



Solar Neutrons in the PAMELA Experiment 2006-2013

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Search of Solar Neutrons (SN). Ideas and Criteria

- Solar neutrons must to be from practically any solar event. A question is only in the PAMELA Neutron Detector (ND) sensitivity threshold to neutrons flux...
- Search of ND counts increasing after SF near equator on solar side of the Earth during 4-10 min in comparison with counts during 1 circuit before SF (a shift on East $\sim 25^\circ$)
- Possible effect of Geomagnetic Cut-off (GM) change by the trajectory shift $\sim 25^\circ$ is need to be taken into account by analysis of ND data using the same PAMELA trajectory 1 day before SF
- TOF for solar neutrons on base Sun-Earth can be used for neutron energy measurements. TOF start – X-ray max in SF.
- Additional criteria of SN registration waiting – pre-pulse of p in SCR from $n \rightarrow p^+ + e^- + \nu_e$ decay during Sun-Earth flight in S1, S2, S3 data.

Solar Events 2011-2013

2011

Mar 08/0105	Mar 08/0800	50	NW/07 2000	Mar 07/2012	M3/SF	N24W59	1164
Mar 21/1950	Mar 22/0135	14	NW/21 0236	N/A	N/A	N/A	1169
Jun 07/0820	Jun 07/1820	72	SW/08 1750	Jun 07/0803	M2/2N	S21W64	1226
Aug 04/0635	Aug 05/2150	96	NW/06 0515	Aug 04/0412	M9/2B	N15W49	1261
Aug 09/0845	Aug 09/1210	26	NW/09 1710	Aug 09/0805	X6/2B	N17W83	1263
Sep 23/2255	Sep 26/1155	35	NE/27 0430	Sep 22/1101	X1/2N	N11E74	1302
Nov 26/1125	Nov 27/0125	80	NW/28 0145	Nov 26/0710	N/A	N08W49	1353

2012

Jan 23/0530	Jan 24/1530	6310	NW/23 0400	Jan 23/0359	M8/2B	N28W36	1402
Jan 27/1905	Jan 28/0205	796	NW/27 1827	Jan 27/1837	X1/1F	N27W71	1402
Mar 07/0510	Mar 08/1115	6530	NE/07 0036	Mar 07/0024	X5/3B	N17E15	1429
Mar 13/1810	Mar 13/2045	469	NW/13 1736	Mar 13/1741	M7/	N18W62	1429
May 17/0210	May 17/0430	255	NW/17 0148	May 17/0147	M5/1F	N12W89	1476
May 27/0535	May 27/1045	14	/27 2112	N/A	N/A	N/A	1482
Jun 16/1955	Jun 16/2020	14	SE/14 1430	Jun 14/1435	M1/1N	S17E14	1504
Jul 07/0400	Jul 07/0745	25	SW/06 2312	Jul 06/2308	X1/	S18W50	1515
Jul 12/1835	Jul 12/2225	96	SW/12 1649	Jul 12/1710	X1/2B	S16W09	1520
Jul 17/1715	Jul 18/0600	136	SW/17 1348	Jul 17/1715	M1/	S17W75	1520
Jul 23/1545	Jul 23/2145	12	SW/23 0236			S16W86	1520
Sep 01/1335	Sep 02/0859	59	SE/31 2012	Aug 31/2043	C8/2F	S06E20	
Sep 28/0300	Sep 28/0445	28	NW/28 0018	Sep 27/2357	C3/1F	N08W41	1577

2013

Mar 16/1940	Mar 17/0700	16	NE/15 0712	Mar 15/0658	M1/1F	N11E12	1692
Apr 11/1055	Apr 11/1645	114	NE/11 0724	Apr 11/0716	M6/3B	N09E12	1719
May 14/1325	May 17/1720	41	NE/15 0148	May 15/0148	X1/2N	N11E51	1748
May 22/1420	May 23/0650	1660	NW/22 1325	May 22/1322	M5/3N	N15W70	1745

-----PARTICLE EVENT-----				ASSOCIATED	-----FLARE AND ACTIVE REGION-----		
Start	Maximum	Proton Flux	CME	Flare Max.	Importance	Location	Region#
(Day/UT)		(pfu @ >10 MeV)		(Loc./ Day UT)	(Xray/Opt.)		(SWO)

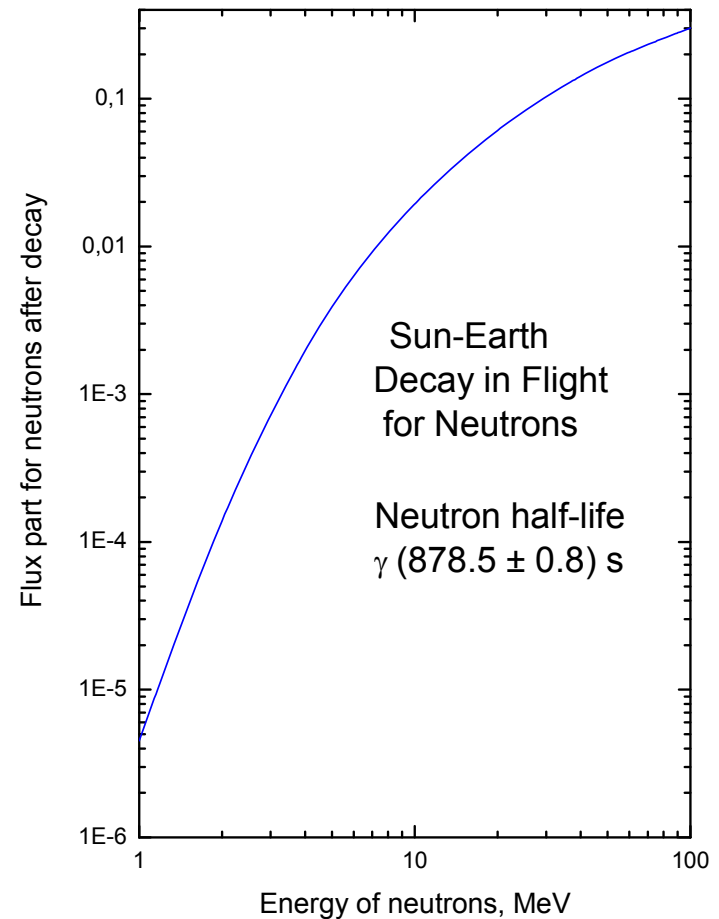
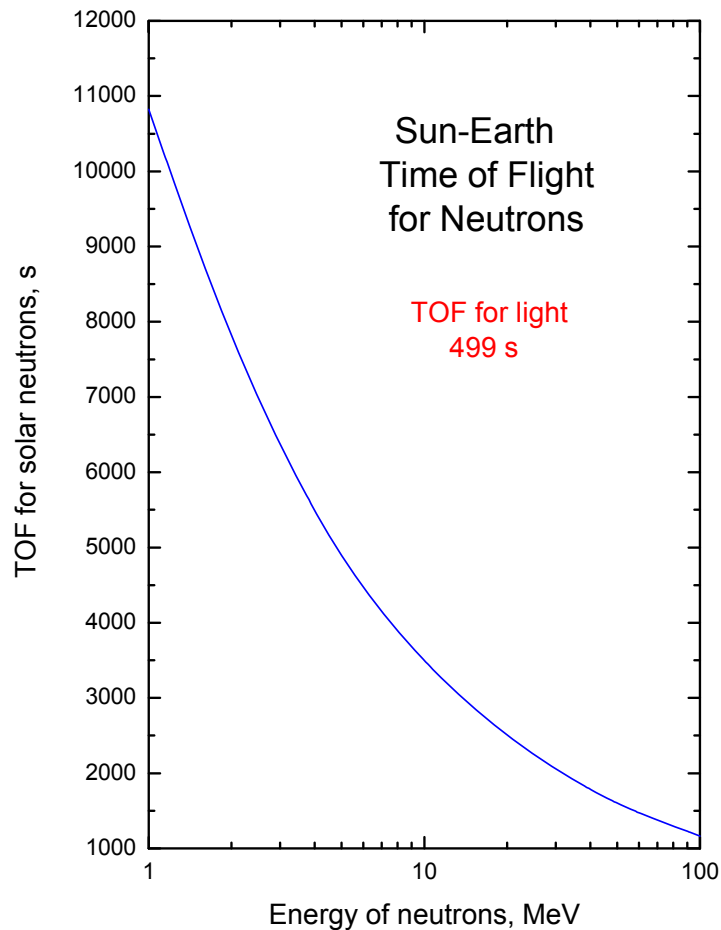
Solar Flashes (SF) 2006-2013

Data	Class	Area	$I_{\text{SCR}}(>100 \text{ MeV}), \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}$
13 December 2006	X3.4	S06 W24	~82000
07 June 2011	M2.5	S22 W53	~42000
23 January 2012	M8.7	N18 W21	~22000
27 January 2012	X1.7	N27 W71	~101000
07 March 2012	X5.4	N17 E27	~75000
17 May 2012	M5.1	N11 W76	~200000
06 July 2012	X1.1	S13 W59	~3000
19 July 2012	M7.7	S13 W88	~7000
11 April 2013	M6.5	N07 E13	~18000
22 May 2013	M5.0	N14 W87	~31000

Selection Criteria: Solar Proton Flux more 100 MeV

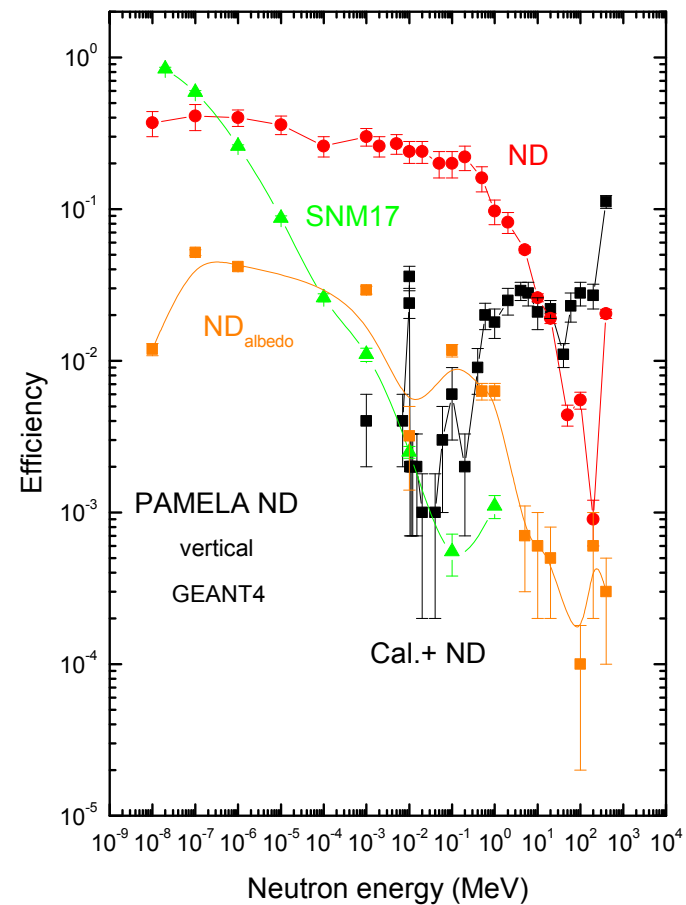
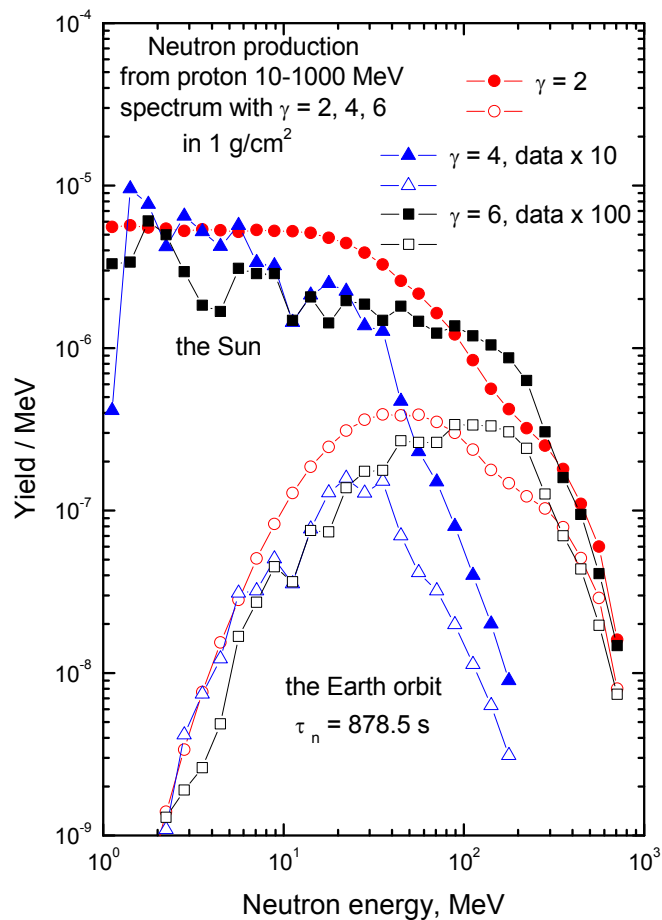
$$> 10^4 \text{ cm}^{-2} \text{ day}^{-1} \text{ sr}^{-1}$$

Energy, Neutron TOF for Sun-Earth, Arrival Probability of Solar Neutrons (SN) to Earth



Neutron Spectra for Sun-Earth

Efficiency of Neutron Registration in ND



GOES11-13. Proton Spectra in SF 2006-2013

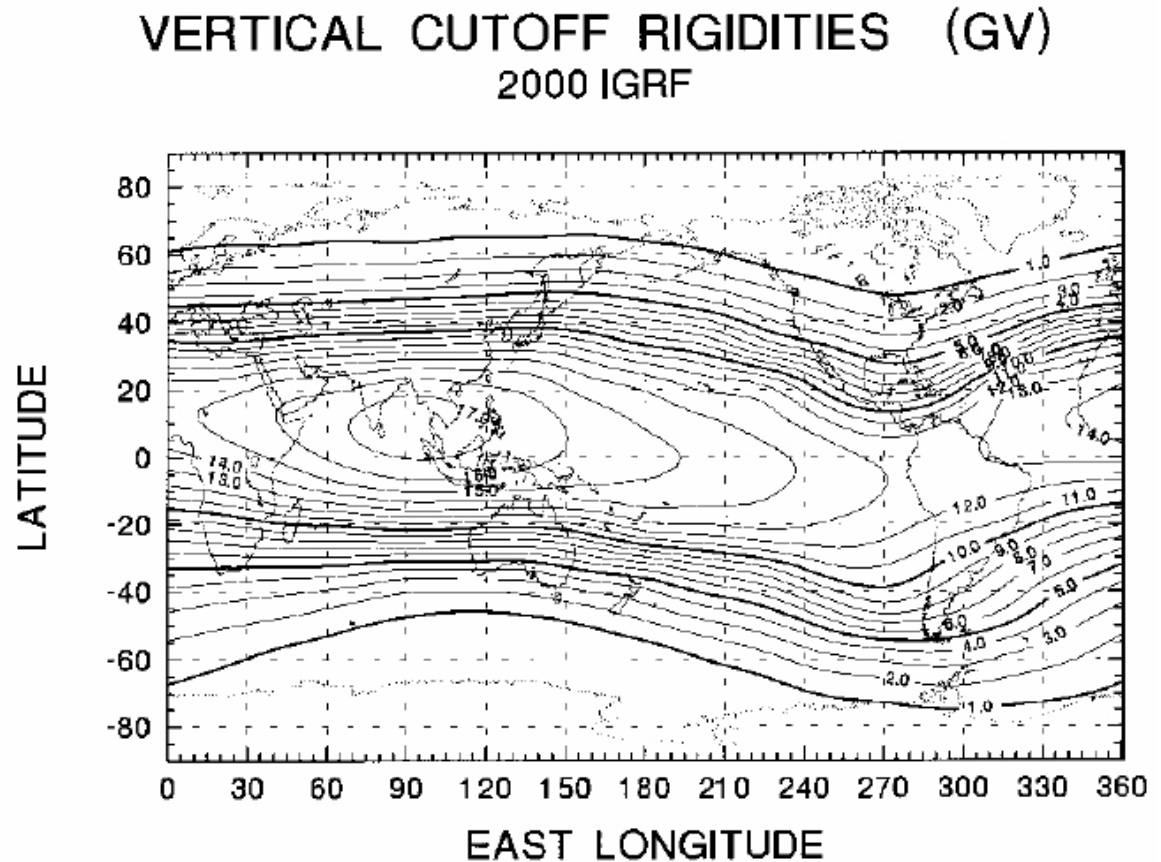
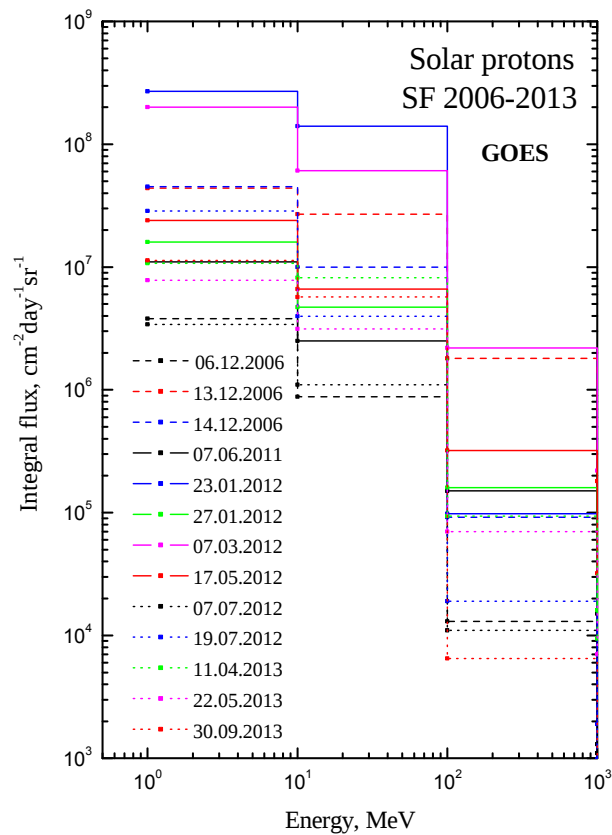
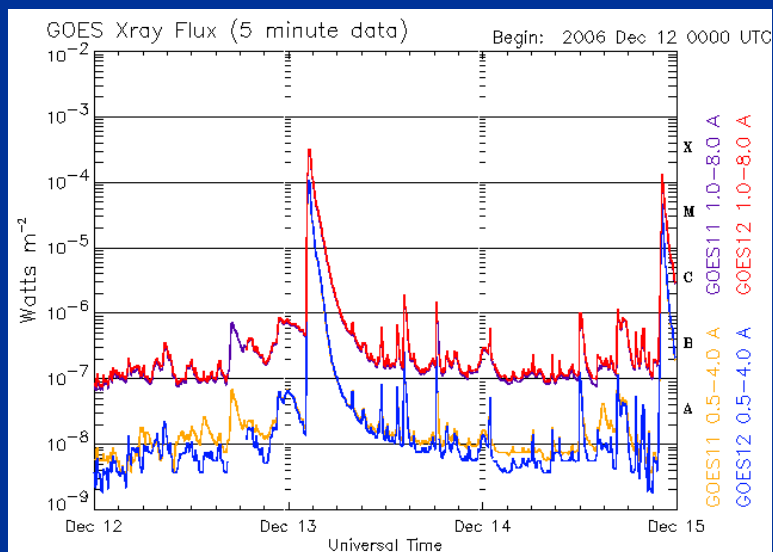
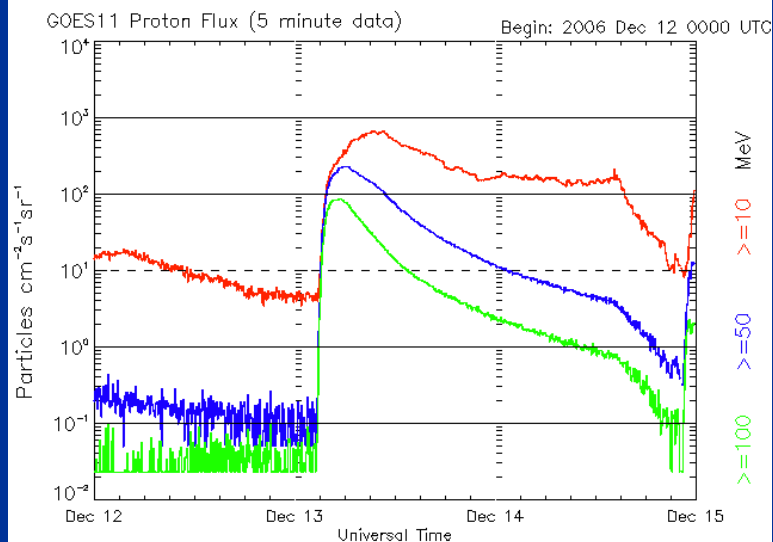


Figure 1: Iso-rigidity contours for vertical geomagnetic cutoff rigidities for epoch 2000.

