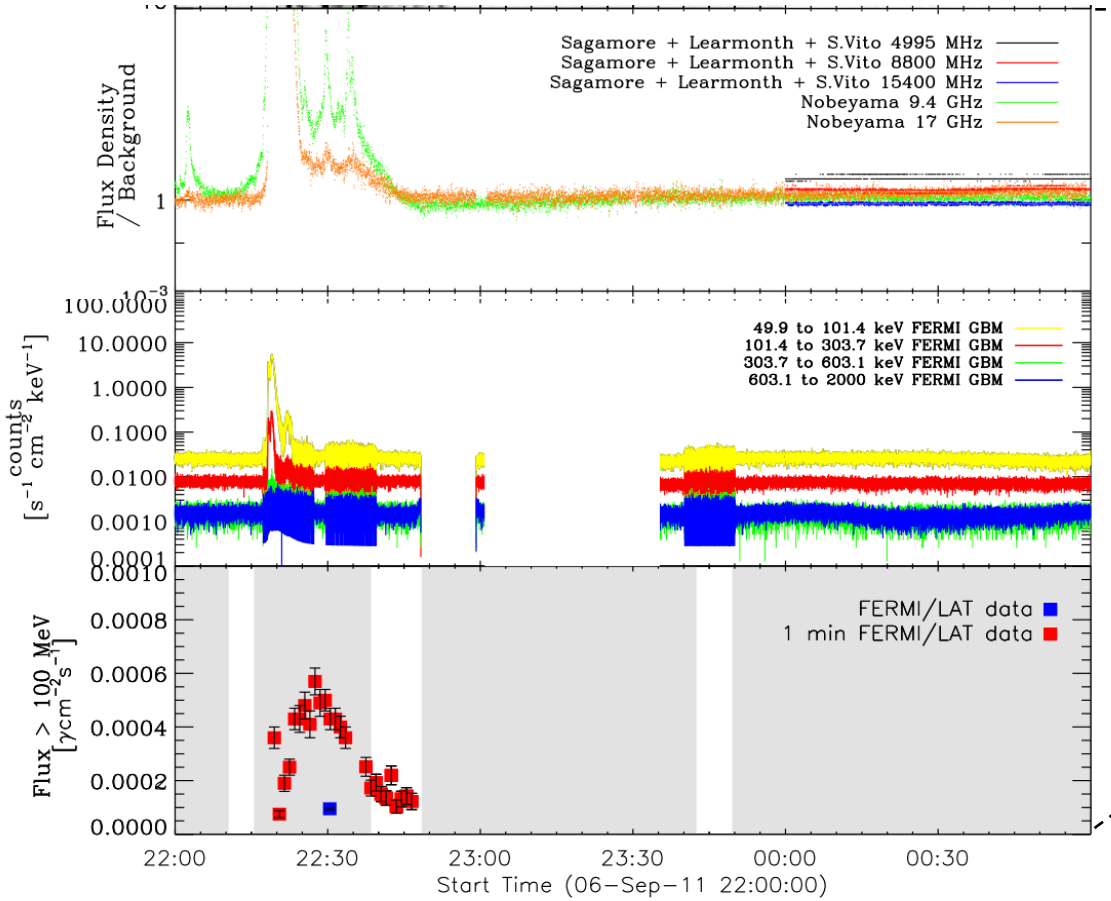


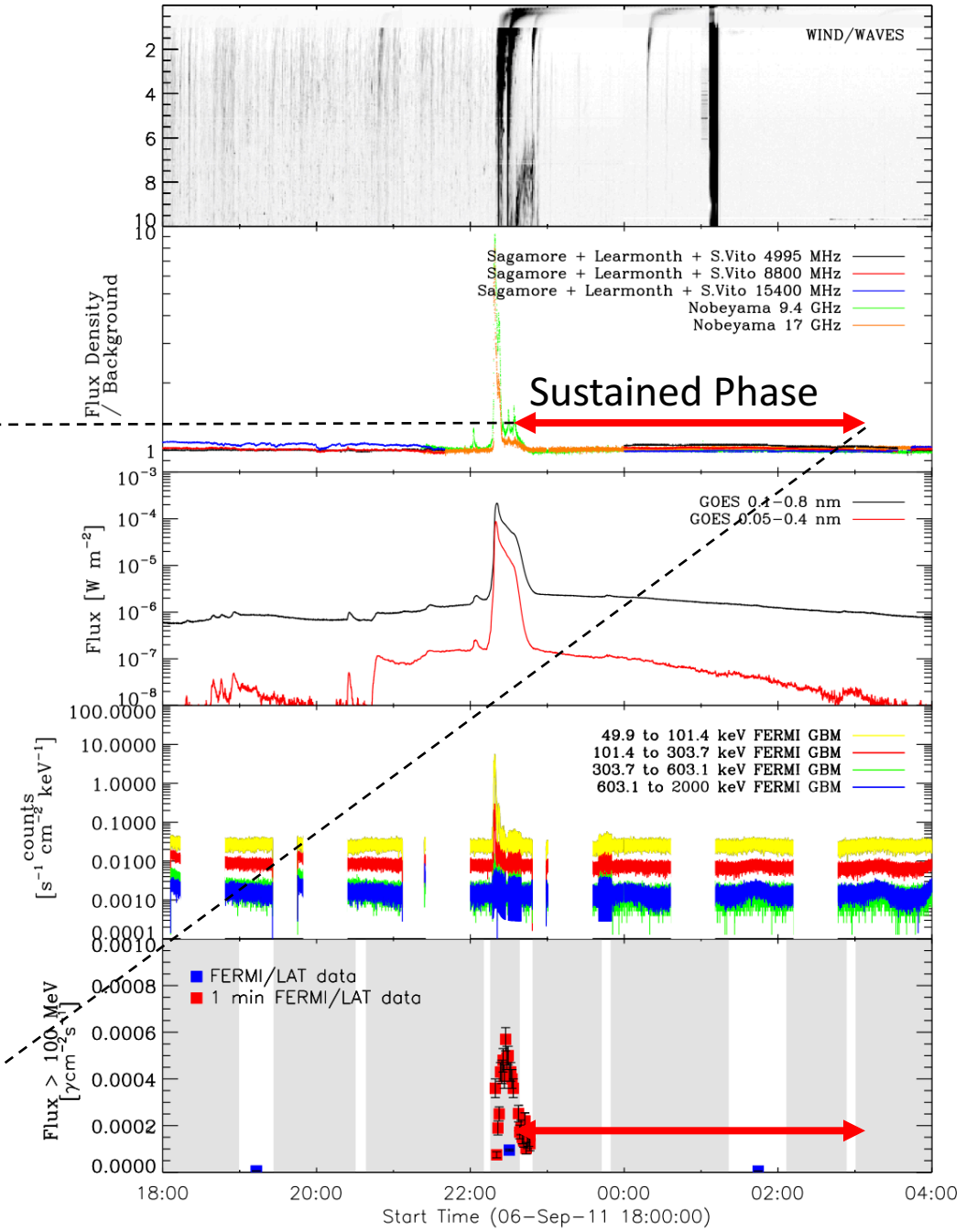


HESPERIA Gamma-ray catalogue

Sample of 26 gamma-ray events

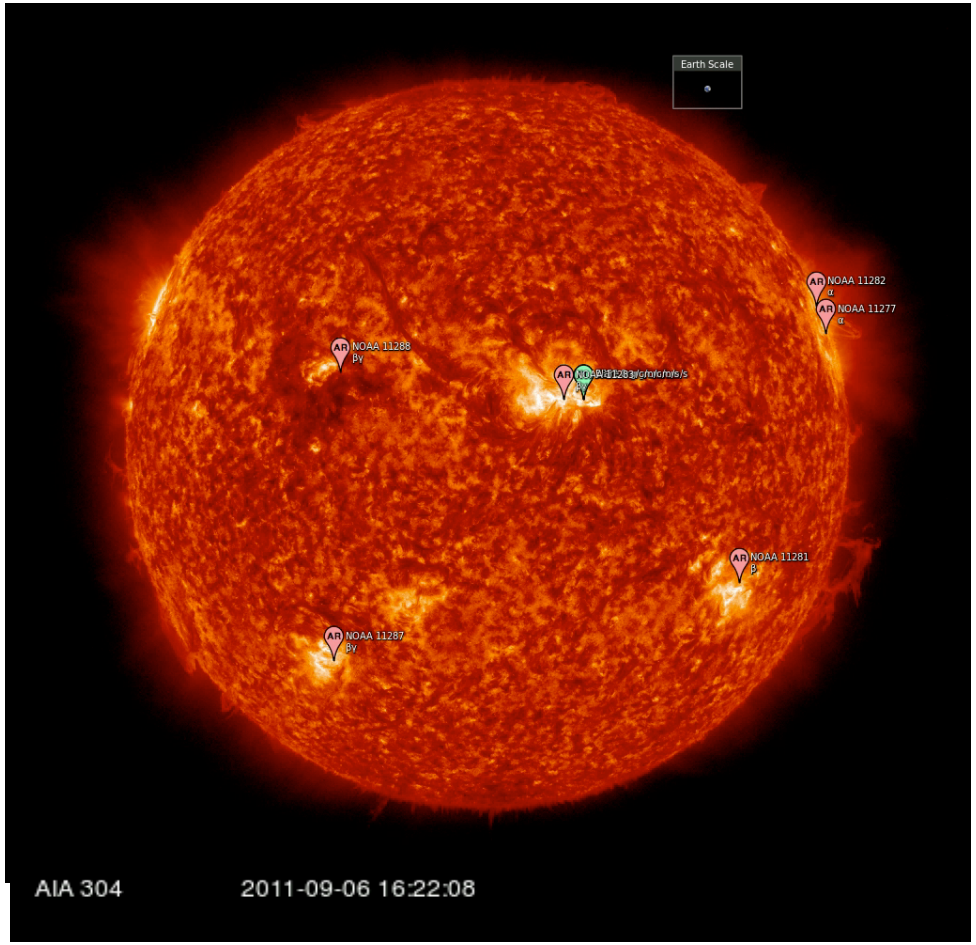
Gamma ray emission lasting <1 hour

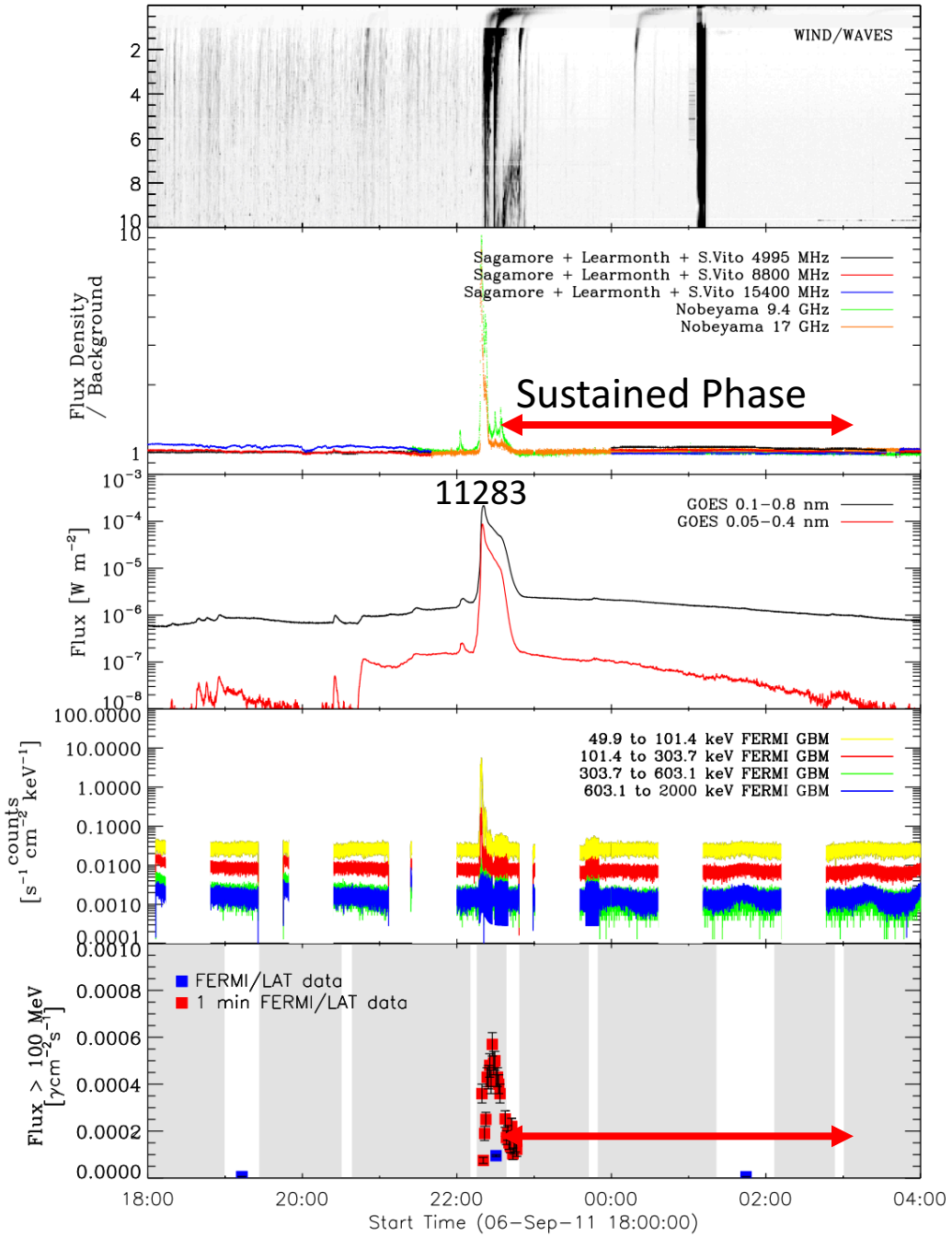




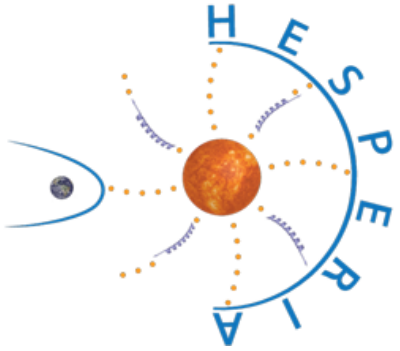
HESPERIA Gamma-ray catalogue

Sample of 26 gamma-ray events
Gamma ray emission lasting <1 hour





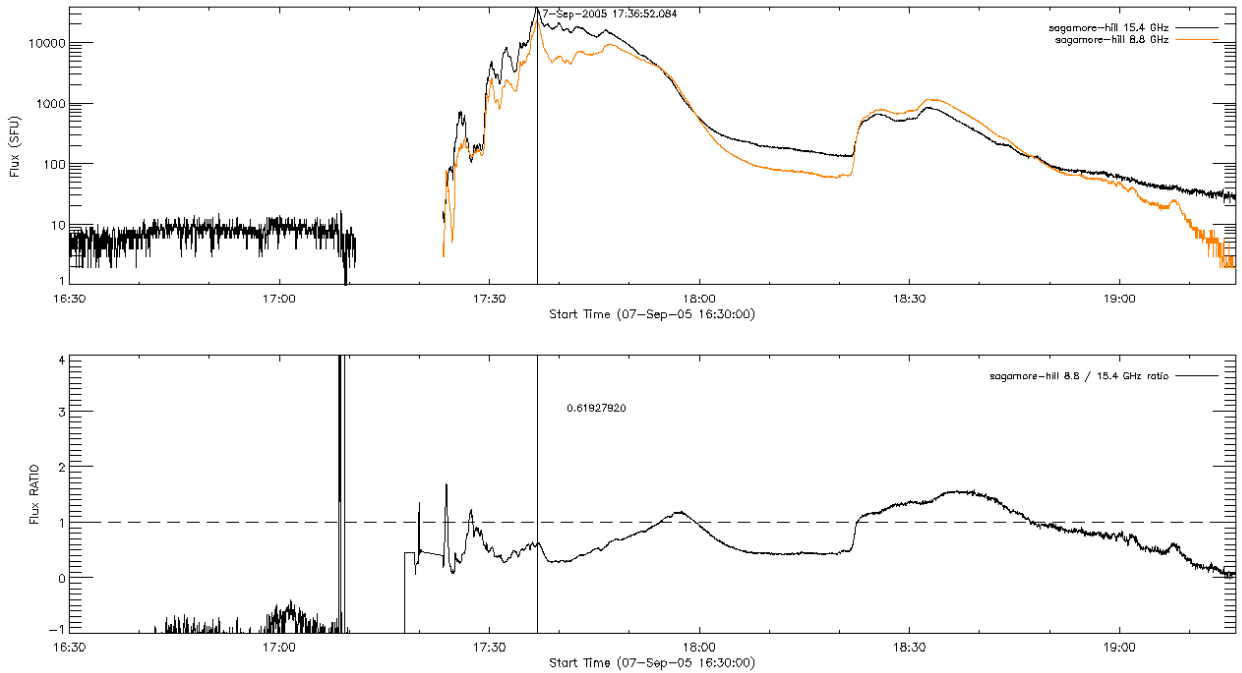
Microwave observations for forecasting the hardness of the proton spectra