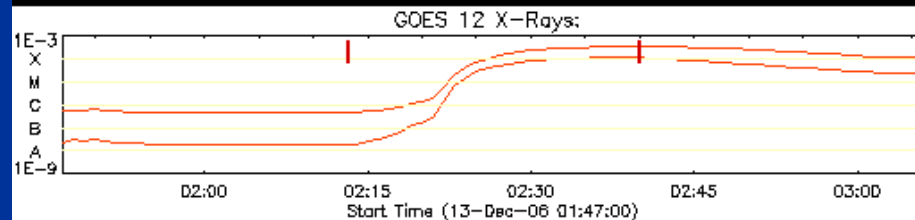
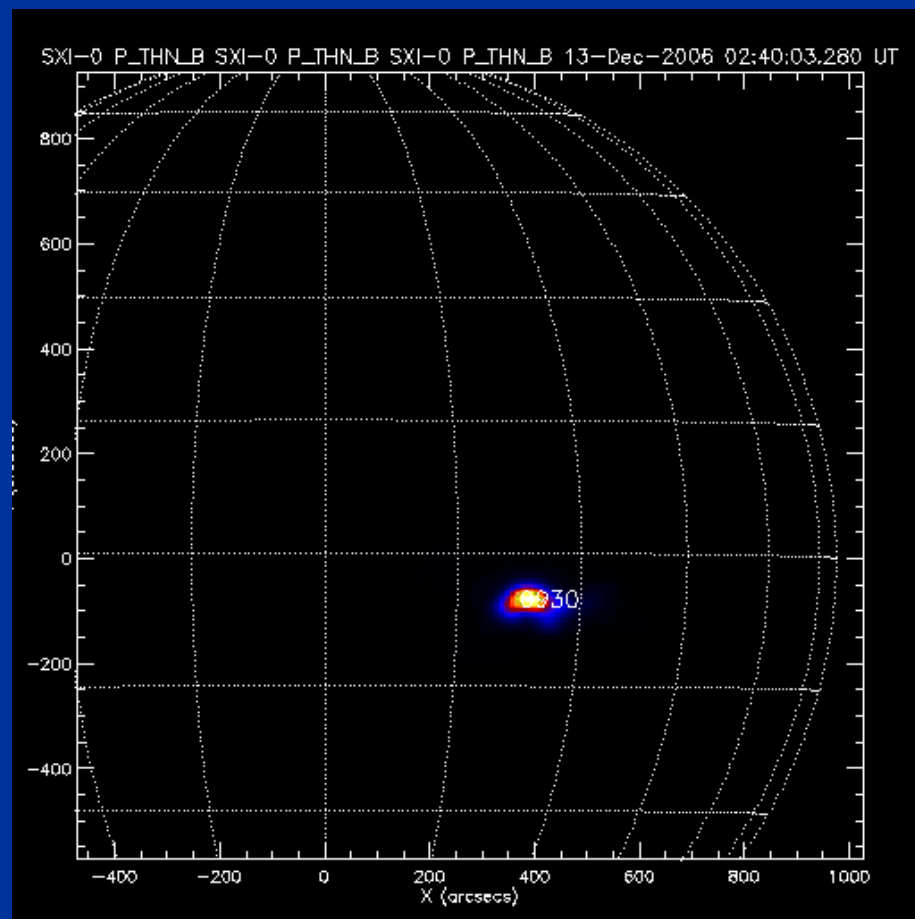
13 December 2006. SF X3.4/4B 02:40 UT Area 930, S05W23



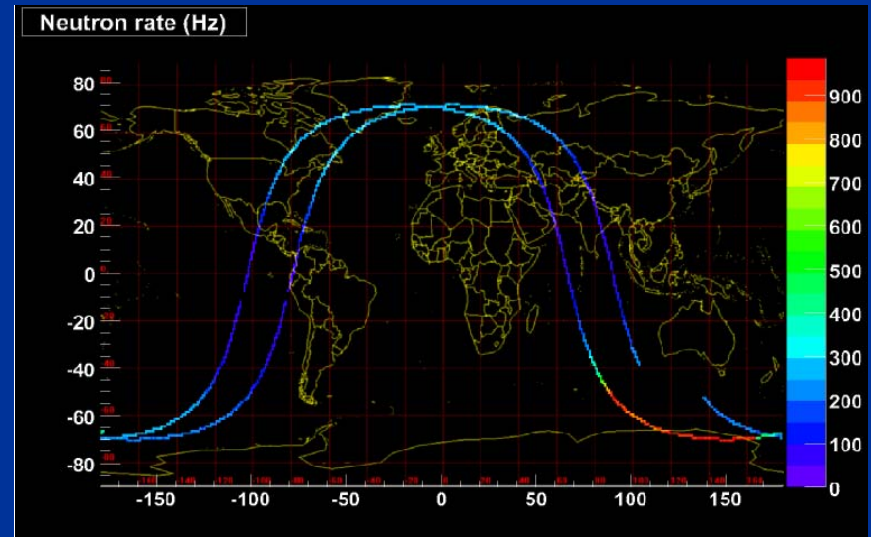
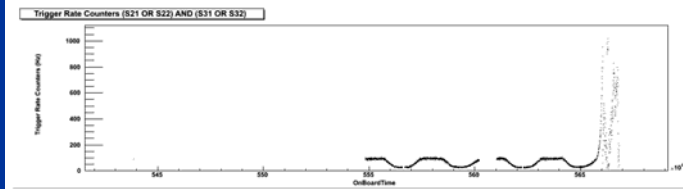
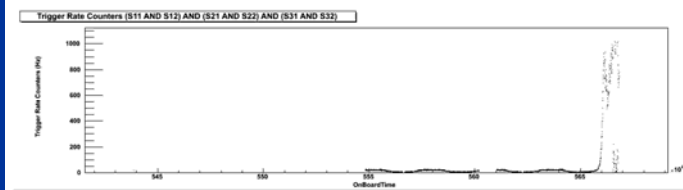
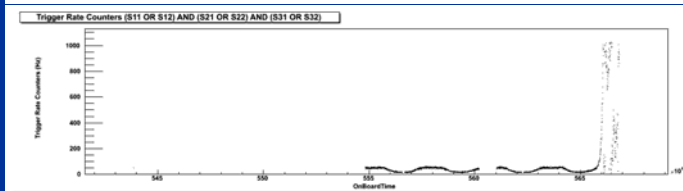
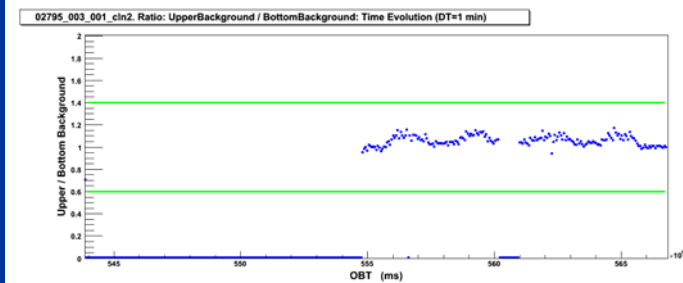
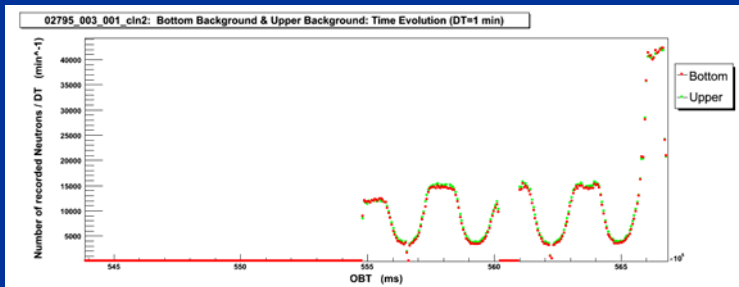
Updated 2008 Dec 14 23:56:07 UTC NOAA/SEC Boulder, CO USA



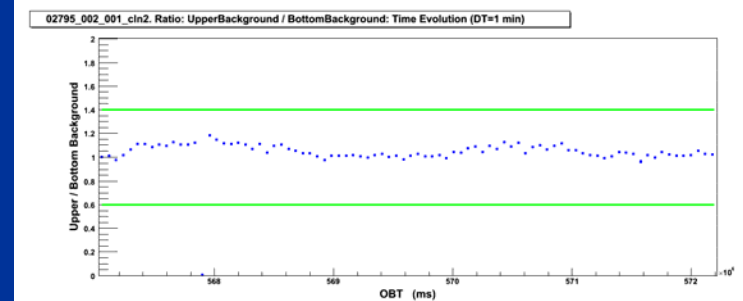
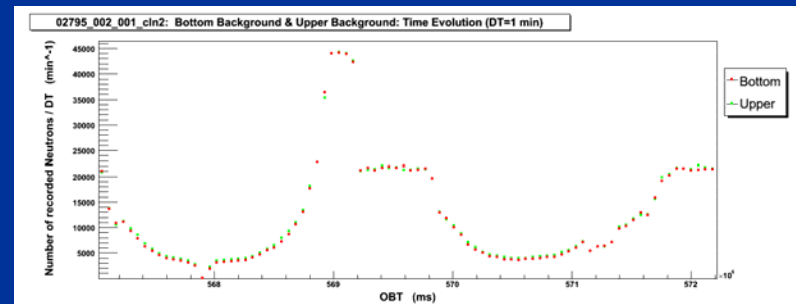
Updated 2008 Dec 14 23:56:05 UTC NOAA/SEC Boulder, CO USA



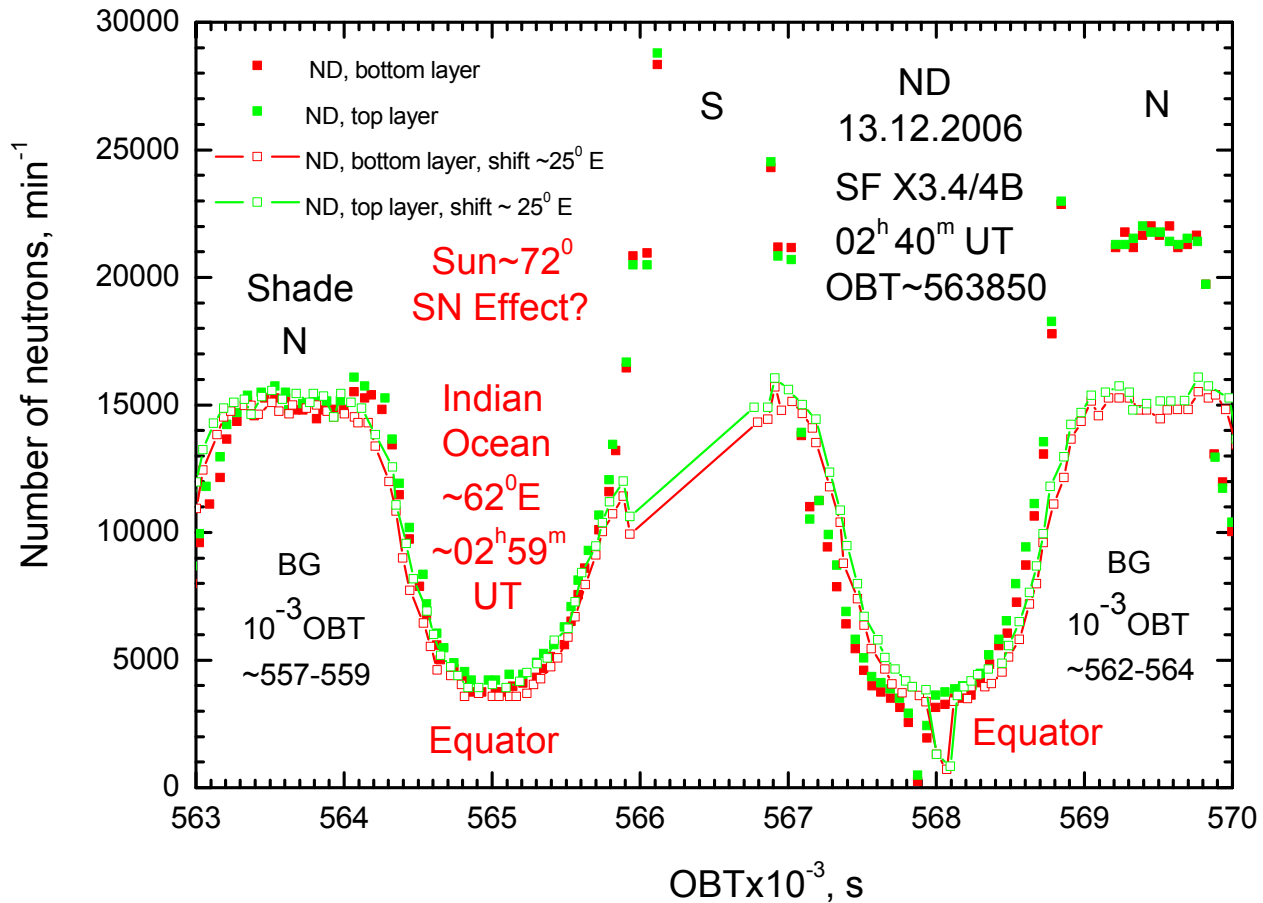
13.12.2006 and PAMELA. QUICKLOOK Data



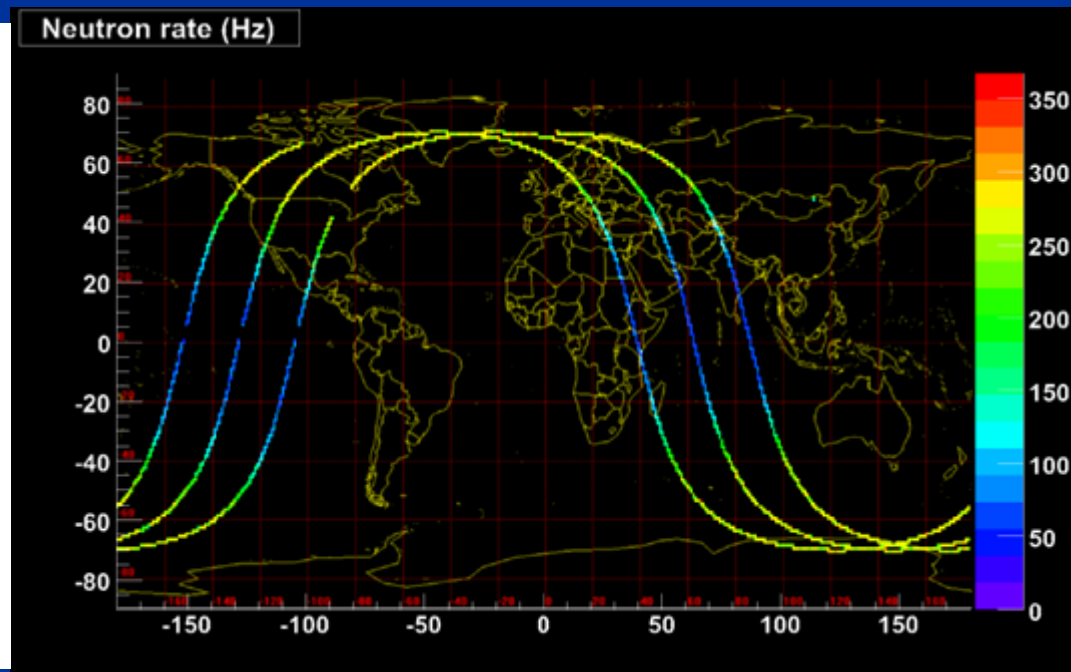
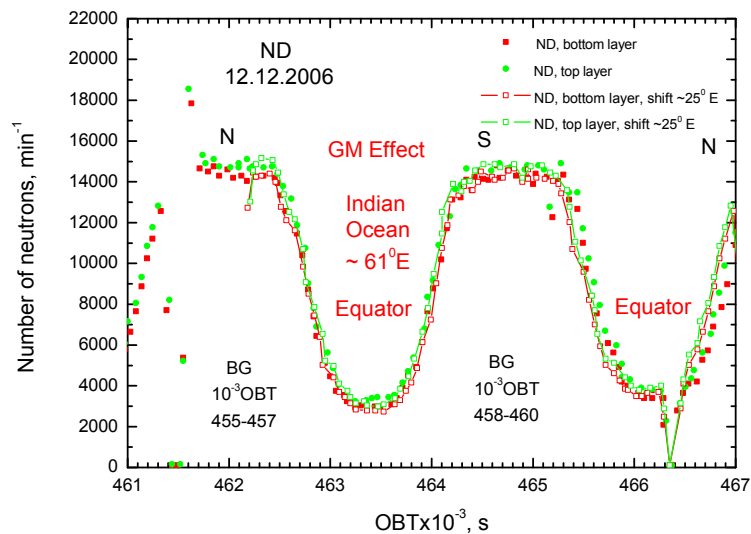
$n > p + e^+$?
Pre-pulse
near North
in S1-S3