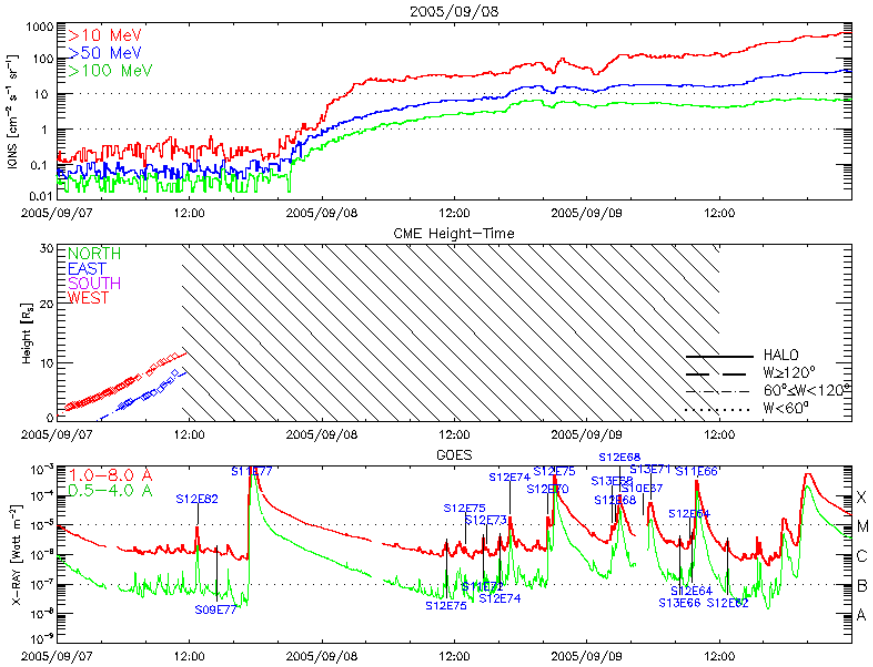


Spectral properties

Proton fluxes with hard (flat) energy spectra ($\delta \leq 1.5$)

"Hard" microwave spectra ($S_9 / S_{15} \leq 1$ and $f_m \geq 15$ GHz)



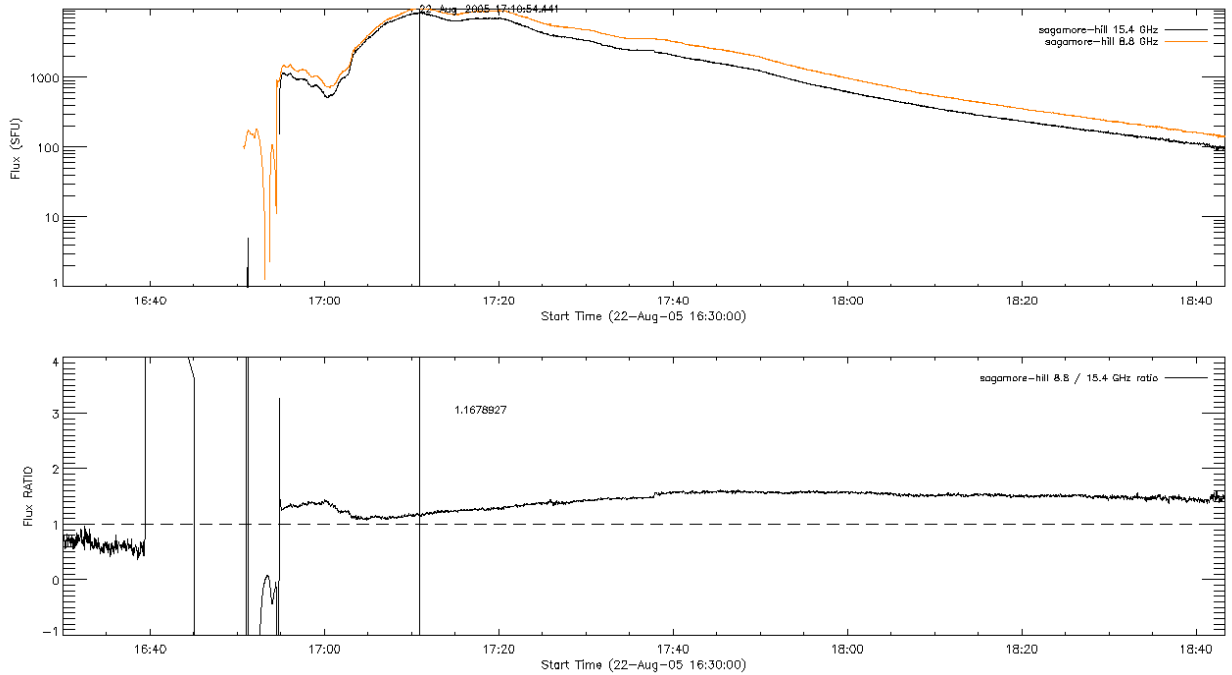


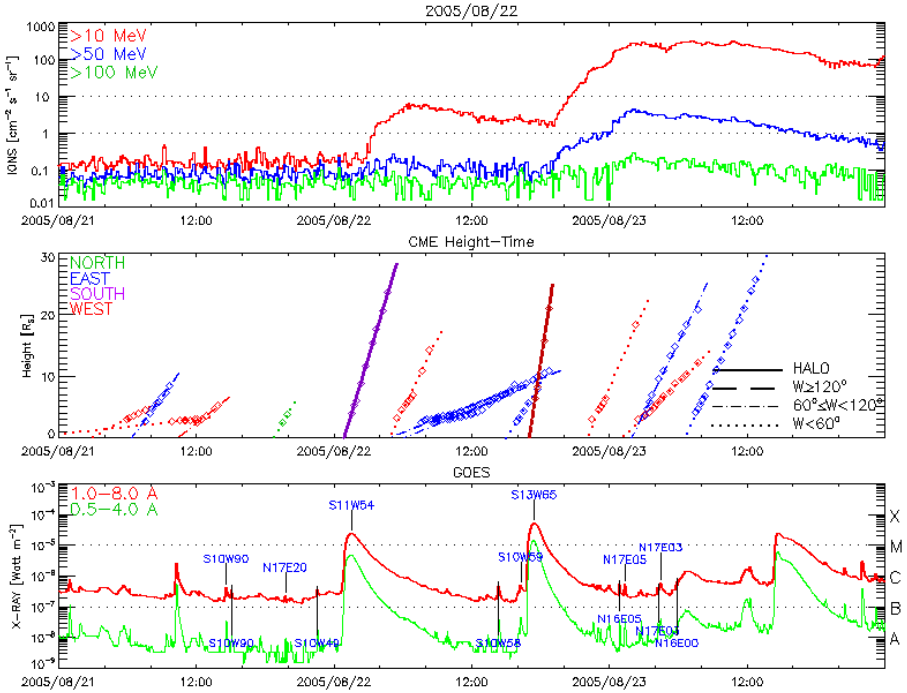
Chertok et al. 2009

Spectral properties

Proton fluxes with soft (steep) energy spectra ($\delta \geq 1.5$-2)

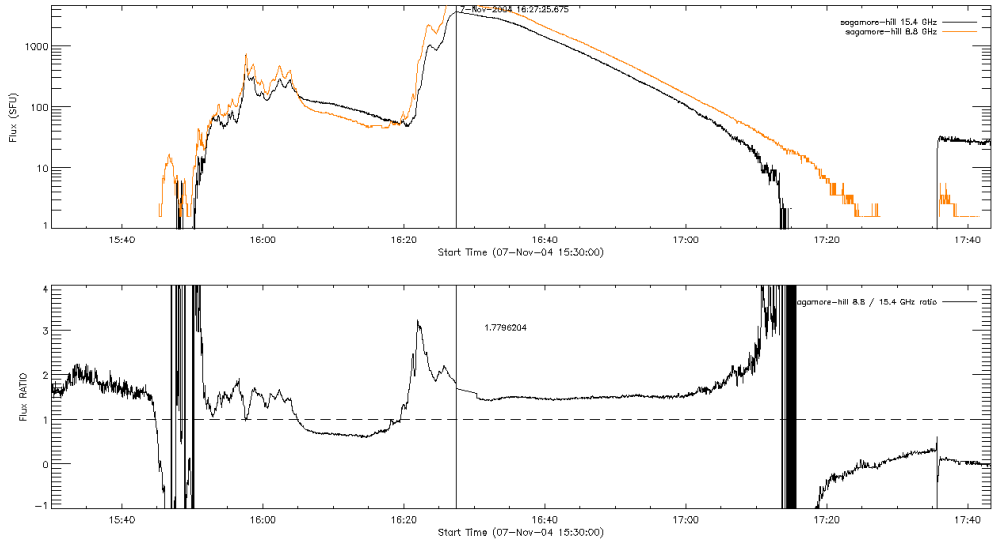
"Soft" microwave spectra ($S_9 / S_{15} \geq 1.5$ and $f_m \leq 5$ GHz)