13.12.2006. QUICKLOOK Data Digitization



12.12.2006. QUICKLOOK Data Digitization



SN 13.12.2006 OBT~564600-565200 ND(b&t): 84693-81647=3046±408 **3.73±0.50%**

GM 12.12.2006 OBT~463120-463840 ND(b&t): 82886-80947=1939±405 **2.40±0.50%**

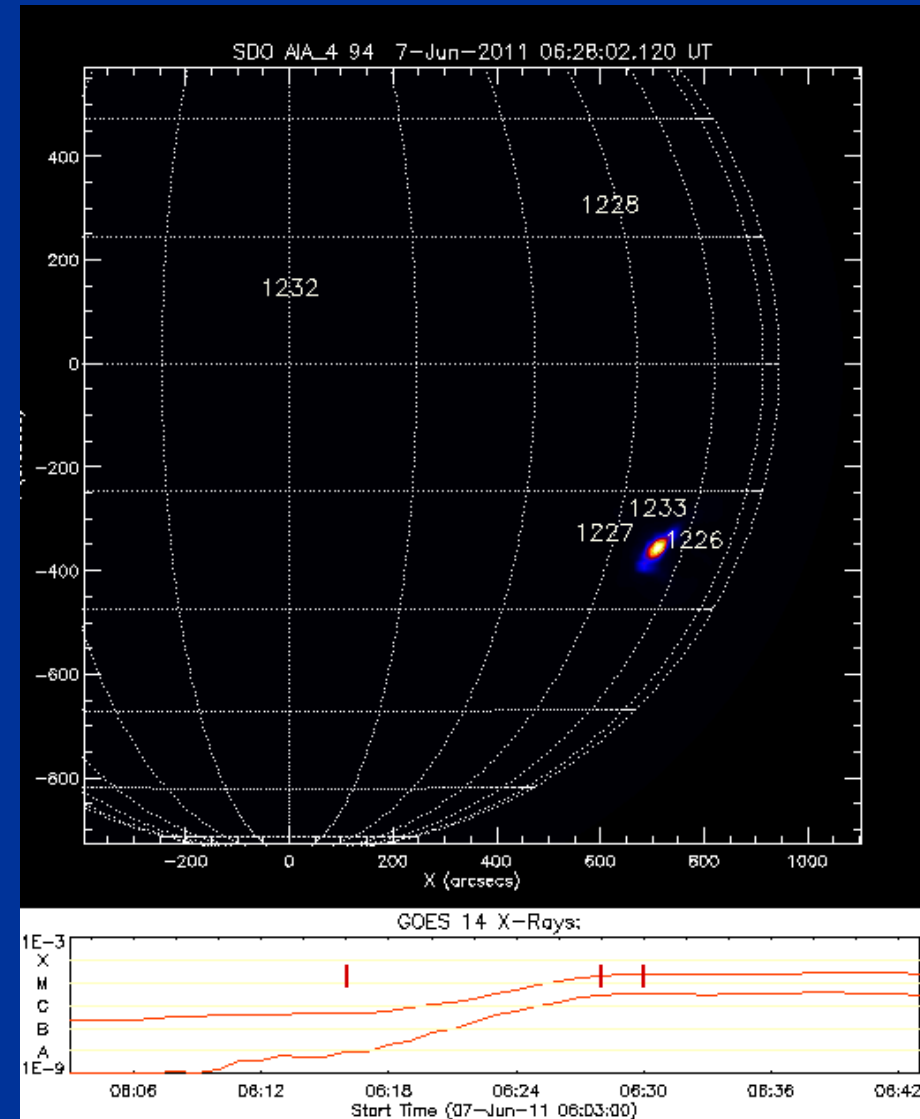
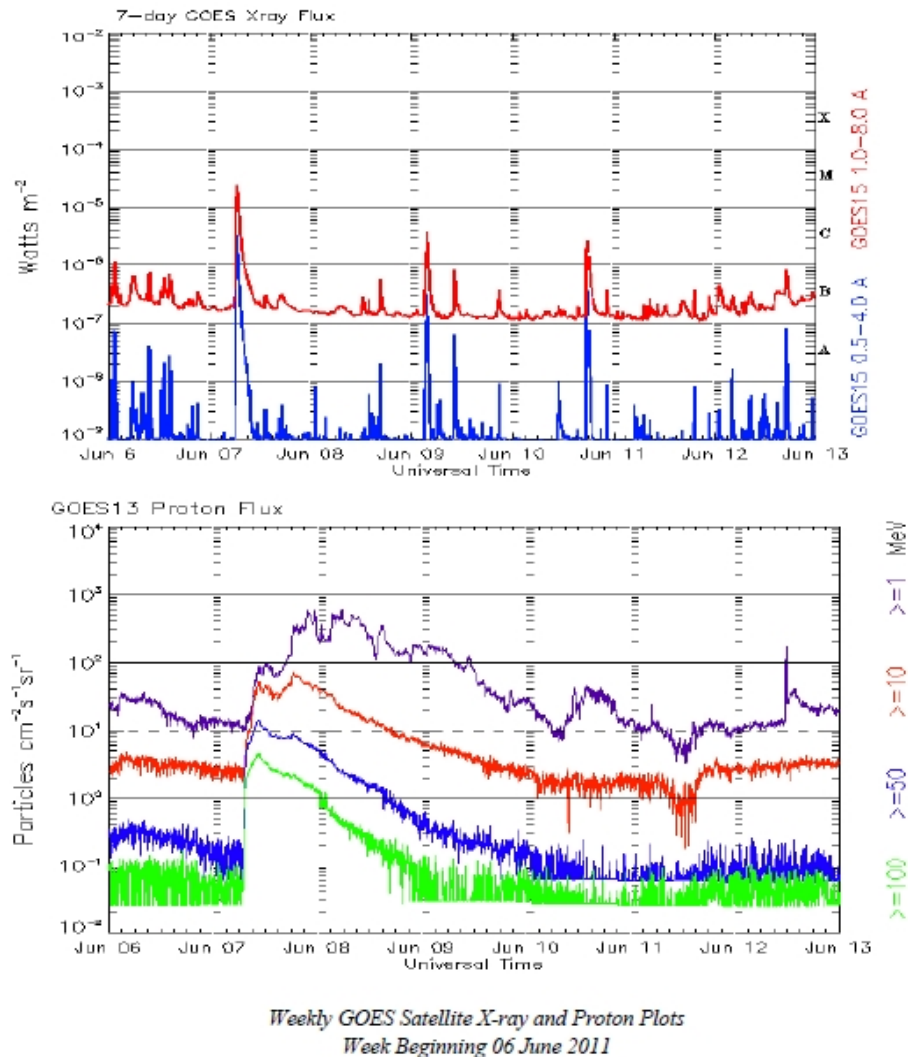
(GM: Cut-off shift ~16.8 - >17.0 GV)

Total Effect SN-GM: +1.33±0.71% for 20-31 min after SF, $E_n \sim 38-96$ MeV,

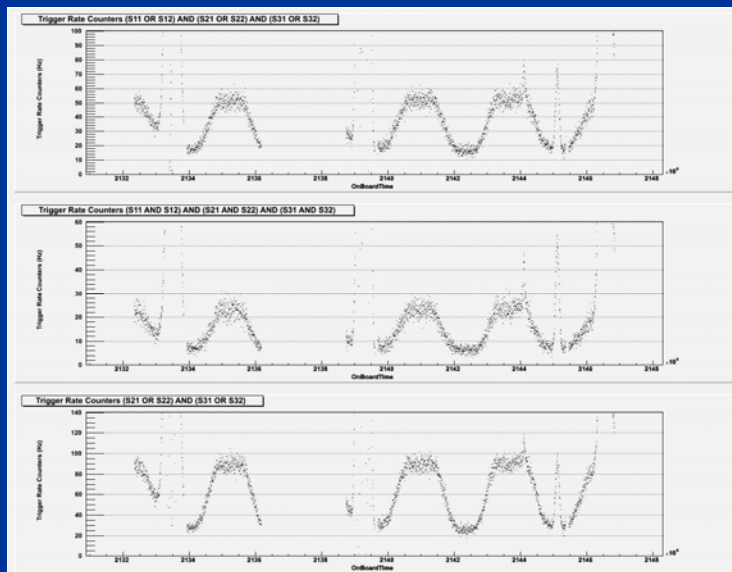
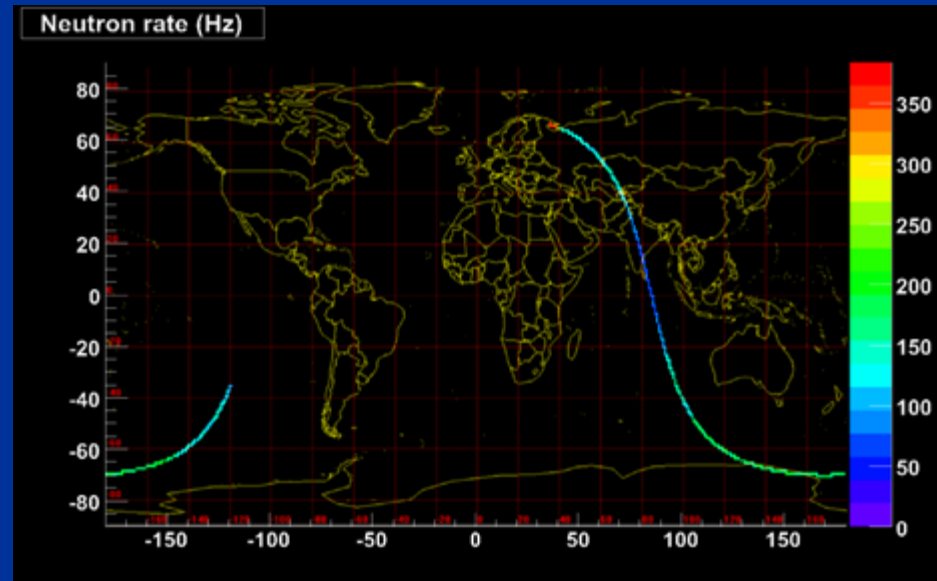
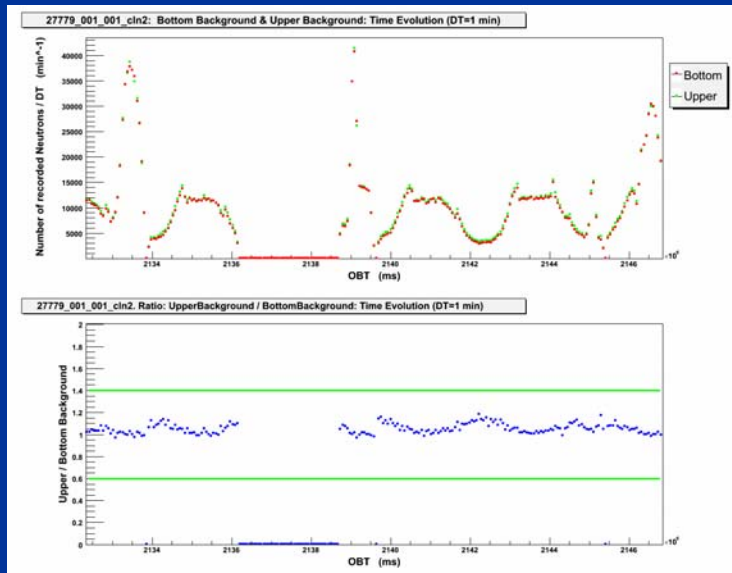
Near the Earth $I_n(38-96 \text{ MeV}) \sim 500 \text{ n/m}^2\text{s}$, on the Sun $n/p \sim 0.1 \dots$ Reasonably

07 June 2011. SF M2.5 06:41 UT

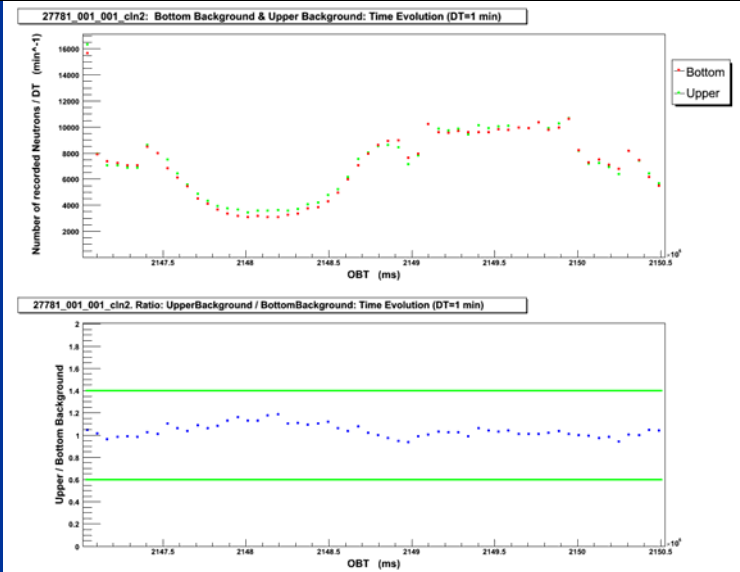
Area 1226, S21W54



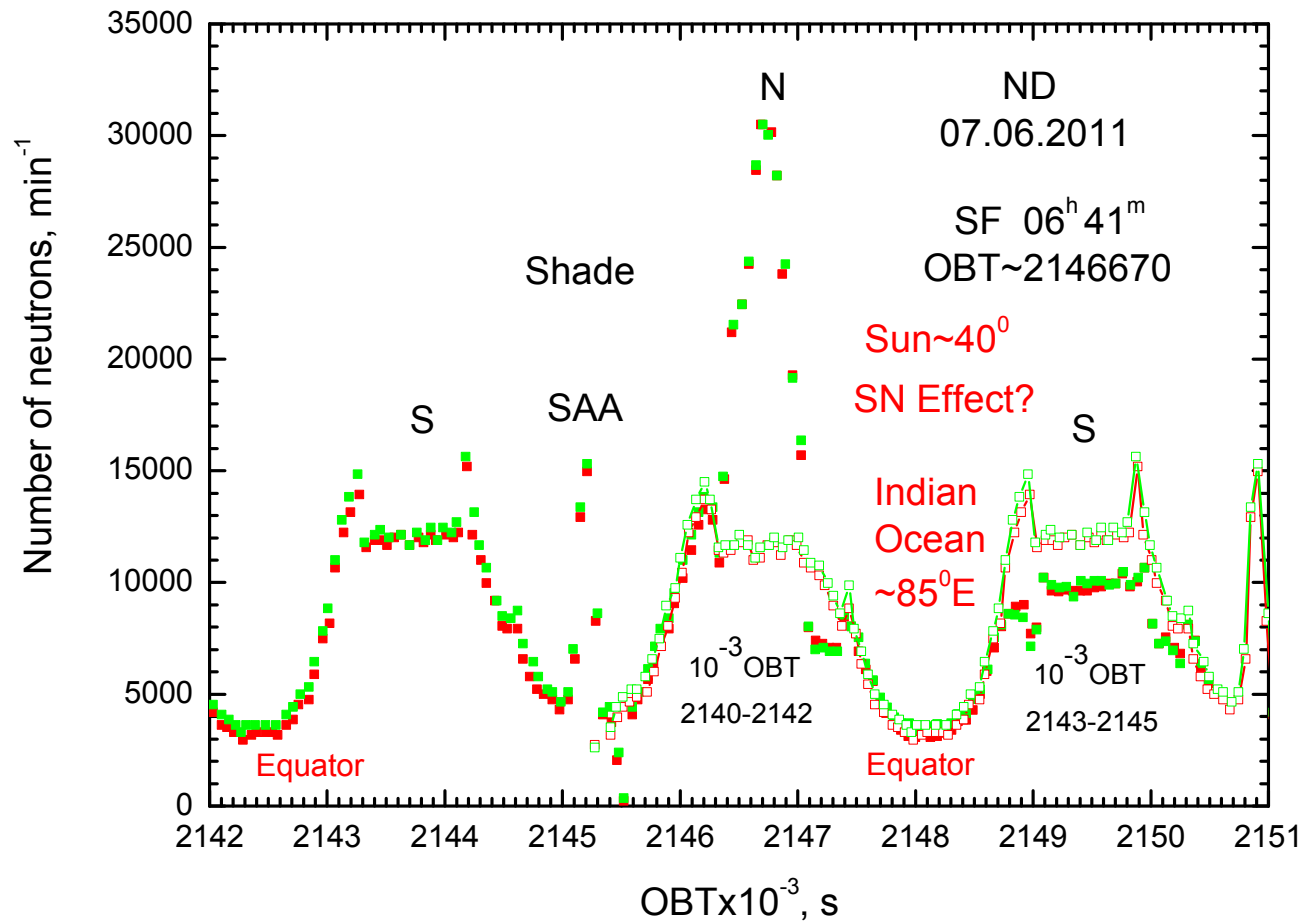
07.06.2011 and PAMELA. QUICKLOOK Data



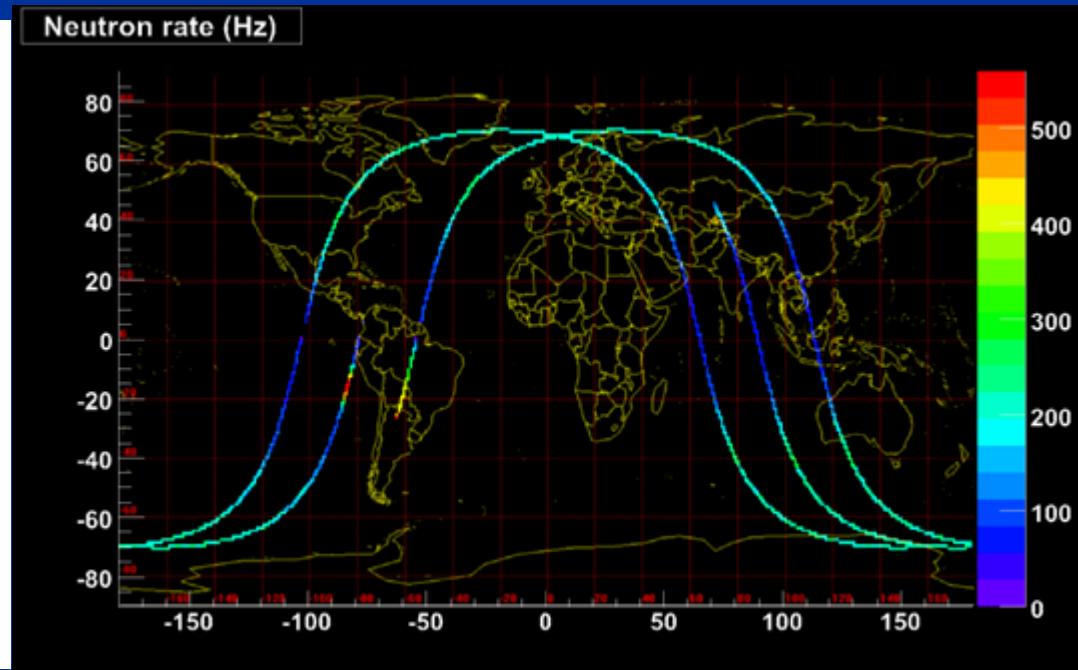
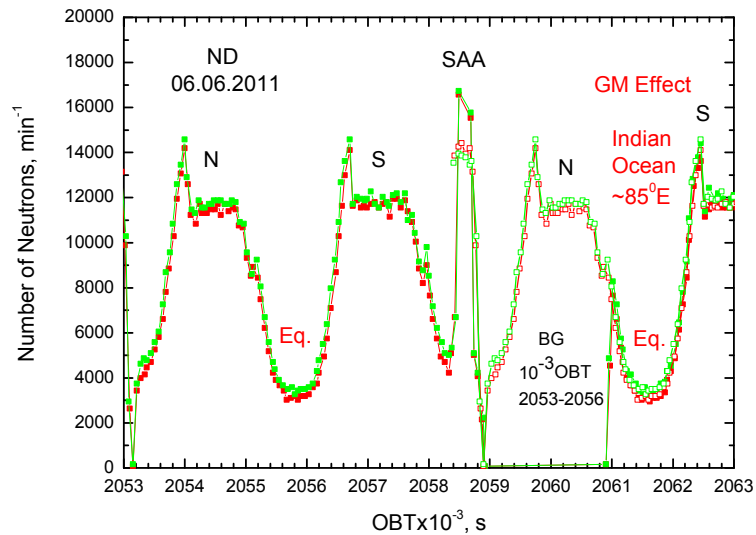
NO
Pre-pulse
Near North
in S1-S3



07.06.2011. QUICKLOOK Data Digitization



06.06.2011. QUICKLOOK Data Digitization



SN: 07.06.2011 OBT~2147830-2148430 ND: 70059-71086= - 1027 ± 376 , - $1.44 \pm 0.53\%$

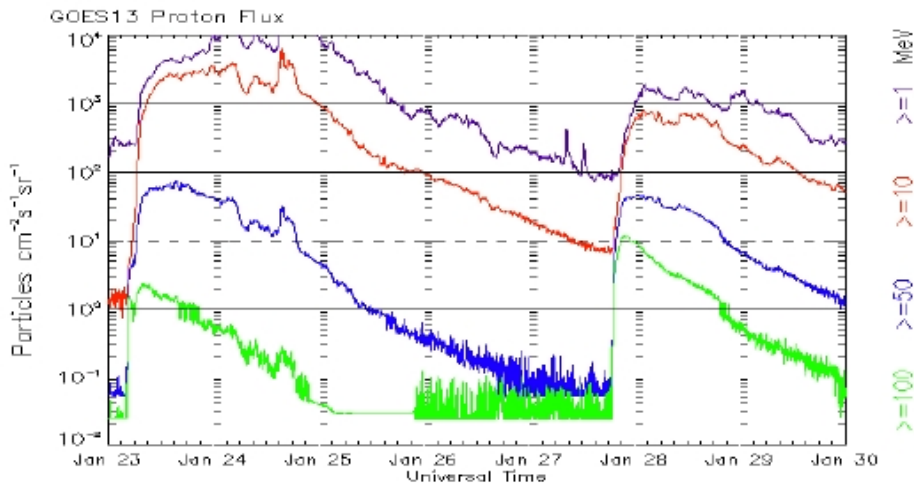
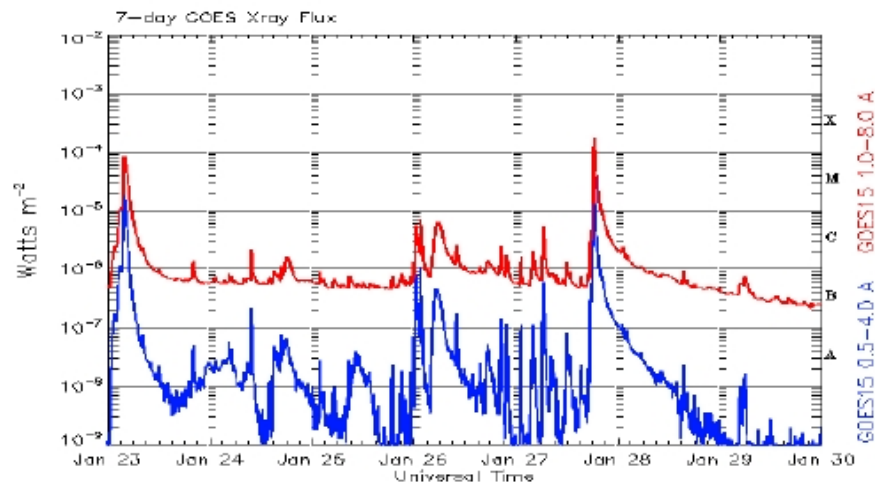
GM: 06.06.2011 OBT~2061320-2061920 ND: 68608-68334= + 274 ± 370 , + $0.40 \pm 0.54\%$

(GM: Cut-off shift $\sim >17.0 - 17.0$ GV)

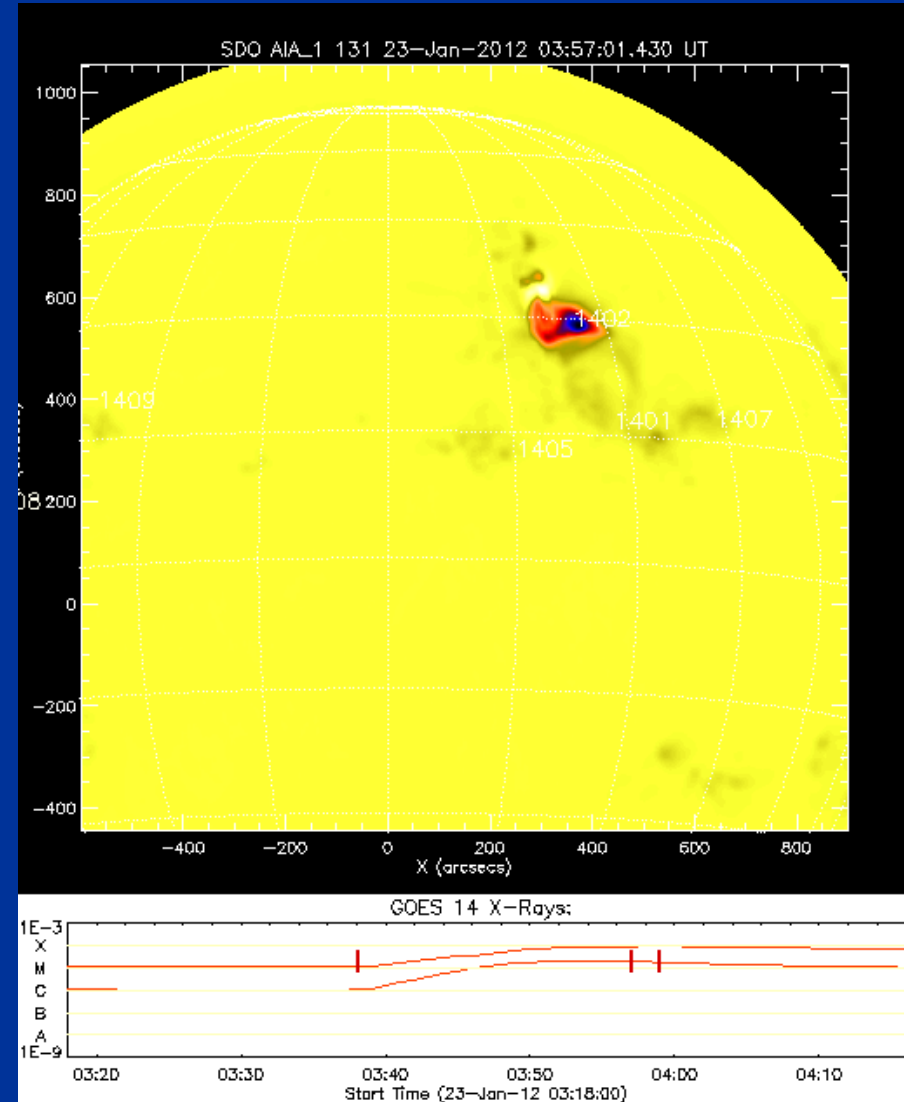
Total Effect SN-GM: - $1.84 \pm 0.76\%$ for 27-37 min after SF, $E_n \sim 27-40$ MeV

NO SOLAR NEUTRONS. Only upper limit.

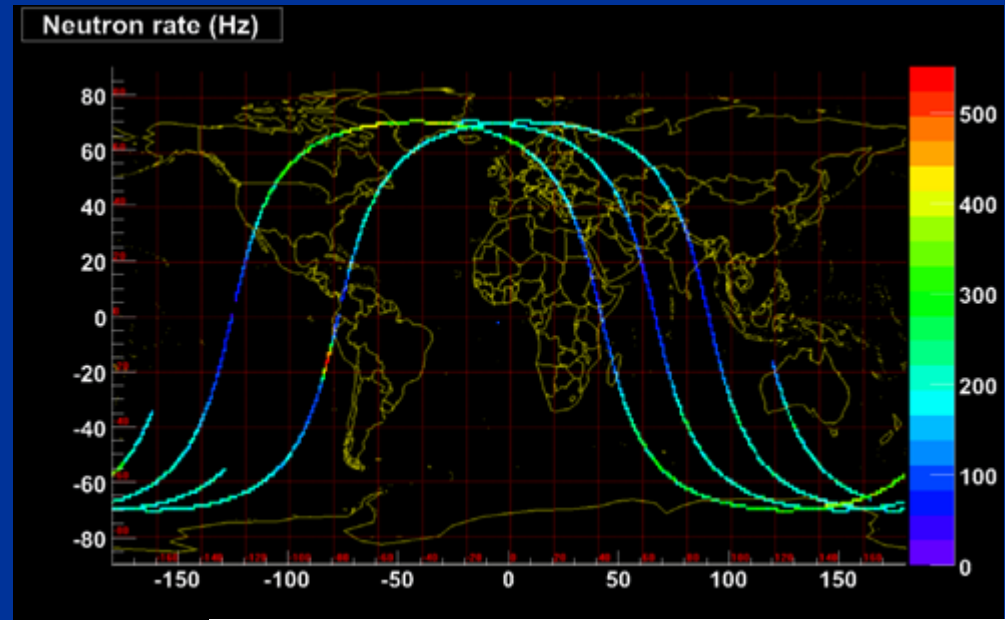
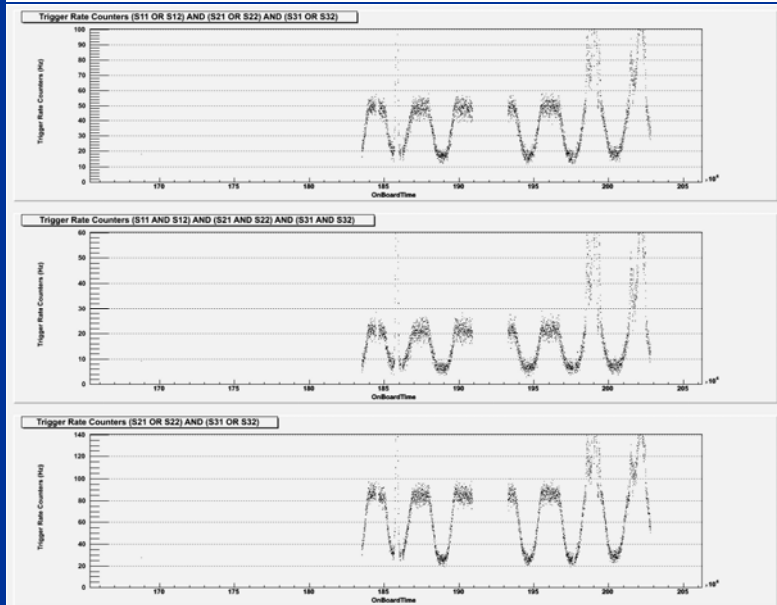
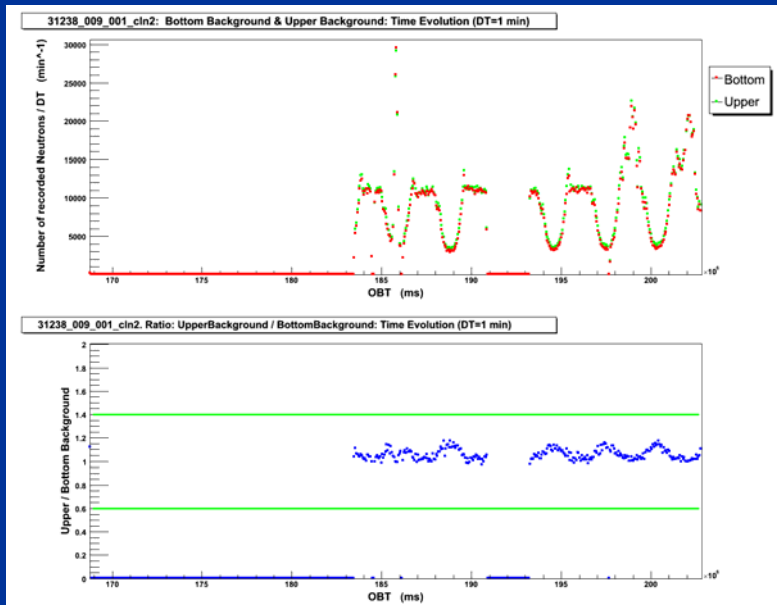
23 January 2012. SF M8.7 03:59 UT Area 1402, N33W21



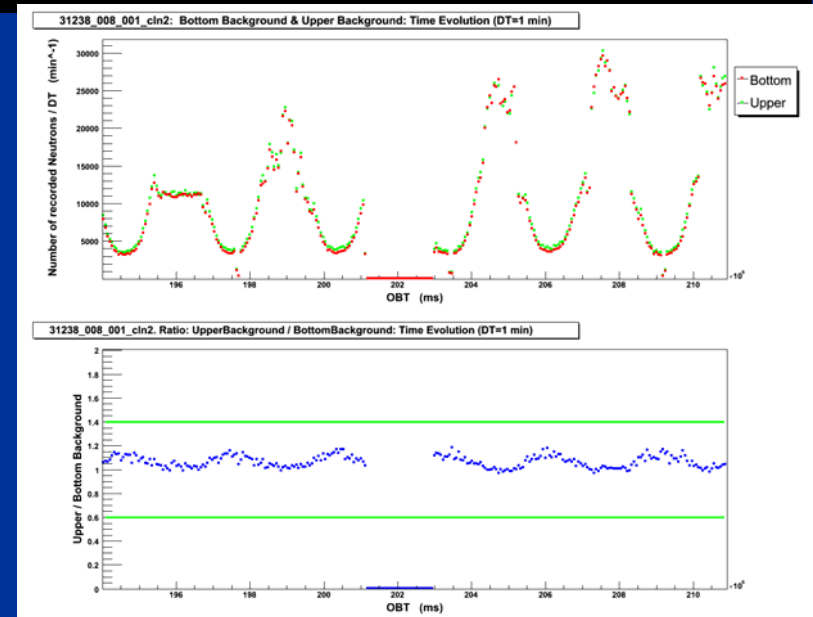
Weekly GOES Satellite X-ray and Proton Plots
Week Beginning 23 January 2012