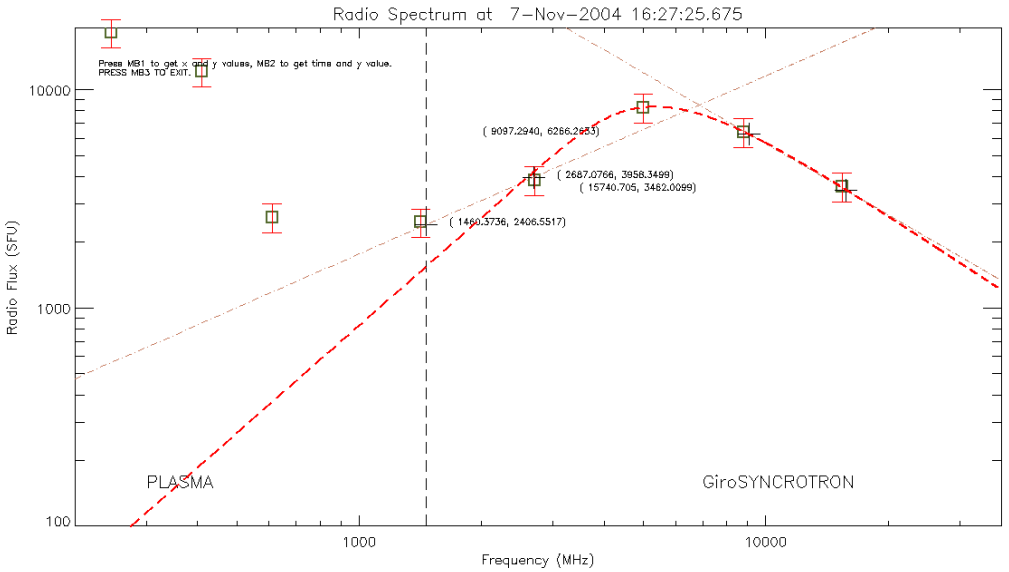
Chertok et al. 2009

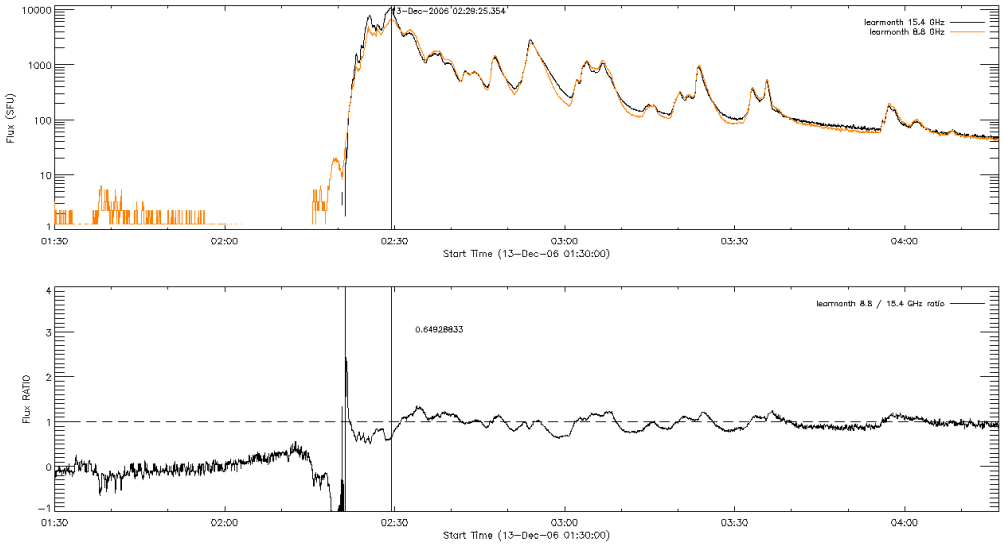
Microwave Spectral Properties



High Ratio

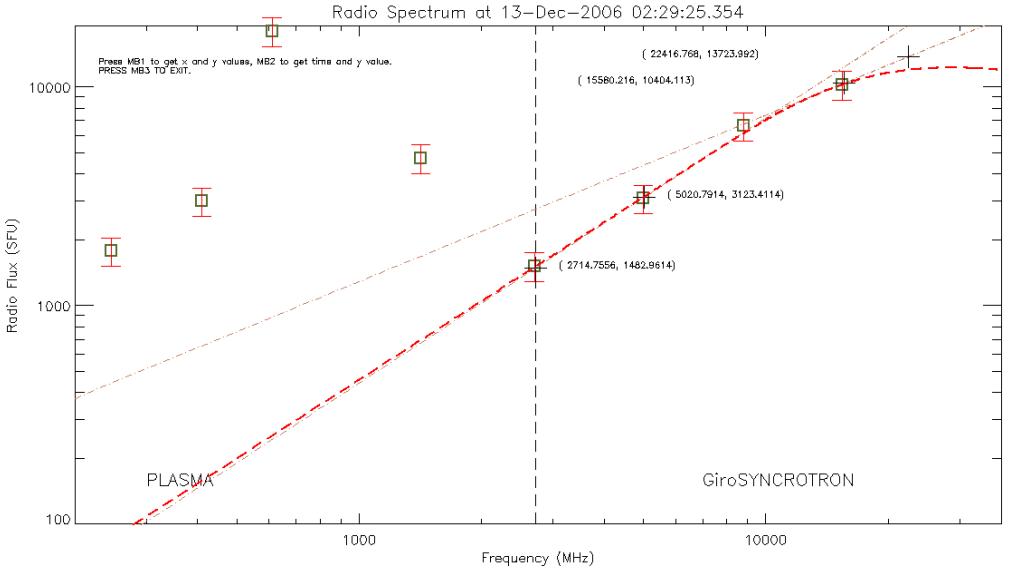
Optically Thin



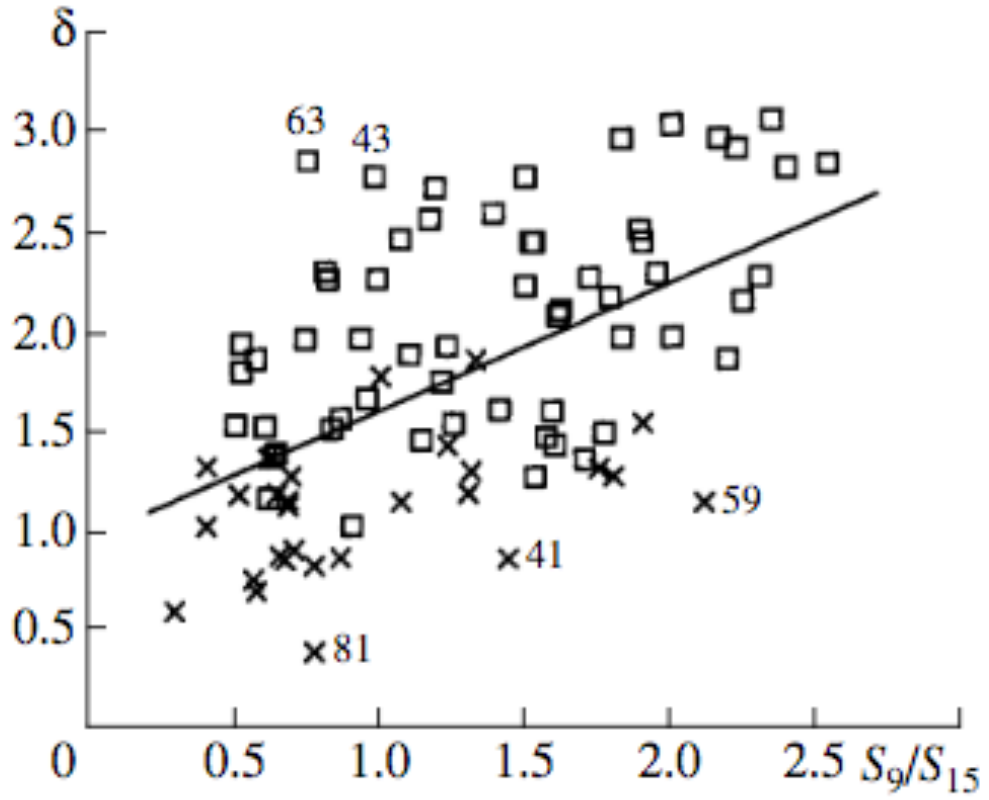


Low Ratio

Optically Thick



HESPERIA sample test for Chertok prediction

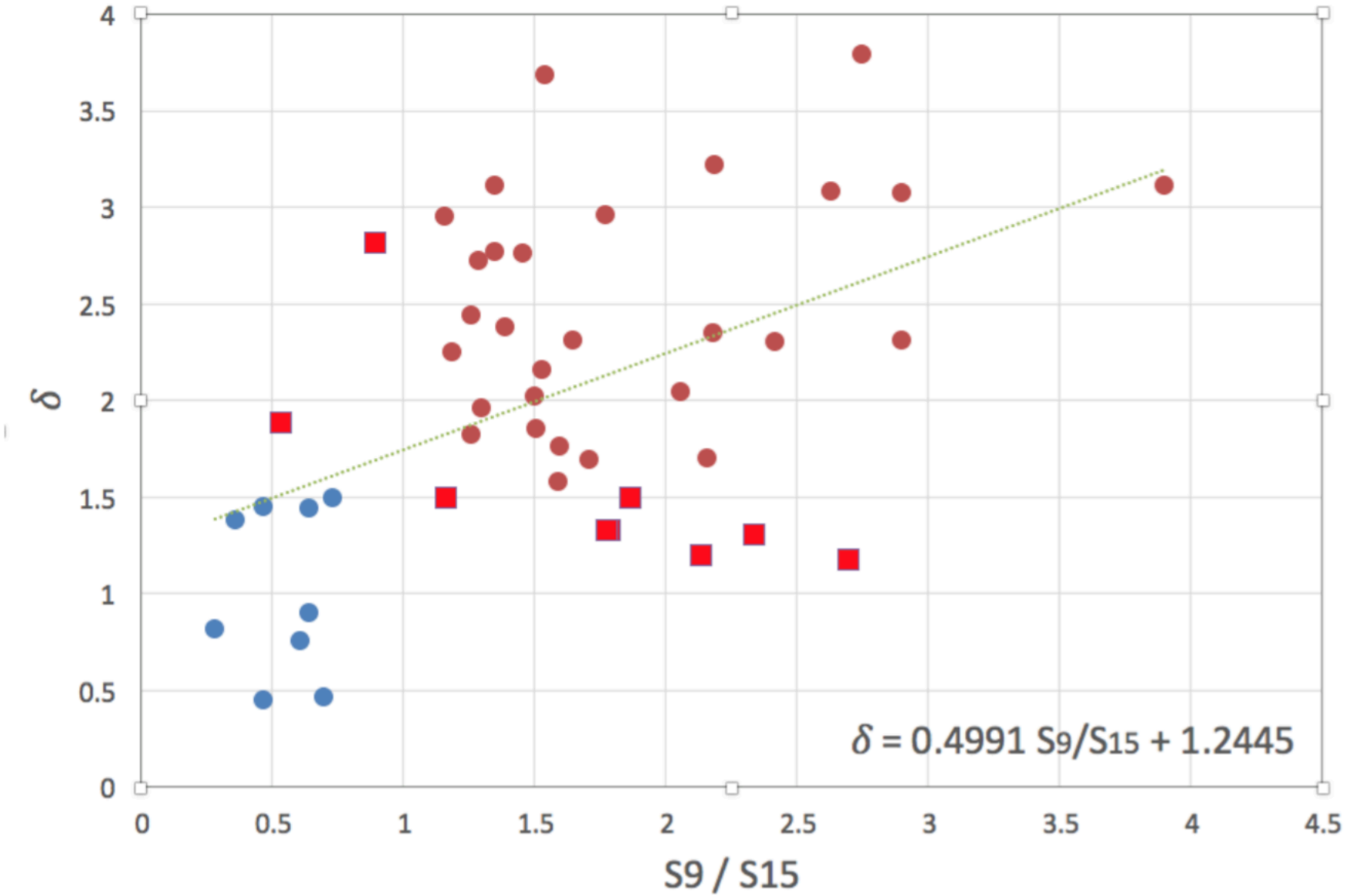


Chertok, 2009

$\delta = 0.60(S_9/S_{15}) + 1.0$

	Date Flare (ratio)	Date SEP	Location	S_9/S_{15} / γ	Peak frequency [GHz]	SEP spectral hardness predicted	observed	Quality of Prediction
1	1997 Nov 06 11:55	Nov 06 12:50	S18 W63	0.47 / 0.45	15.4	hard	hard	A
2	1998 May 02 13:42	May 02 14:00	S15 W15	2.34 / 1.3	8.8	soft	hard	C
3	1998 May 06 08:09	May 06 08:25	S11 W65	1.51 / 1.85	8.8	soft	soft	D
4	1998 Aug 24 22:12	Aug 24 23:10	N30 E07	2.16 / 1.70	4.9	soft	soft	D
5	1999 Jun 04 07:03	Jun 04 09:25	N17 W69	1.26 / 2.44	10	soft	soft	D
6	2000 Nov 24 15:13	Nov 24 16:30	N22W07	0.54 / 1.88	15.4	hard	soft	B
7	2000 Apr 04 15:41	Apr 04 17:05	N16W66	1.46 / 2.76	2.9	soft	soft	D
8	2000 Jul 22 11:34	Jul 22 12:25	N14W56	1 / 1.69	8.8	soft	soft	D
9	2000 Nov 08 23:28	Nov 08 23:50	N05W77	1.87 / 1.49	8.8	soft	hard	C
10	2000 Nov 24 05:02	Nov 24 07:20	N20W05	0.36 / 1.38	17	hard	hard	A
11	2001 Mar 29 10:15	Mar 29 13:00	N24W12	1.53 / 2.16	8.8	soft	soft	D
12	2001 Apr 02 21:51	Apr 02 23:15	N14W82	0.47 / 1.45	15.4	hard	hard	A
13	2001 Apr 10 05:26	Apr 10 08:30	S23W09	1.39 / 2.38	8.8	soft	soft	D
14	2001 Apr 15 13:50	Apr 15 14:10	S20W85	0.28 / 0.81	15.4	hard	hard	A
15	2001 Apr 26 13:12	Apr 27 00:55	N17W31	1.50 / 2.02	8.8	soft	soft	D
16	2001 Sep 15 11:28	Sep 15 12:50	S21W49	1.26 / 1.82	4.9	soft	soft	D
17	2001 Oct 19 16:30	Oct 19/1840	N15W29	1.59 / 1.58	8.8	soft	soft	D
18	2001 Oct 22 17:59	Oct 22/1815	S18E16	0.64 / 1.44	15.4	hard	hard	A
19	2001 Nov 04 16:20	Nov 04/1640	N06W18	1.79 / 1.32	8.8	soft	hard	C
20	2001 Nov 22 23:30	Nov 22 23:20	S15W34	2.90 / 3.07	4.9	soft	soft	D
21	2001 Dec 26 05:40	Dec 26 05:50	N08W54	2.14 / 1.19	8.8	soft	hard	C
22	2002 Feb 20 06:12	Feb 20 07:00	N12W72	1.29 / 2.72	9.4	soft	soft	D
23	2002 Apr 17 08:24	Apr 17 11:35	S14W34	2.63 / 3.08	4.9	soft	soft	D
24	2002 Apr 21 01:51	Apr 21 02:00	S14W84	2.06 / 2.04	8.8	soft	soft	D
25	2002 May 22 03:54	May 22 08:05	S19W56	1 / 2.31	8.8	soft	soft	D
26	2002 Jul 15 20:08	Jul 16 13:40	N19W01	1.35 / 3.11	8.8	soft	soft	D
27	2002 Aug 14 02:12	Aug 14 03:55	N09W54	3.90 / 3.11	2.9	soft	soft	D
28	2002 Aug 22 01:57	Aug 22 03:05	S07W62	1.78 / 1.32	4.9	soft	hard	C
29	2002 Nov 09 13:23	Nov 09/1610	S12W29	1.54 / 3.68	4.9	soft	soft	D
30	2003 May 28 00:27	May 28 07:25	S07 W17	1.60 / 1.76	8.8	soft	soft	D
31	2003 May 31 02:24	May 31 04:40	S07 W65	0.73 / 1.49	15.4	hard	hard	A
32	2003 Oct 26 18:19	Oct 26 18:25	N02 W38	1.35 / 2.77	8.8	soft	soft	D
33	2003 Oct 28 11:10	Oct 28 12:15	S16 E08	1.17 / 1.49	8.8	soft	hard	C
34	2003 Nov 20 23:53	Nov 21 06:05	N02 W17	2.42 / 2.3	3.9	soft	soft	D
35	2004 Apr 11 04:19	Apr 11 06:10	S14 W47	2.18 / 2.35	5.4	soft	soft	D
36	2004 Sep 12 00:56	Sep 13 21:05	N04 E42	2.19 / 3.22	3.4	soft	soft	D
37	2004 Nov 07 16:06	Nov 07 18:25	N09 W17	1.77 / 2.96	5.4	soft	soft	D
38	2005 Jan 17 09:52	Jan 17 13:05	N15 W25	1.19 / 2.25	5.4	soft	soft	D
39	2005 Jan 20 07:01	Jan 20 06:55	N12 W58	0.7 / 0.46	35	hard	hard	A
40	2005 Jun 16 20:22	Jun 16 05:00	N09 W87	2.7 / 1.17	5.4	soft	hard	C
41	2005 Jul 14 10:34	Jul 14 13:40	N10 W80	0.90 / 2.81	15.4	hard	soft	B
42	2005 Jul 27 05:02	Jul 27 23:00	N11 E90	1.65 / 2.31	5.4	soft	soft	D
43	2005 Aug 22 17:27	Aug 22 20:40	S12 W60	1.16 / 2.95	8.8	soft	soft	B
44	2005 Sep 07 17:40	Sep 07 21:50	S06 E89	0.61 / 0.75	15.4	hard	hard	A
45	2006 Dec 06 08:23	Dec 06 15:55	S07 E79	2.75 / 3.79	8.8	soft	soft	D
46	2006 Dec 13 02:40	Dec 13 03:10	S05 W23	0.64 / 0.9	22	hard	hard	A
47	2006 Dec 14 22:15	Dec 14 22:55	S06 W46	1.3 / 1.96	8.8	soft	soft	D