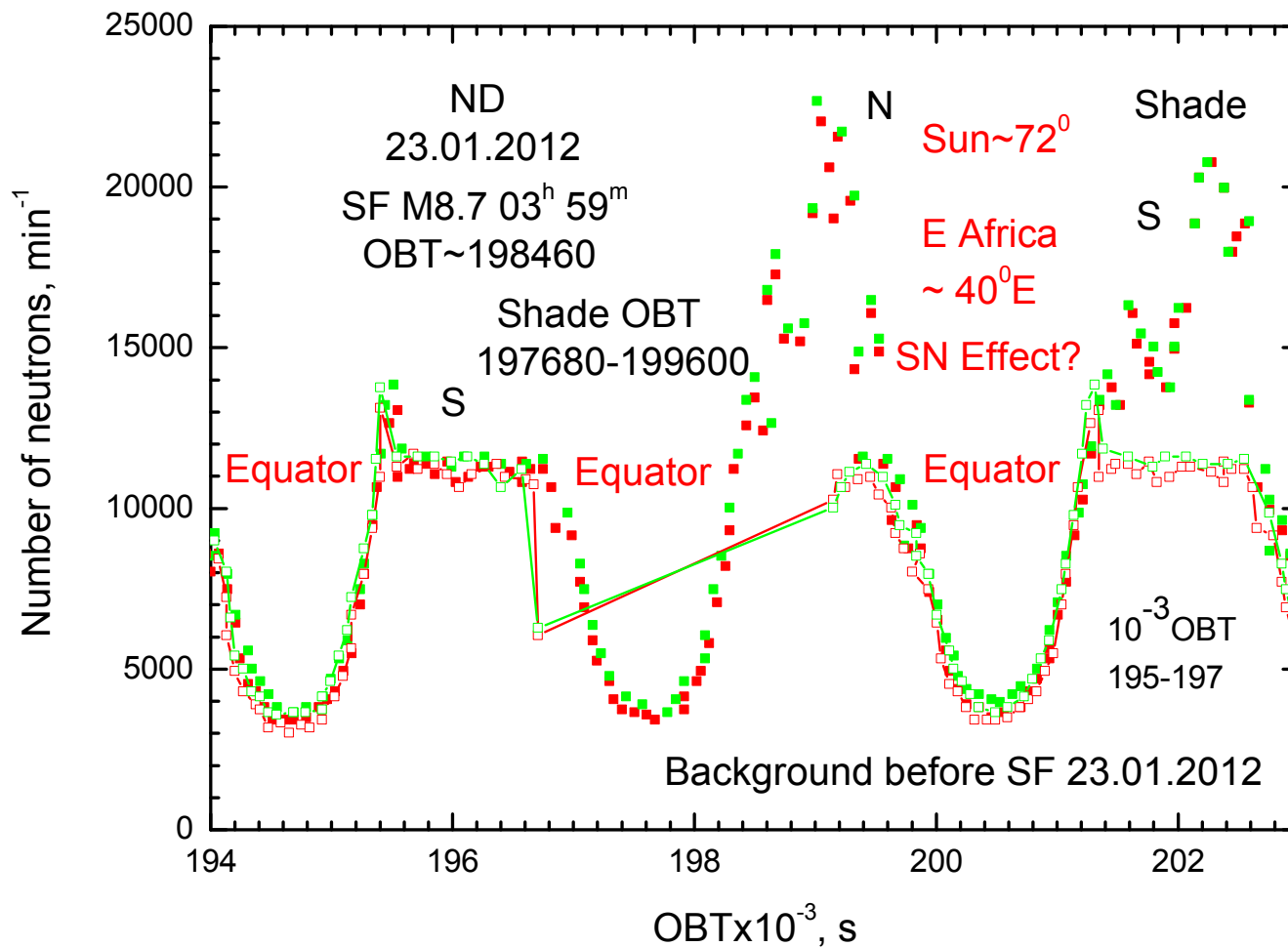
23.01.2012 and PAMELA. QUICKLOOK Data



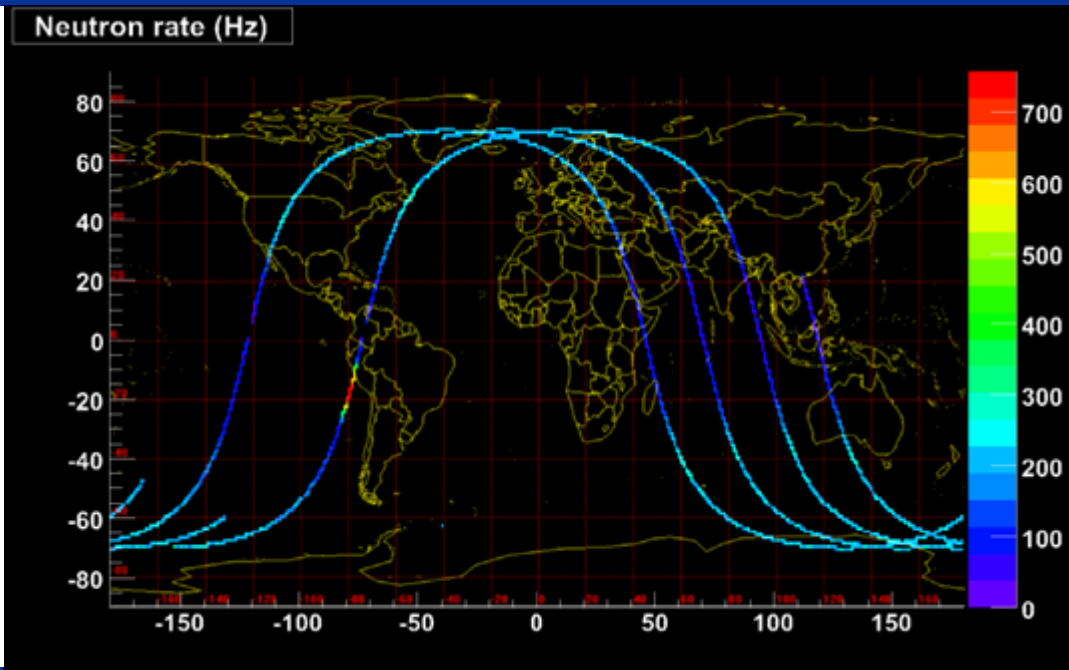
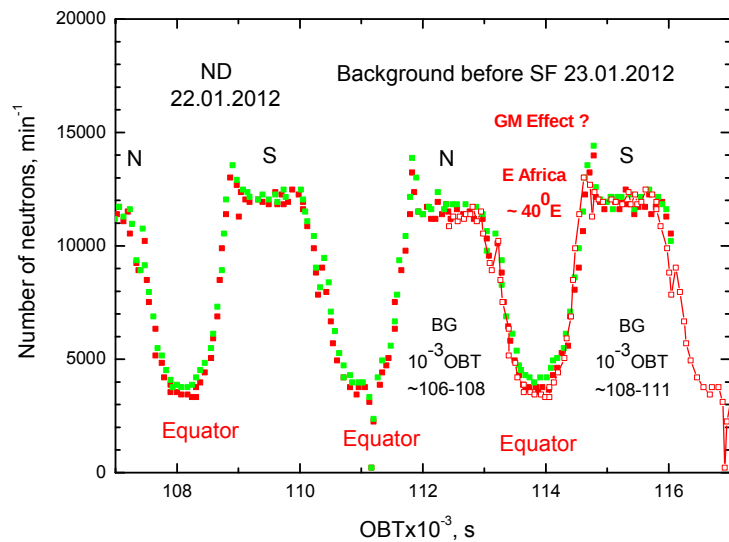
$n > p + e + \dots$?
Pre-pulse
near North
in S1-S3



23.01.2012. QUICKLOOK Data Digitization



22.01.2012. QUICKLOOK Data Digitization



SN: 23.01.2012 OBT $\sim$ 200100-200700 ND: 80107-73959= 6148 ± 393 , $8.31\pm 0.53\%$

GM: 22.01.2012 OBT $\sim$ 113510-114110 ND: 81226-76074= 5152 ± 397 , $6.77\pm 0.72\%$

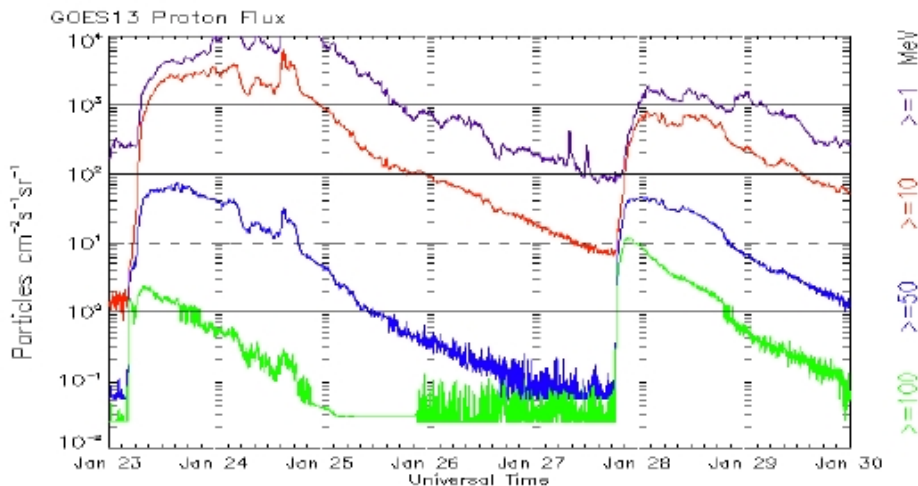
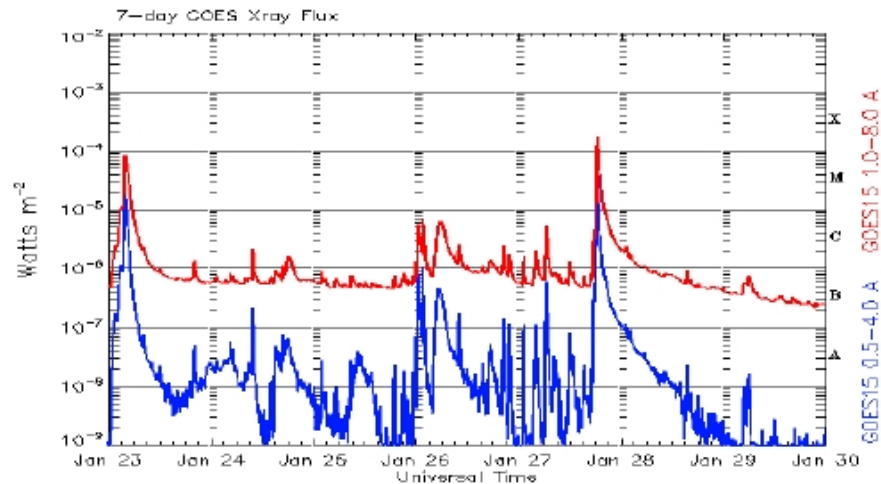
(GM: Cut-off shift ~ 16.0 - 16.6 GV)

Total effect SN-GM: $+1.54\pm 0.74\%$ for ~ 34 - 44 min after SF, $E_n \sim 18$ - 23 MeV

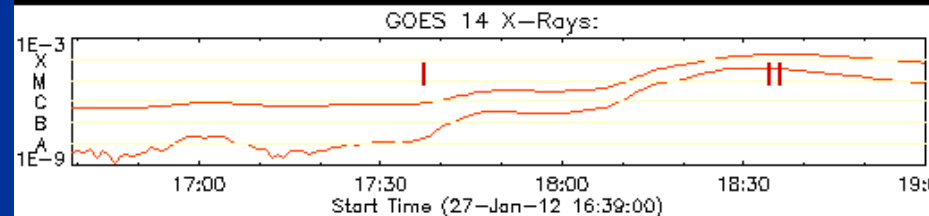
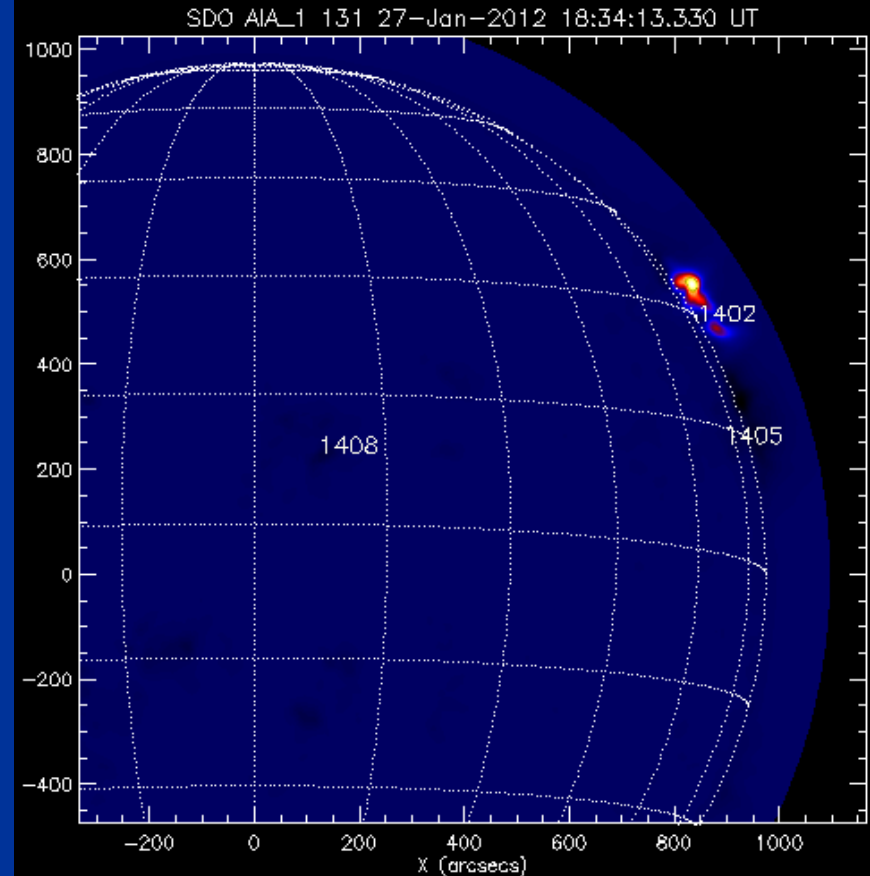
Near the Earth $I_n(18$ - 23 MeV) ~ 530 n/ m^2s

27 January 2012. SF X1.7 18:36 UT

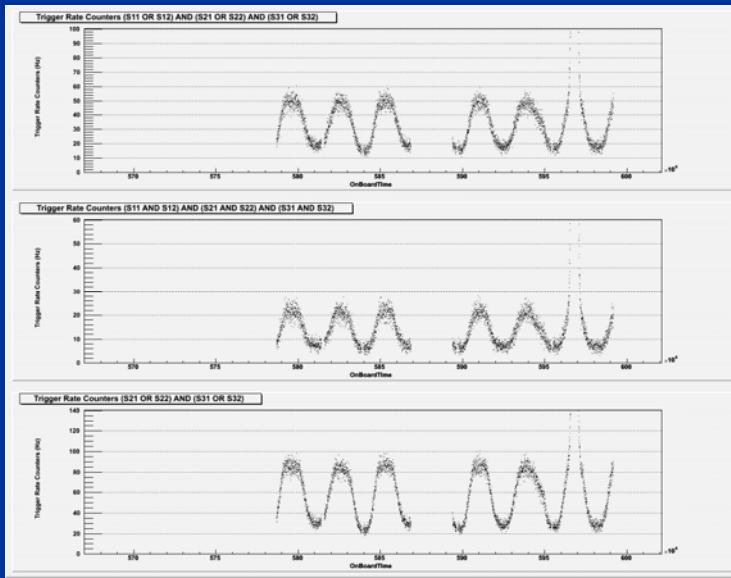
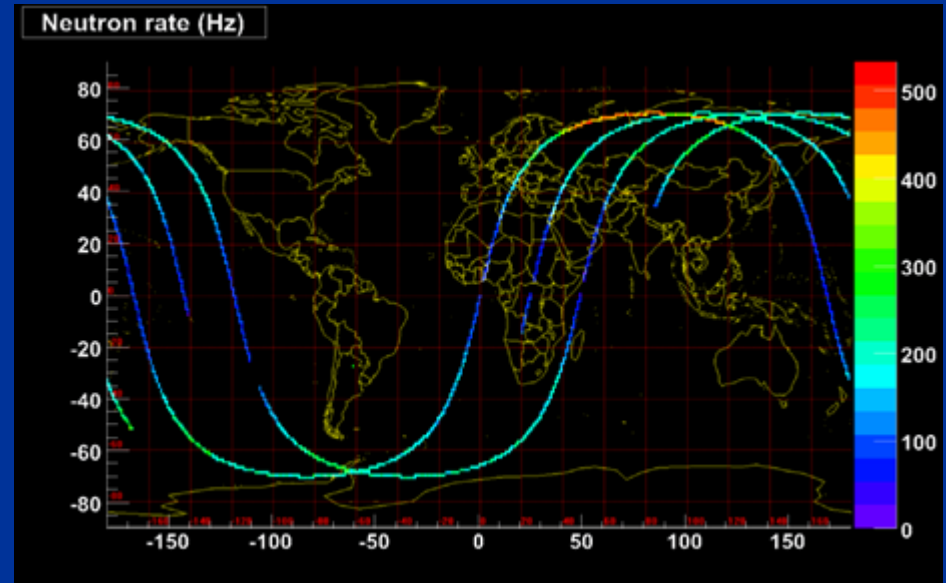
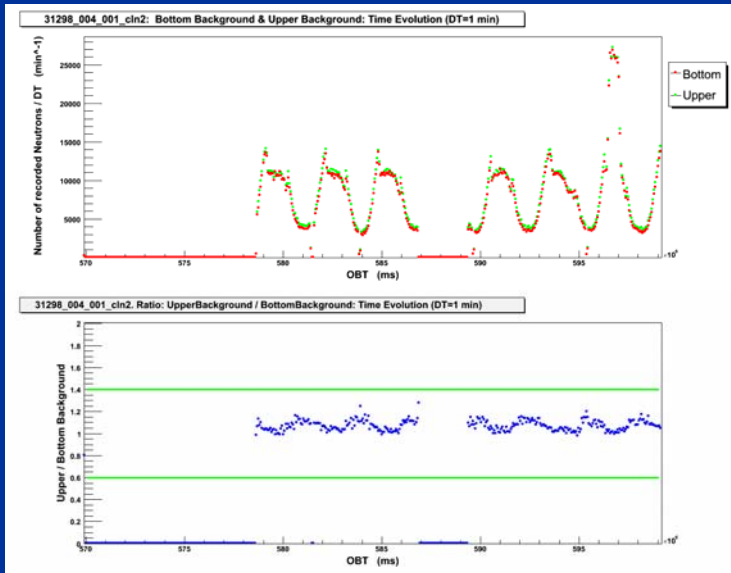
Area 1402, N27W71



Weekly GOES Satellite X-ray and Proton Plots
Week Beginning 23 January 2012



27.01.2012. QUICKLOOK Data



NO
Pre-pulse
near North
in S1-S3

ND
27.01.2012
SF X1.7 18^h 36^m
OBT ~596540

Shade

OBT~595640-597380

S

Equator

Sun~66⁰

SN Effect?