HESPERIA sample test for Chertok prediction



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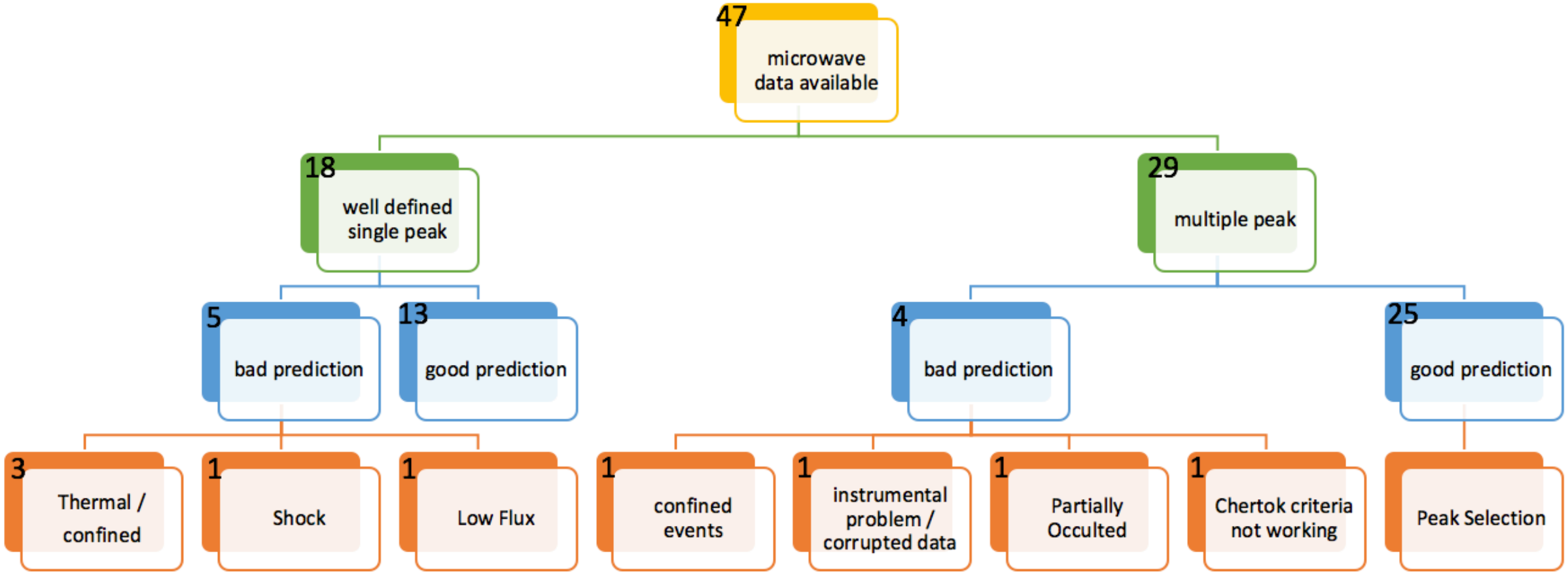
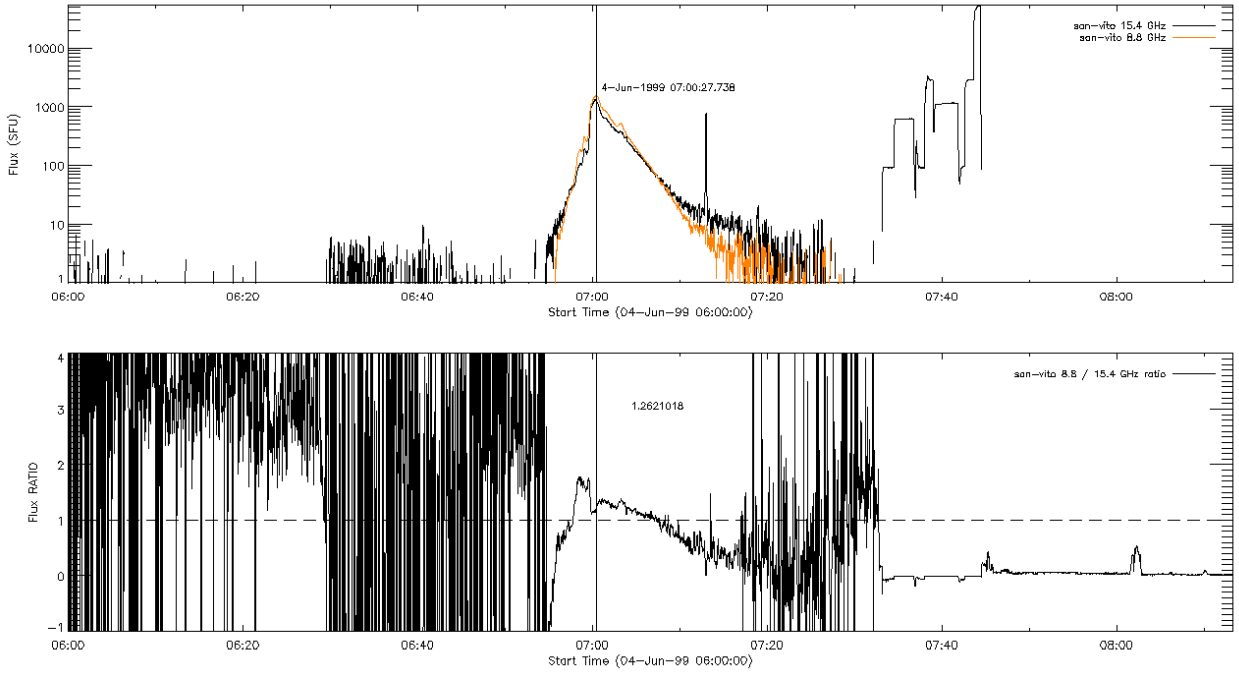
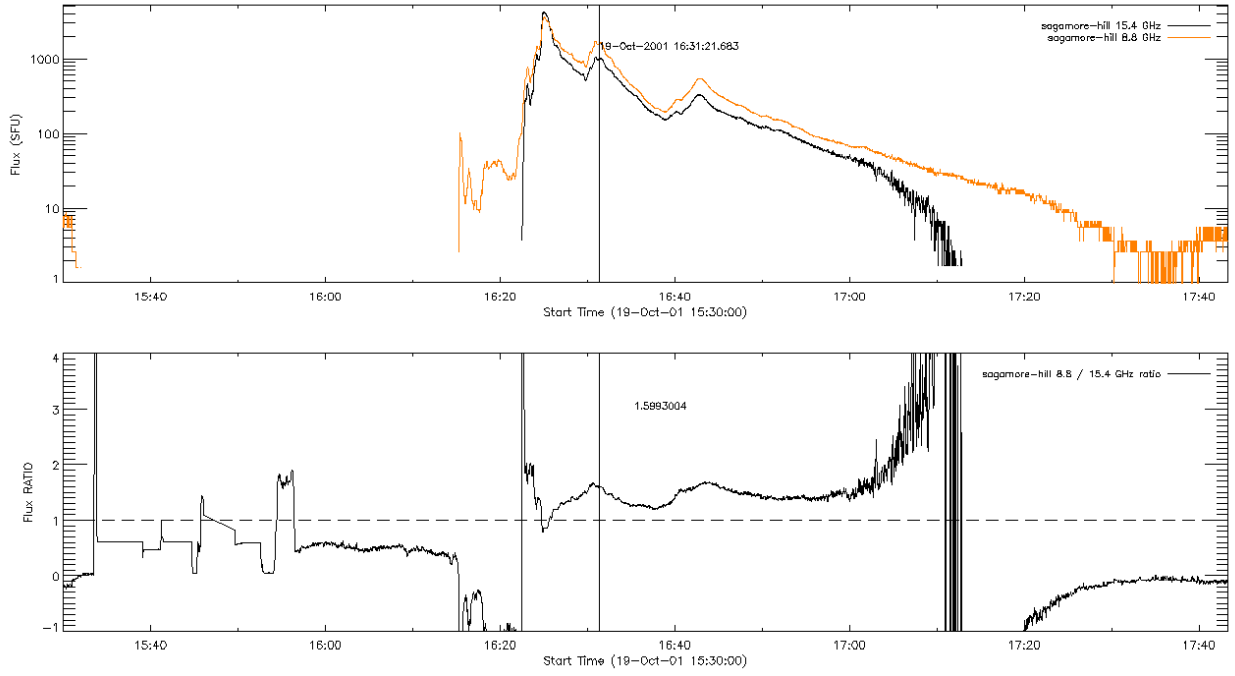