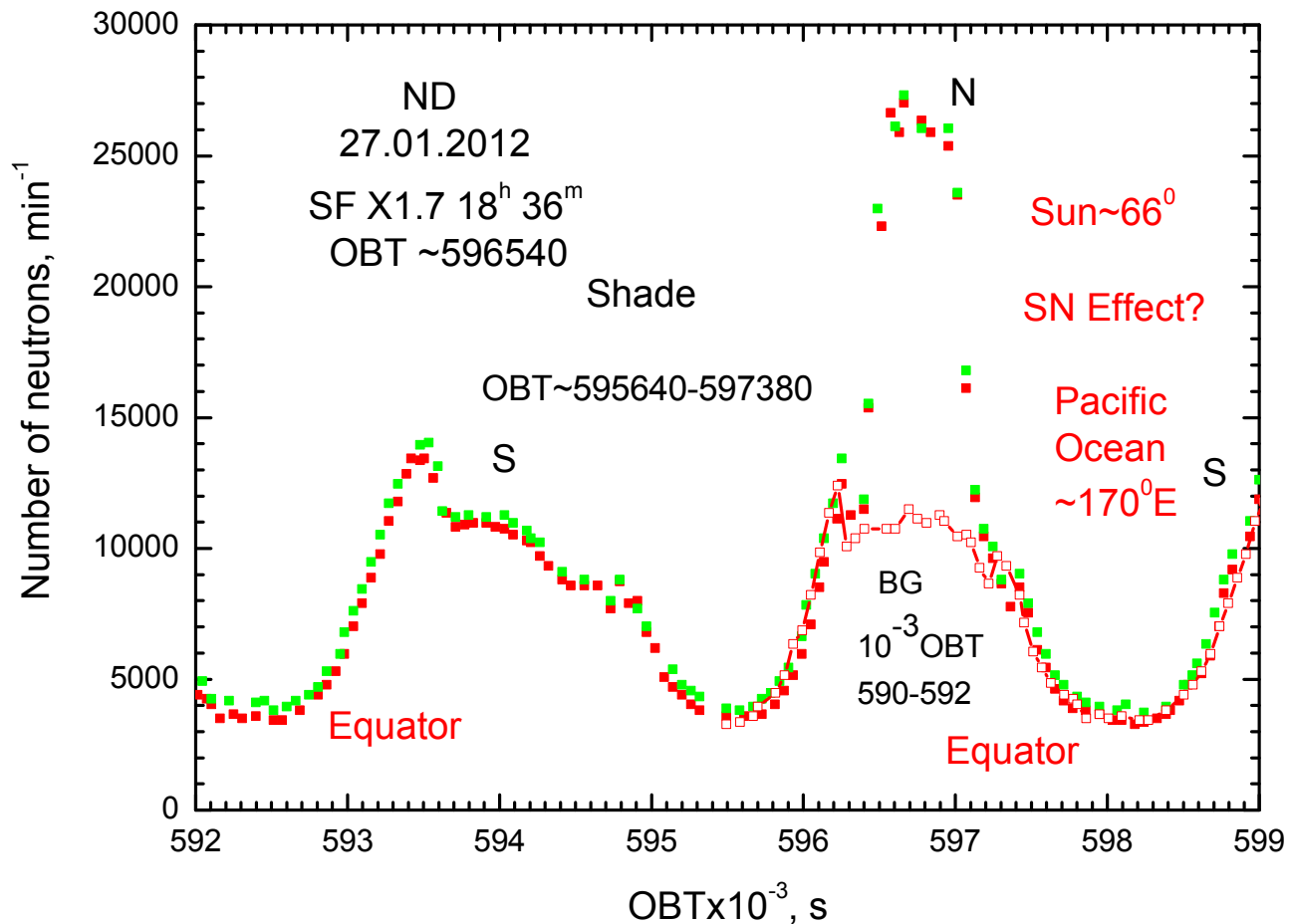
Pacific Ocean
~170⁰E

Equator

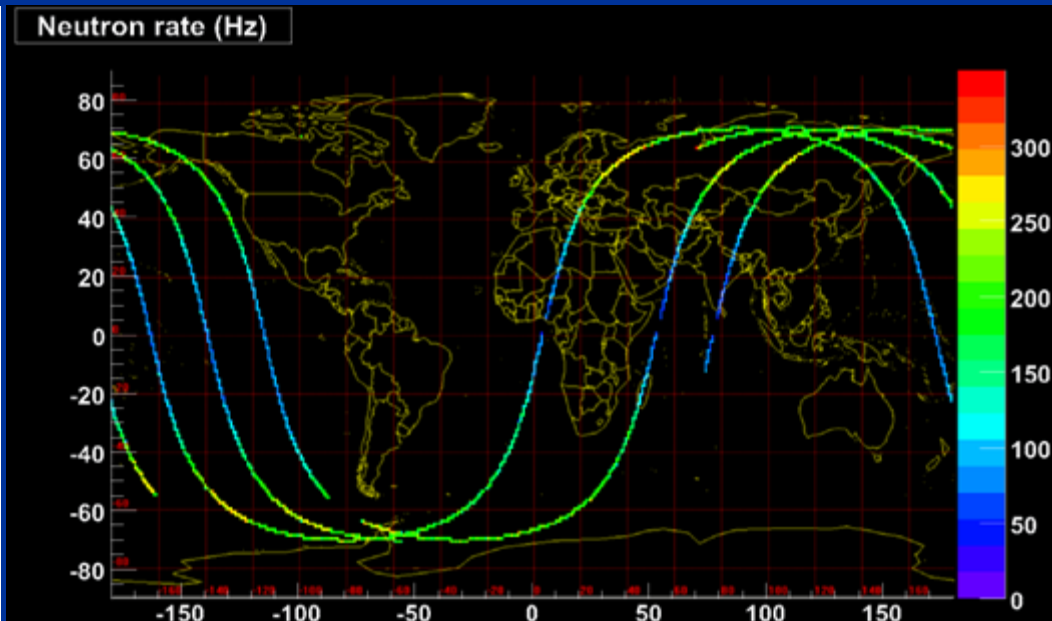
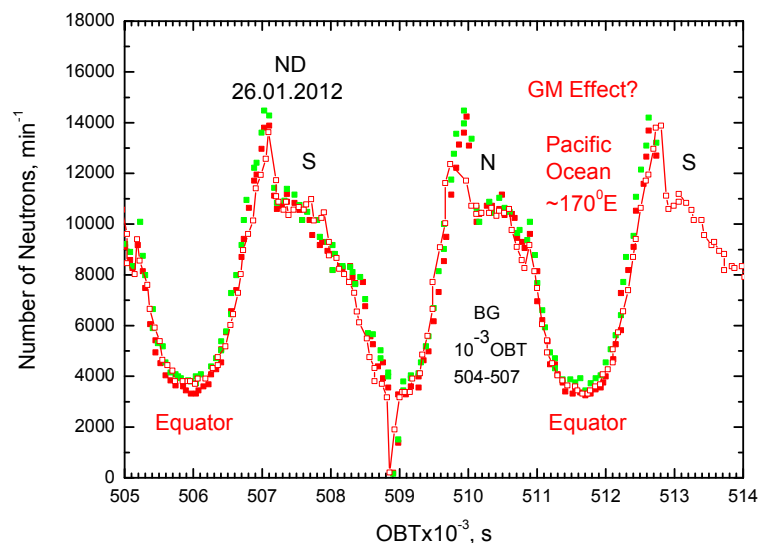
BG
10⁻³ OBT
590-592

Number of neutrons, min⁻¹

OBTx10⁻³, s



26.01.2012. QUICKLOOK Data Digitization



SN: 27.01.2012 OBT $\sim$ 597870-598470 ND: 74876-77519= - 2643 $\pm$ 390, - 3.41 $\pm$ 0.50%

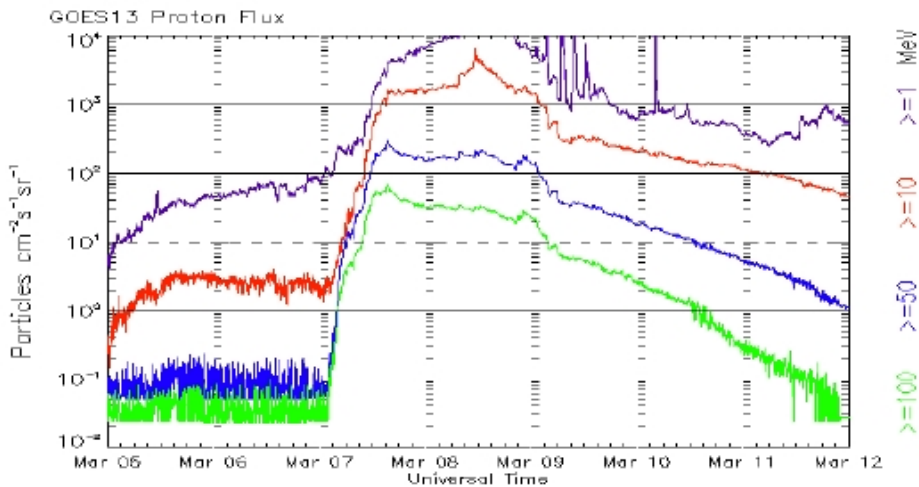
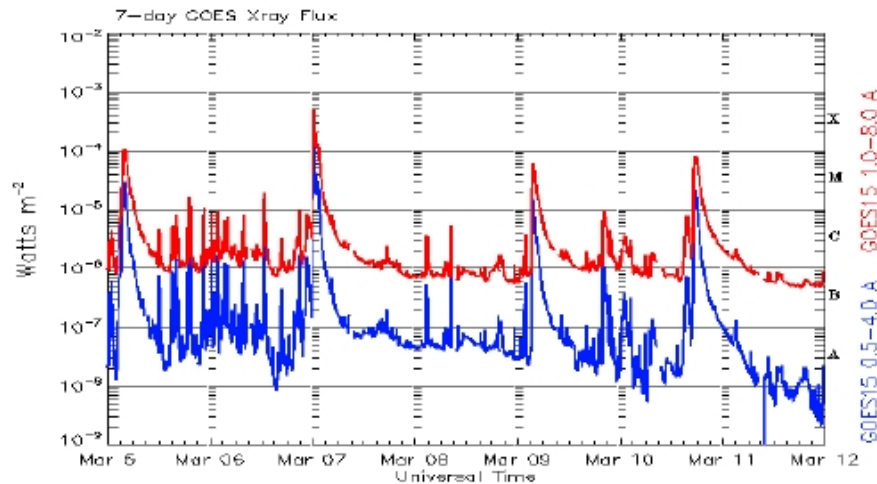
GM: 26.01.2012 OBT $\sim$ 511390-511990 ND: 72437-75113= - 1543 $\pm$ 279, -3.56 $\pm$ 0.51%

(GM Cut-off shift $\sim$ 15.5-15.0 GV)

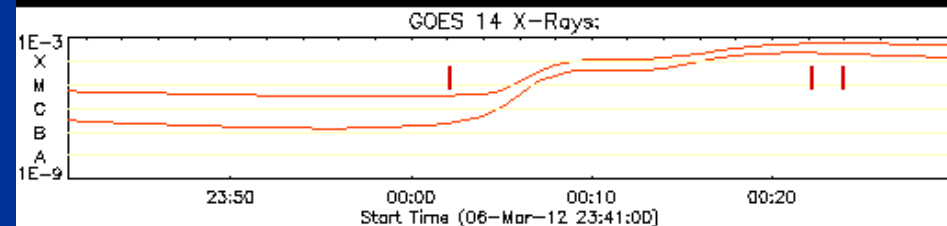
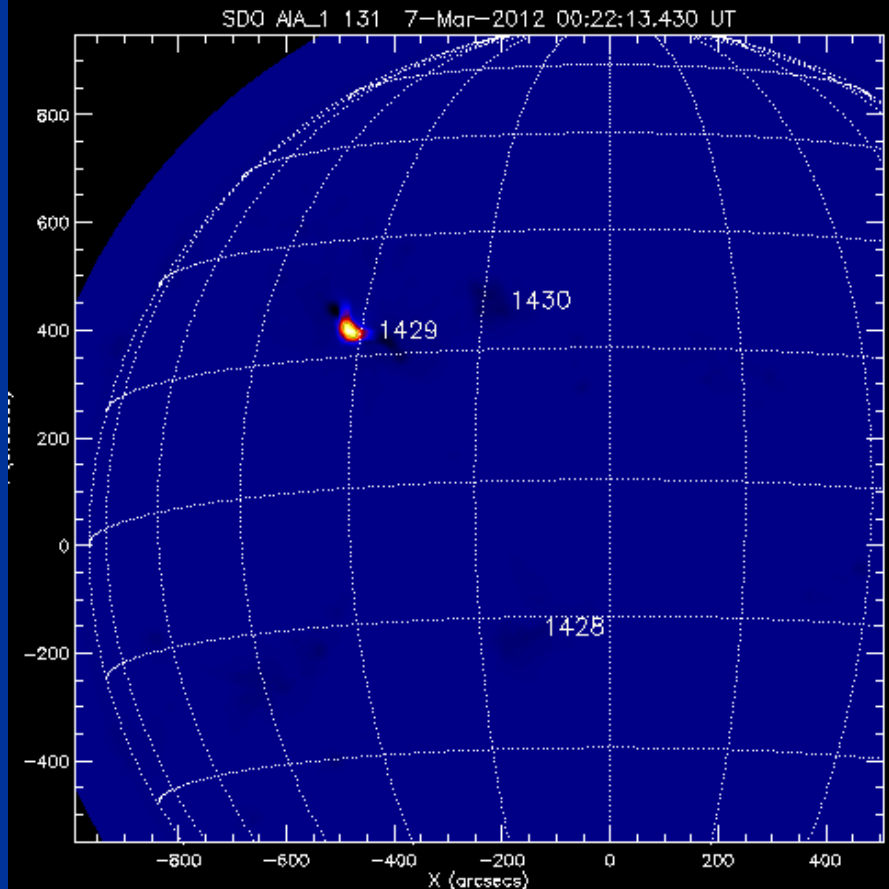
Total Effect SN-GM: +0.15 $\pm$ 0.72% for $\sim$ 42-52 min after SF, $E_n \sim$ 23-38 MeV

NO SOLAR NEUTRONS? Only upper limit $I_n(23-38 \text{ MeV}) \sim 310 \text{ n/m}^2\text{s}$

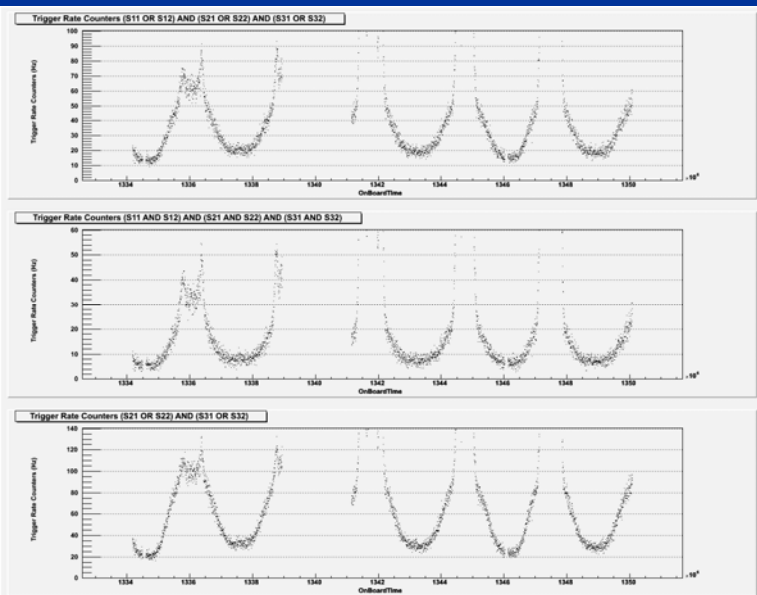
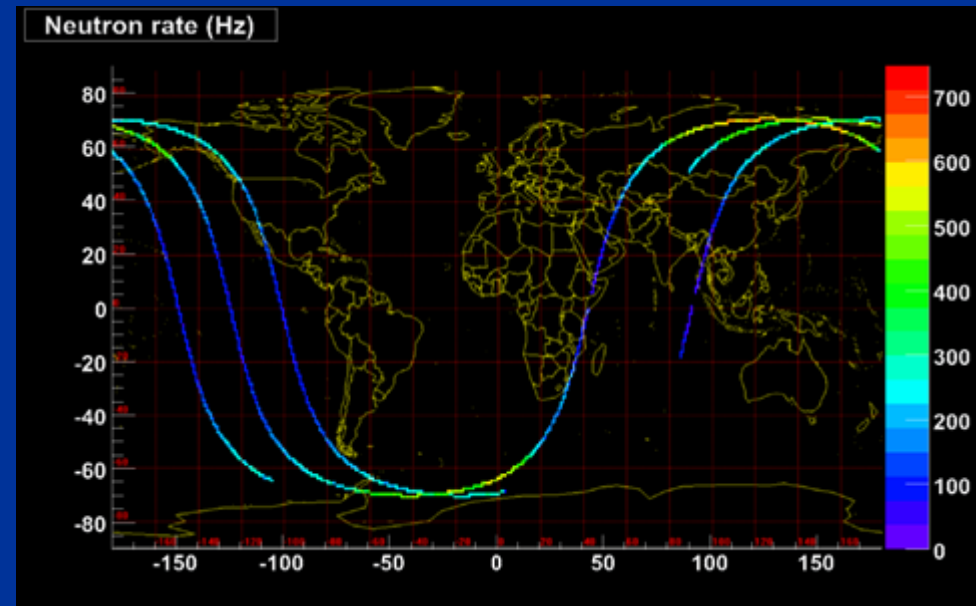
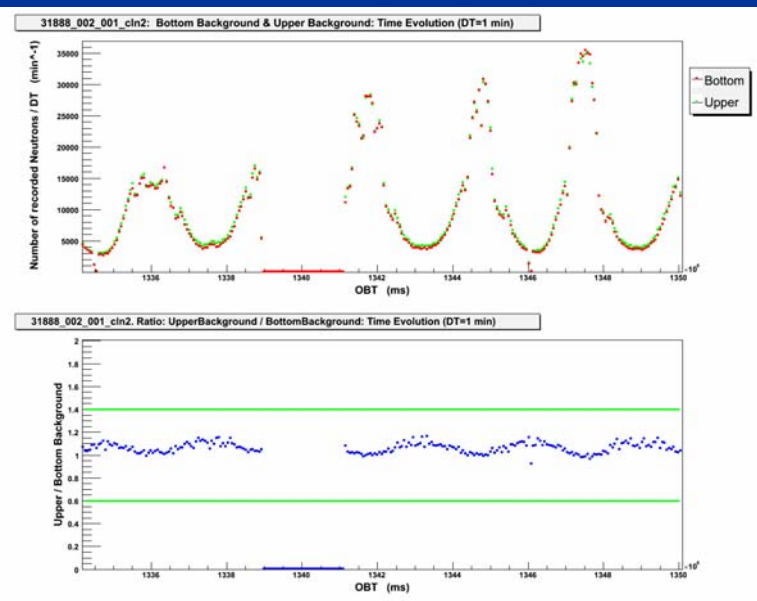
07 March 2012. SF X5.4 00:24 UT Area 1430, N14E27



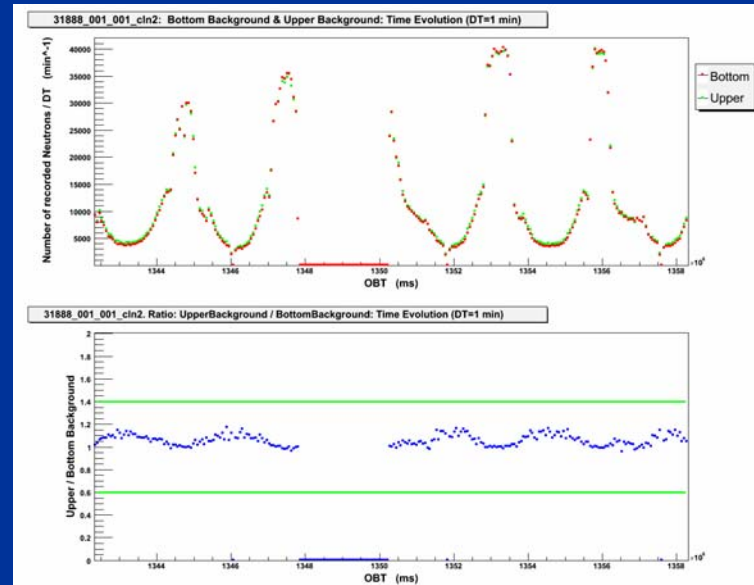
Weekly GOES Satellite X-ray and Proton Plots
Week Beginning 05 March 2012



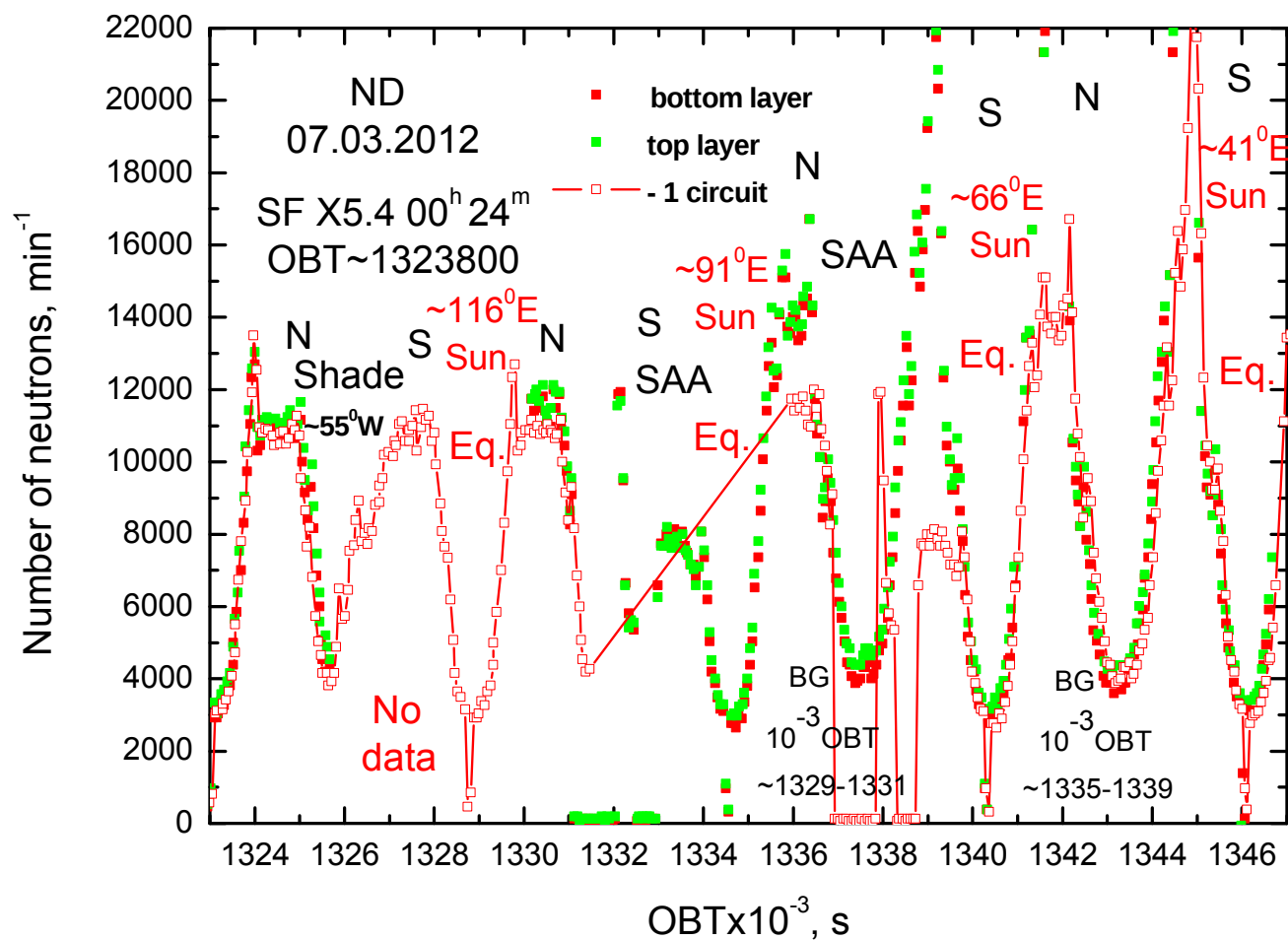
07.03.2012. QUICKLOOK Data



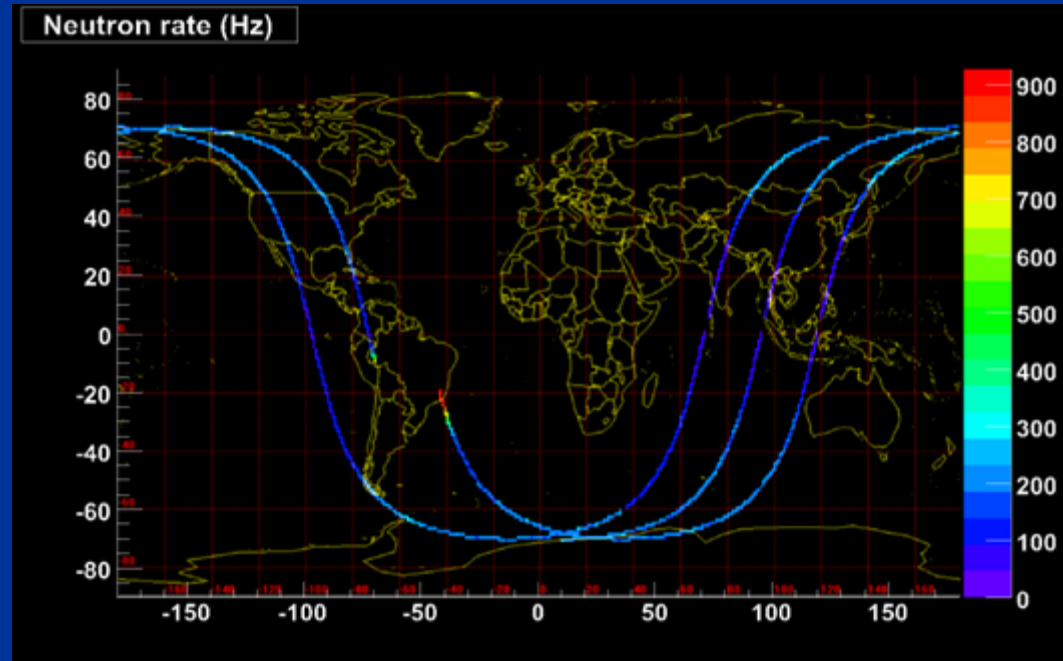
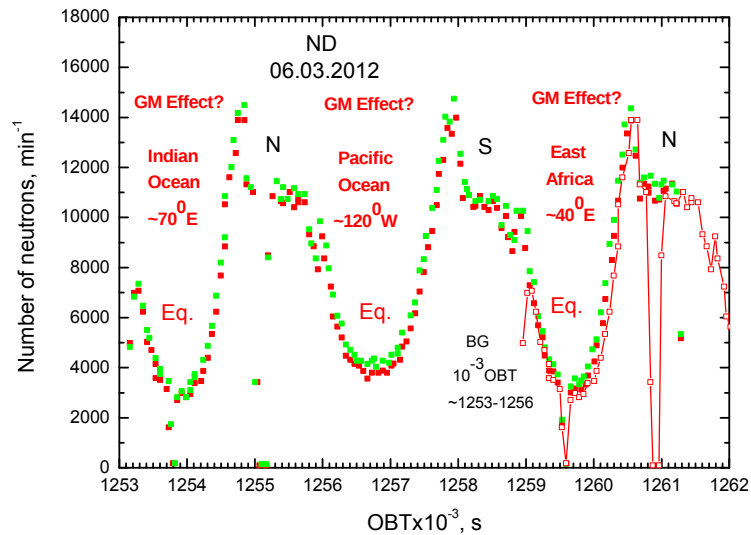
$n > p + e + \dots$?
Pre-pulse
near South
in S1-S3



07.03.2012. QUICKLOOK Data Digitization



06.03.2012. QUICKLOOK Data Digitization



SF 07.03.2012 X5.4 00:24 UT, Common Data: Fermi LAT found $E_\gamma = 0.1-4.0 \text{ GeV}$!!!,

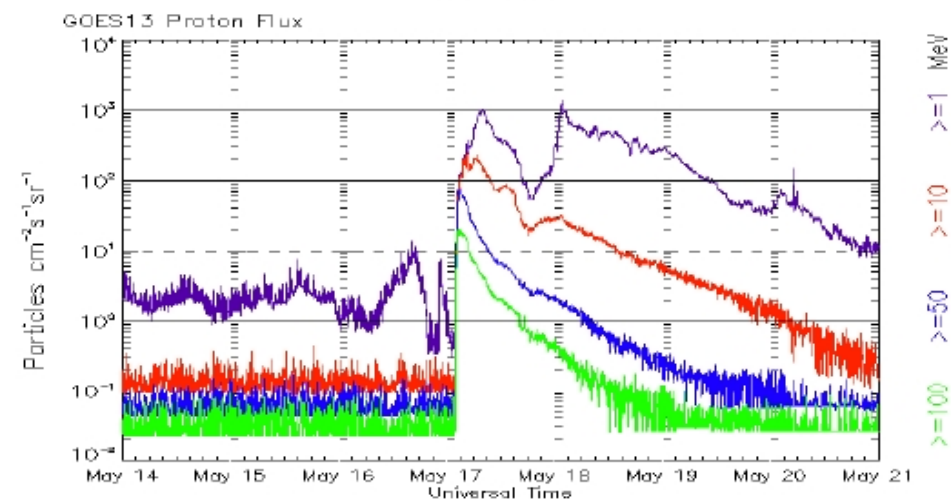
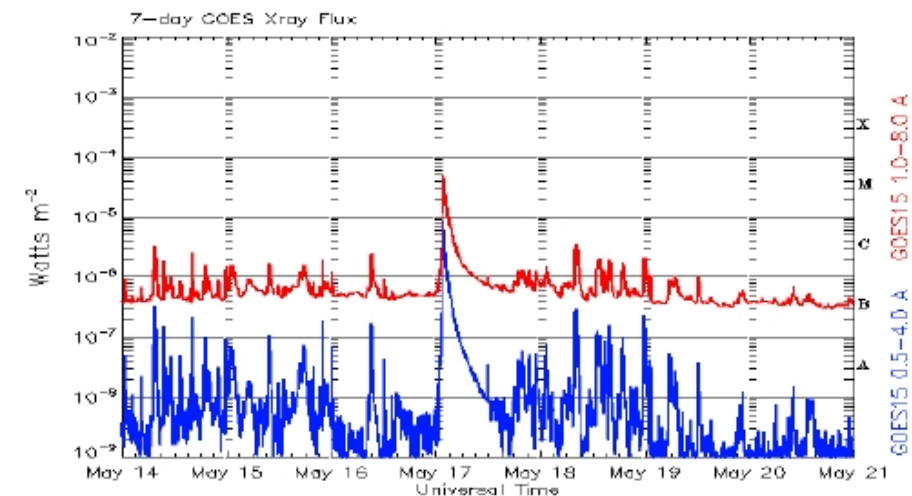
PAMELA: the first SCR went in $\sim 04:03$!!!

NB. No QUICKLOOK data near 00:55-02:41 UT (OBT $\sim 1325670-1332000$ s)

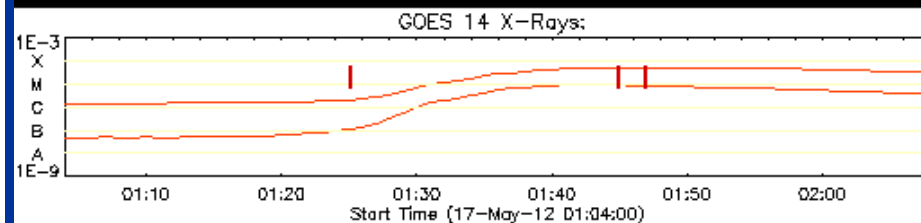
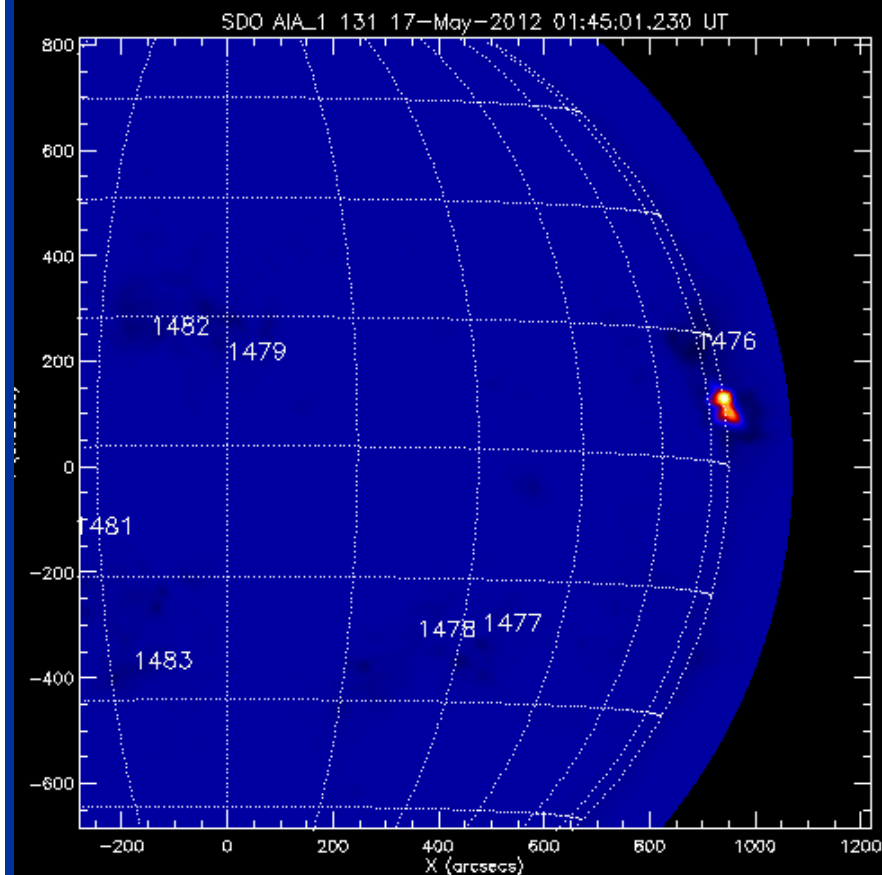
NO SOLAR NEUTRONS.

17 May 2012. SF M5.1 01:47 UT

Area 1476, N11W76

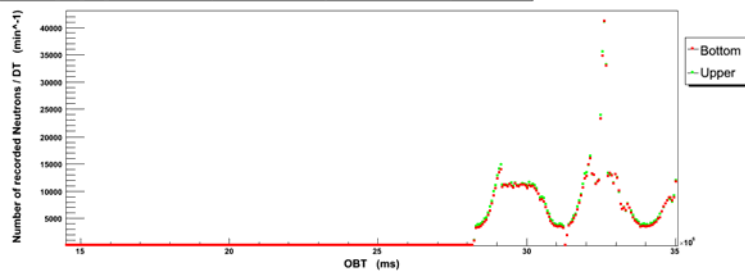


Weekly GOES Satellite X-ray and Proton Plots
Week Beginning 14 May 2012

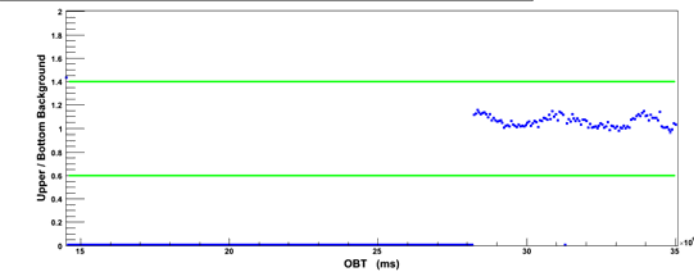


17.05.2012. QUICKLOOK Data

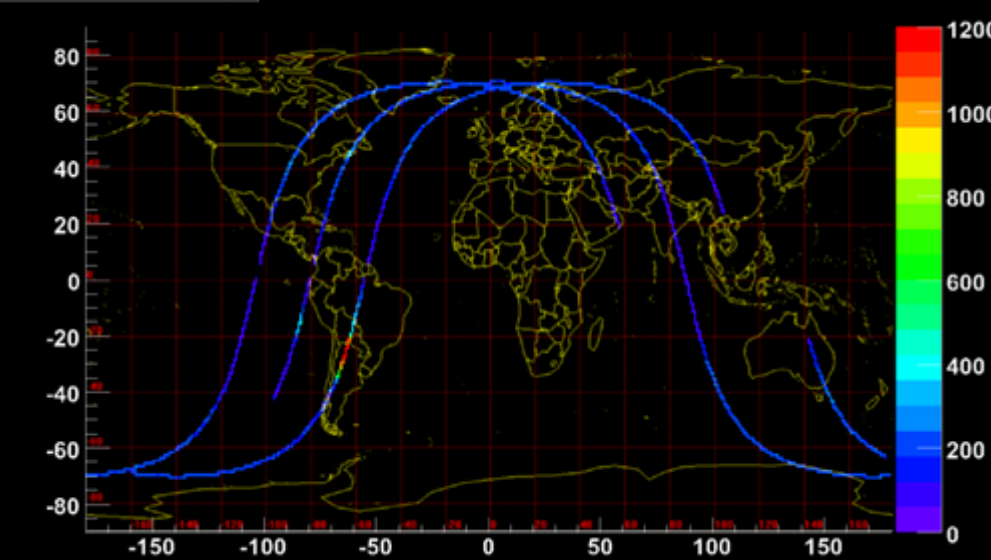
32954_074_002_cln2: Bottom Background & Upper Background: Time Evolution (DT=1 min)



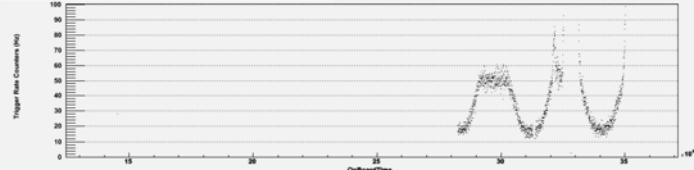
32954_074_002_cln2: Ratio: UpperBackground / BottomBackground: Time Evolution (DT=1 min)



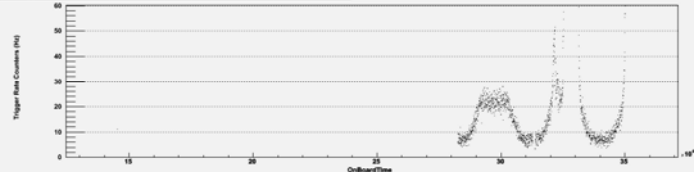
Neutron rate (Hz)



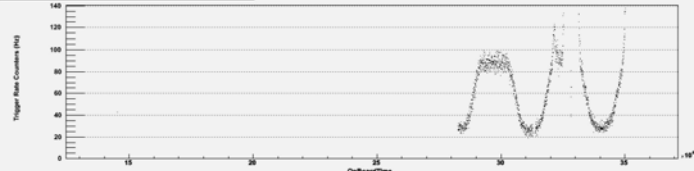
Trigger Rate Counters (S11 OR S12) AND (S21 OR S22) AND (S31 OR S32)



Trigger Rate Counters (S11 AND S12) AND (S21 AND S22) AND (S31 AND S32)

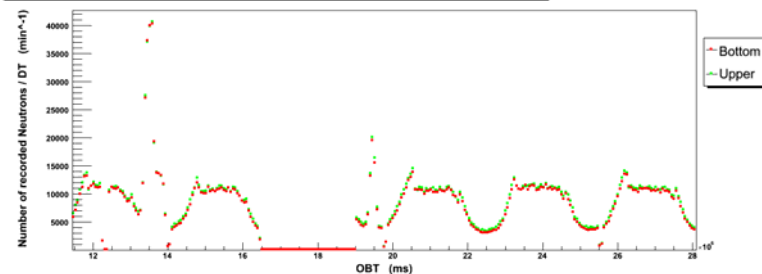


Trigger Rate Counters (S21 OR S22) AND (S31 OR S32)