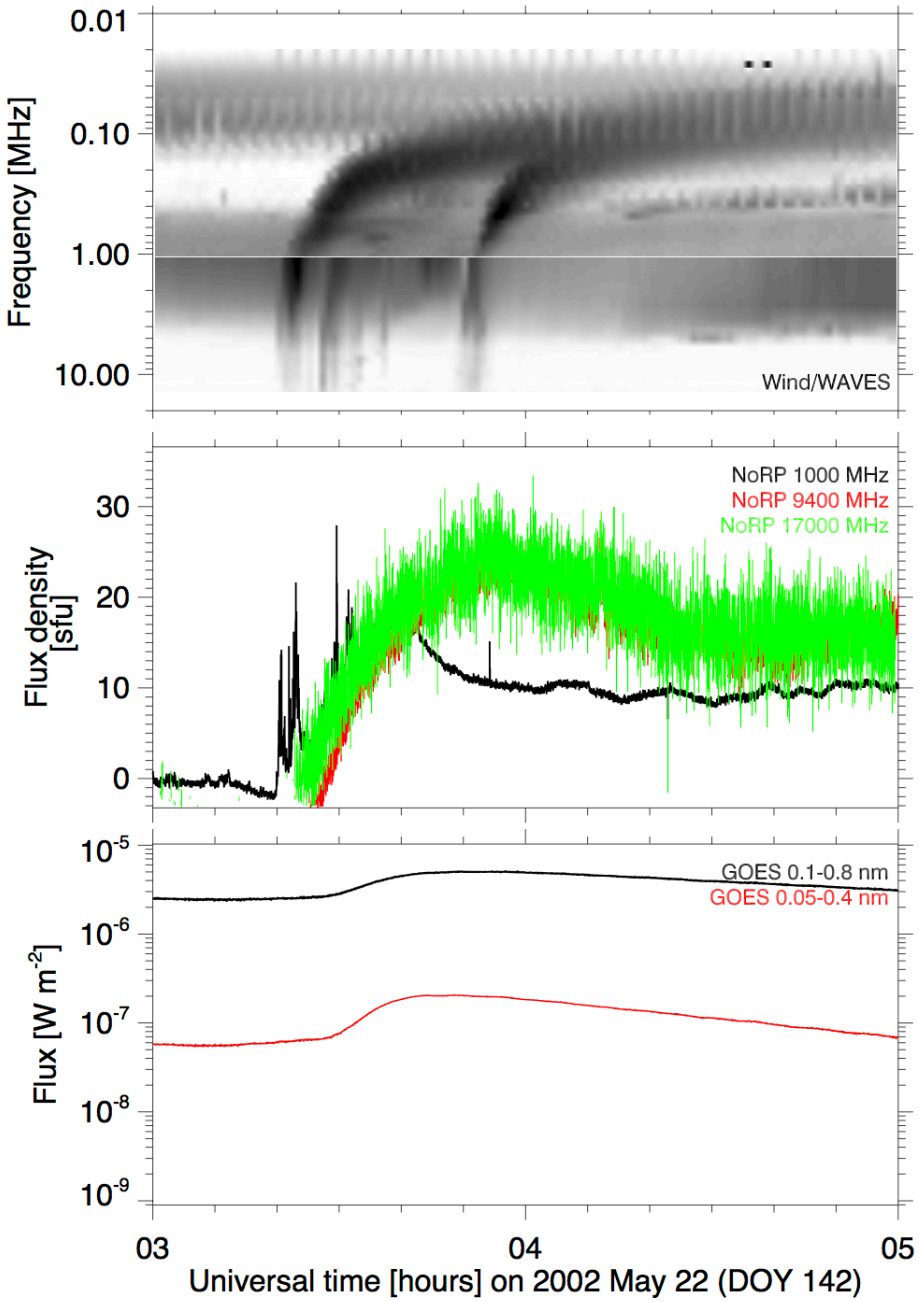
Single Peak



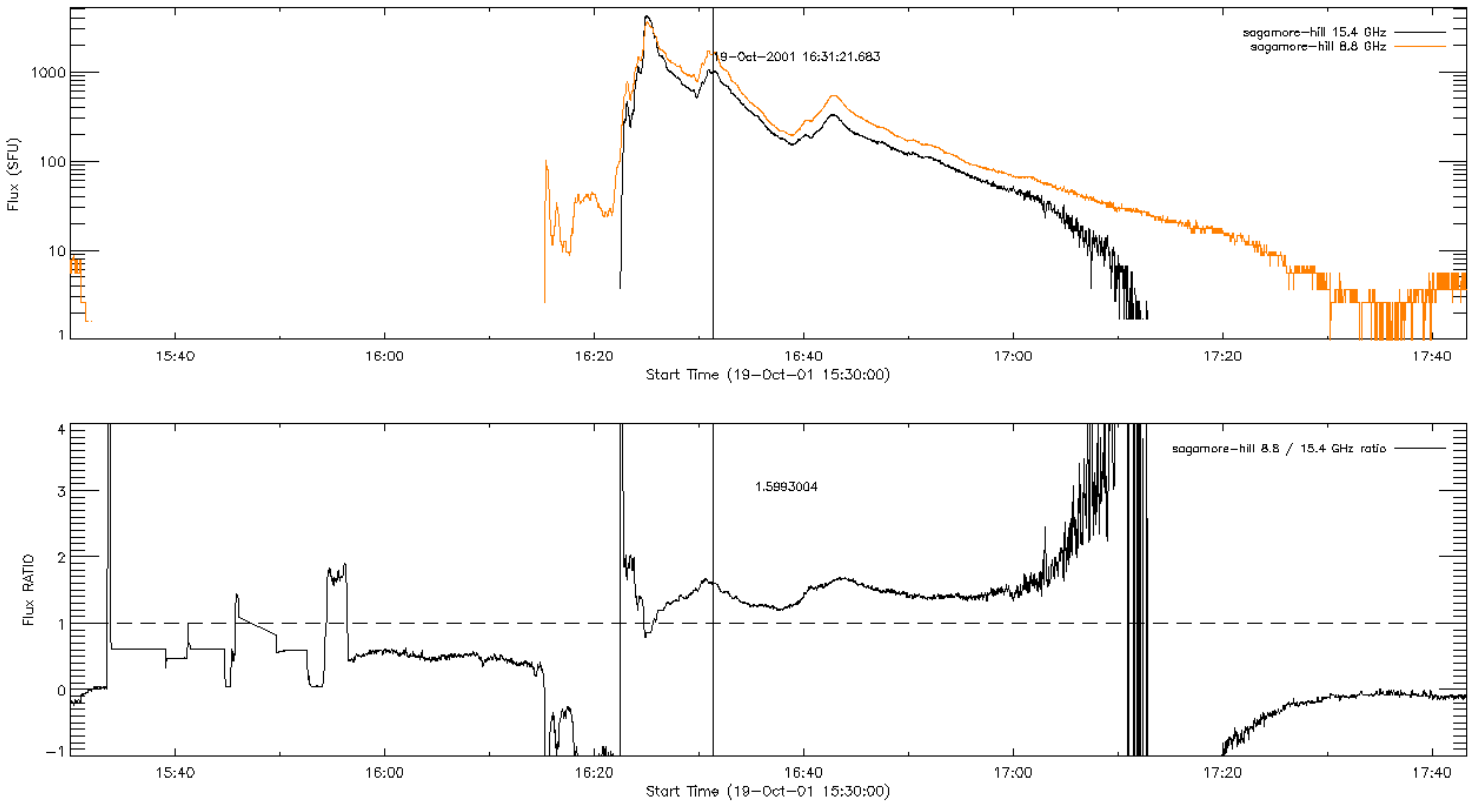
Multi Peak

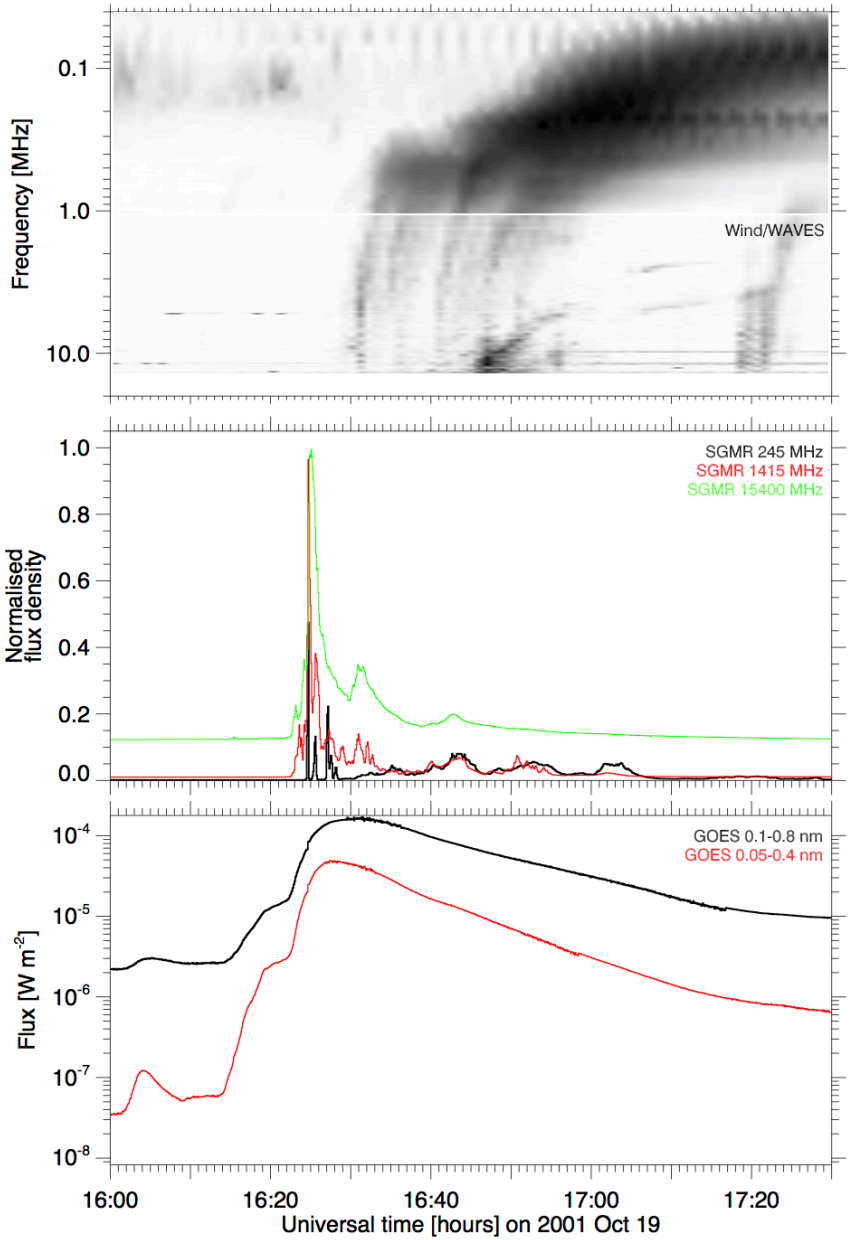


Thermal Events

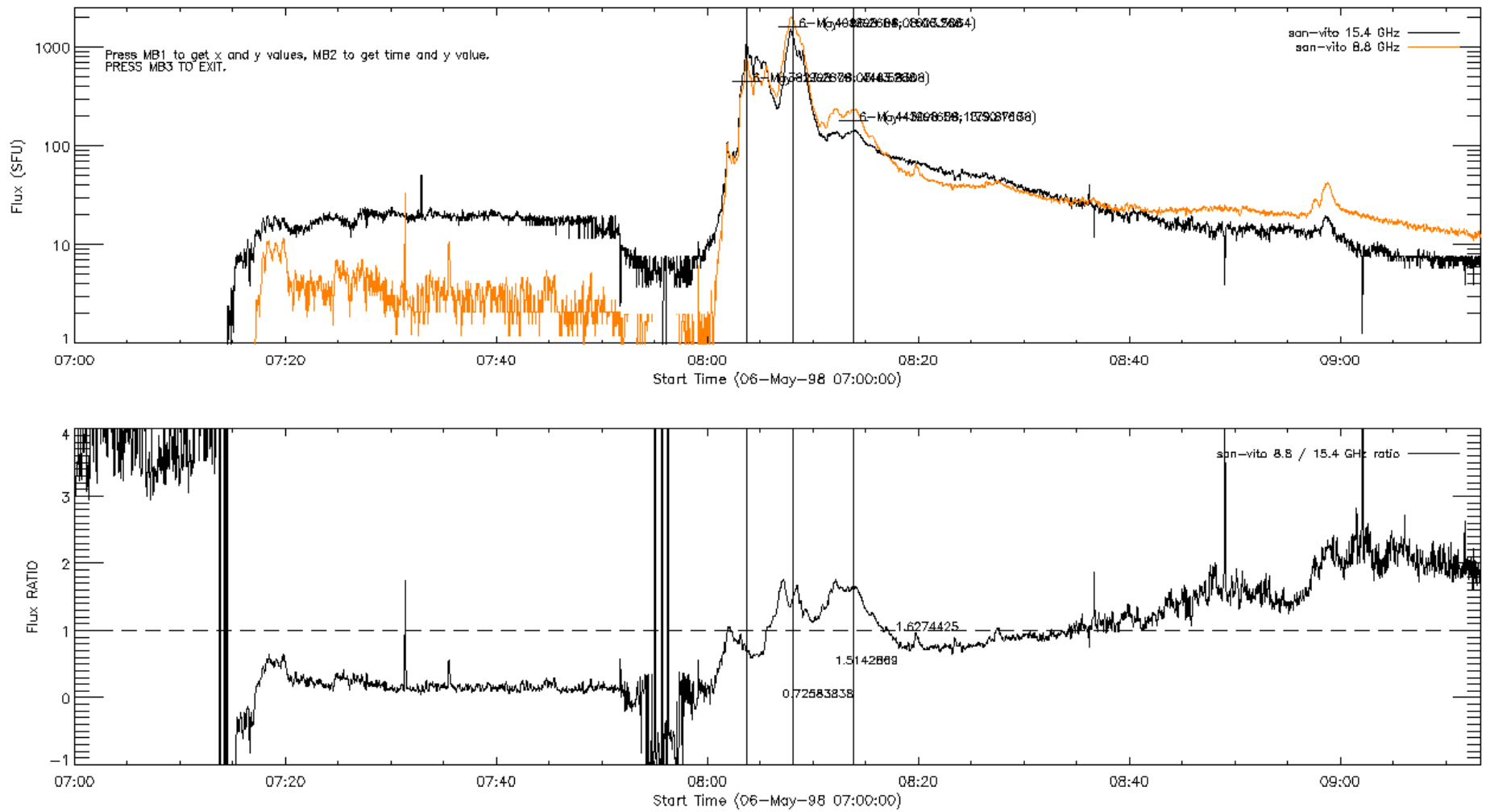


Multi Peak Selection





Multi Peak extended study



Multi Peak extended study