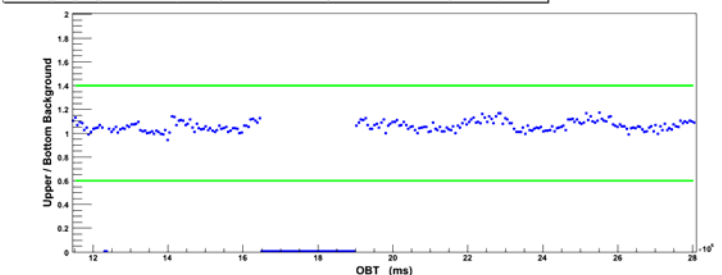


$n > p + e + \dots$?
Pre-pulse
Near North
in S1-S3

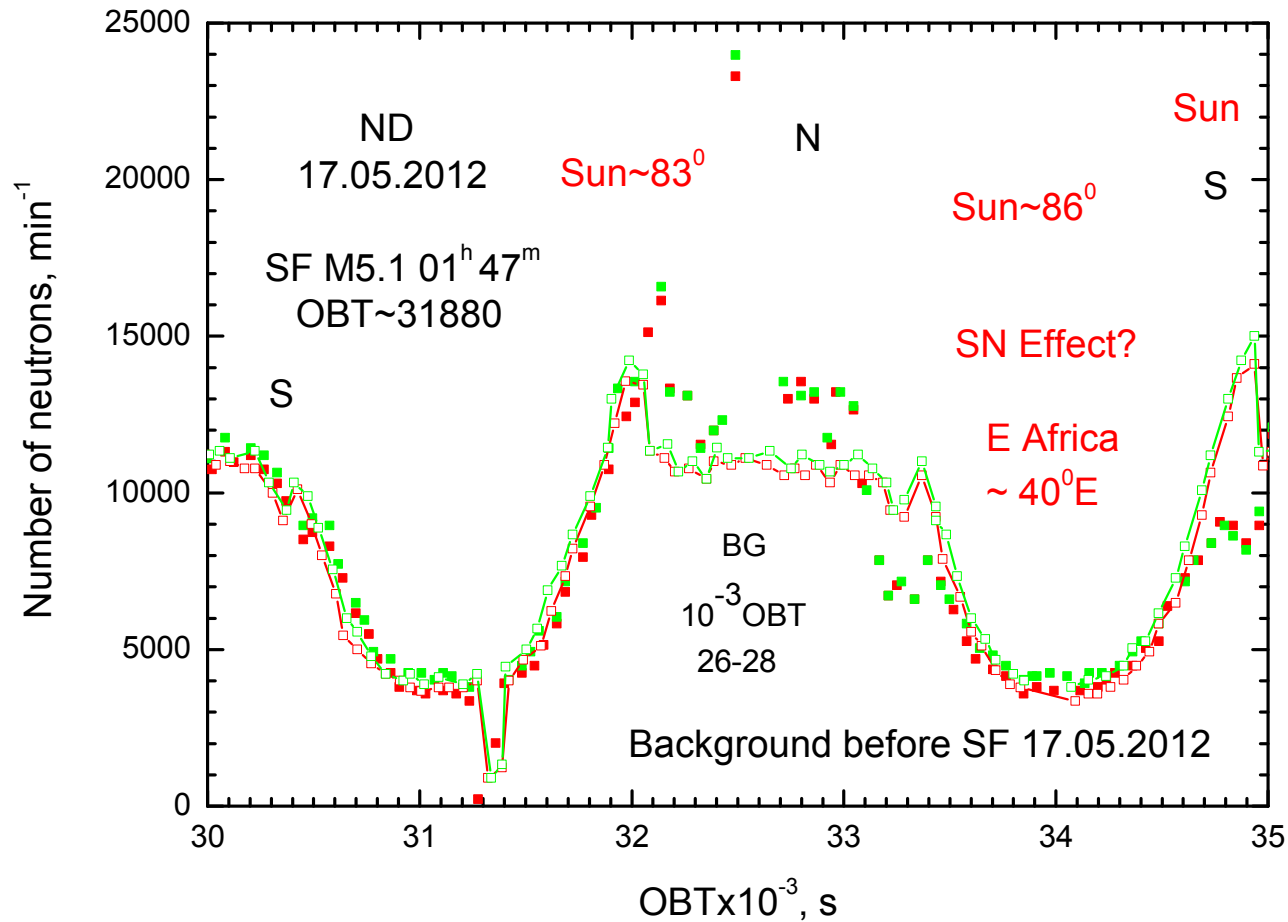
32957_003_001_cln2: Bottom Background & Upper Background: Time Evolution (DT=1 min)



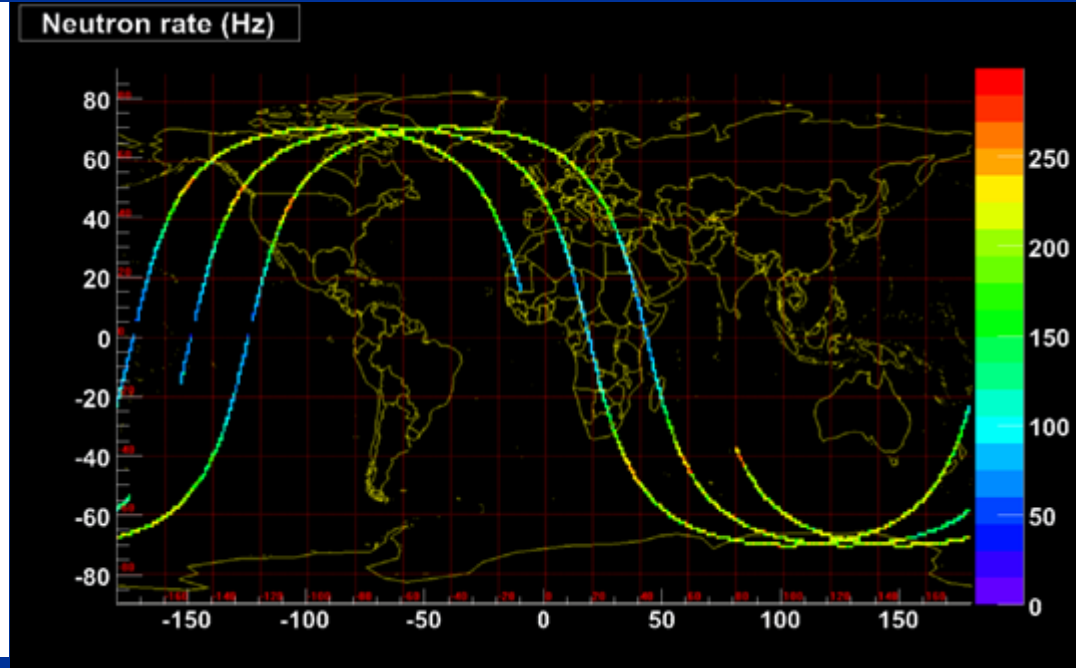
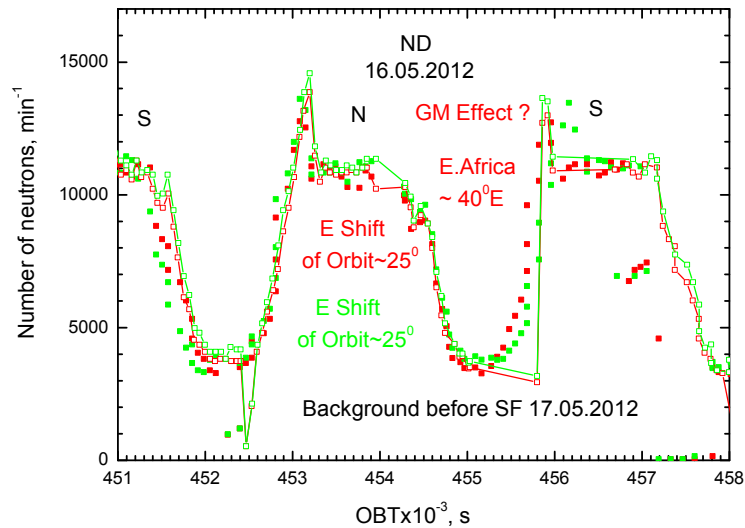
32957_003_001_cln2: Ratio: UpperBackground / BottomBackground: Time Evolution (DT=1 min)



17.05.2012. QUICKLOOK Data Digitization



16.05.2012. QUICKLOOK Data Digitization



SN: 17.05.2012 OBT~33580-33880 ND(b&t): 45838-47507=1669±306, -3.51±0.64%

GM: 16.05.2012 OBT~454720-455020 ND(b&t):41659-44021= 2362±293, -5.37±0.67%

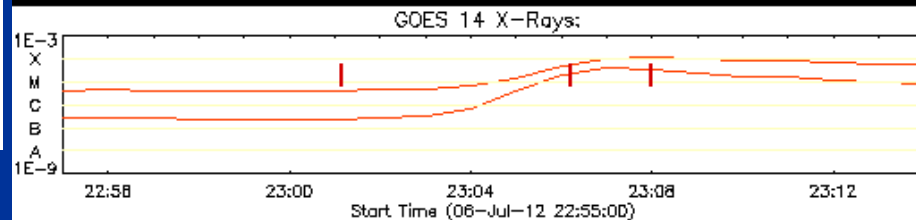
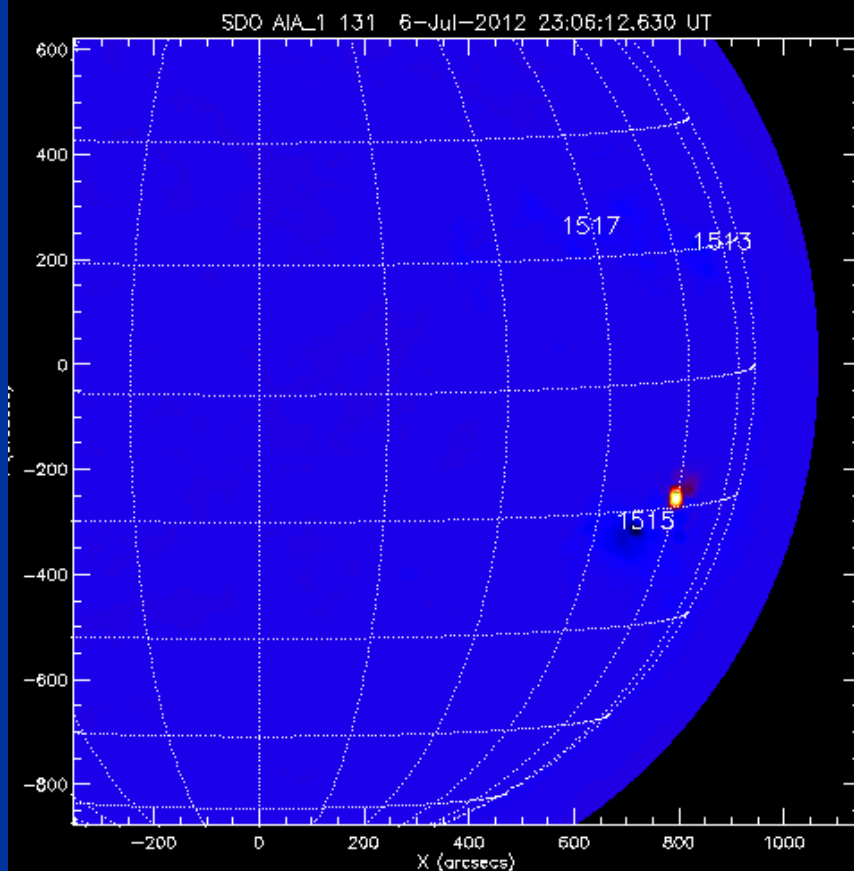
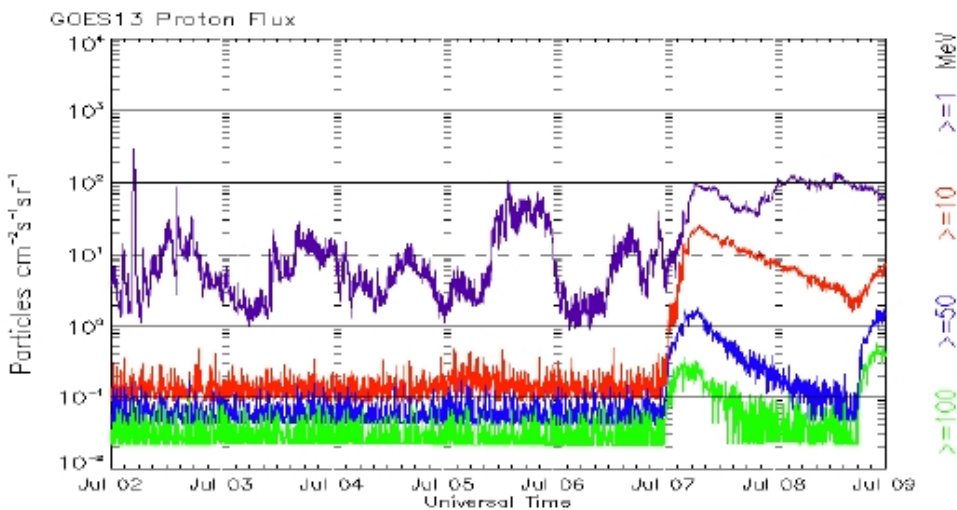
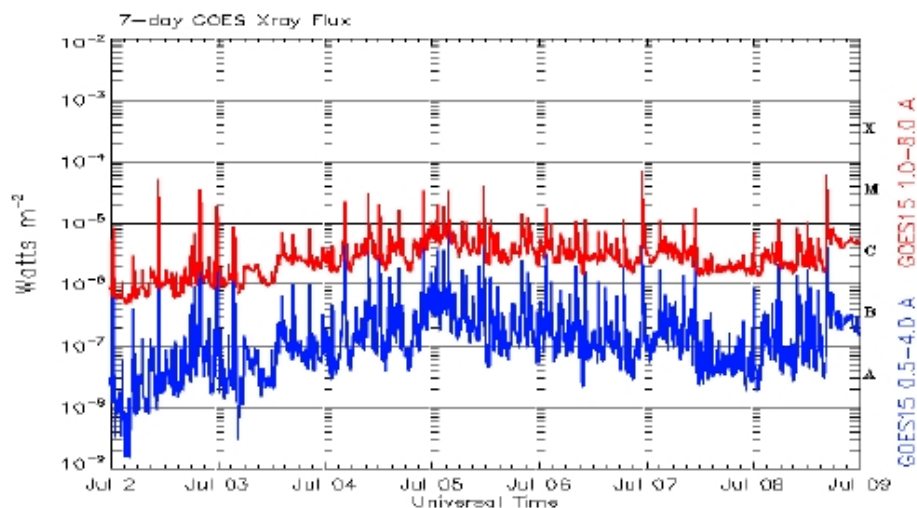
(GM: Cut-off shift ~ 15.9-16.8GV). **NB.** Quality of QL data for 16.05.2012 is so so...

Total Effect SN-GM: +1.85±0.93% for 36-41 min after SF, E_n ~22-27 MeV

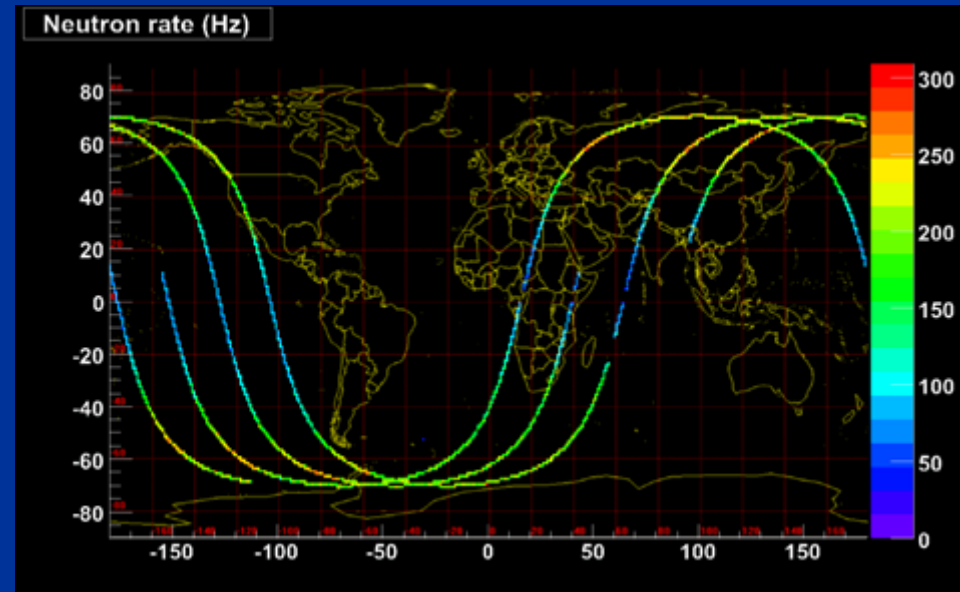
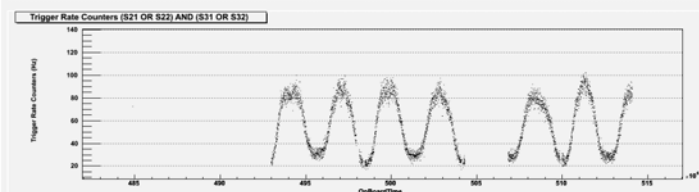
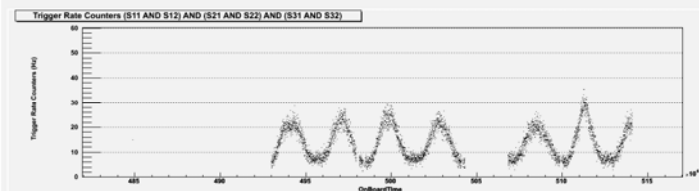
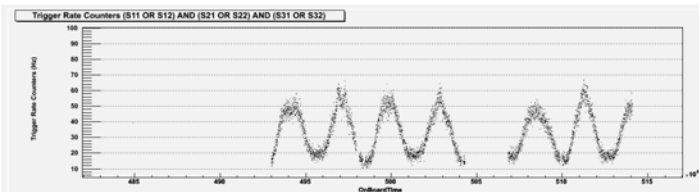
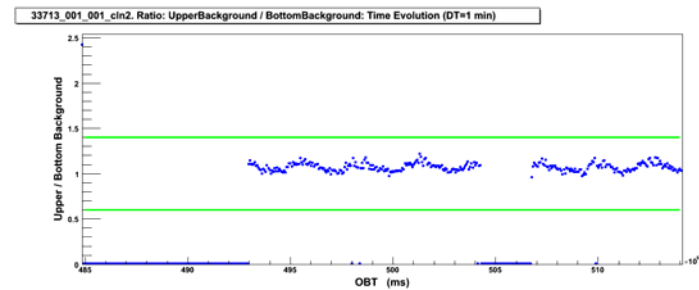
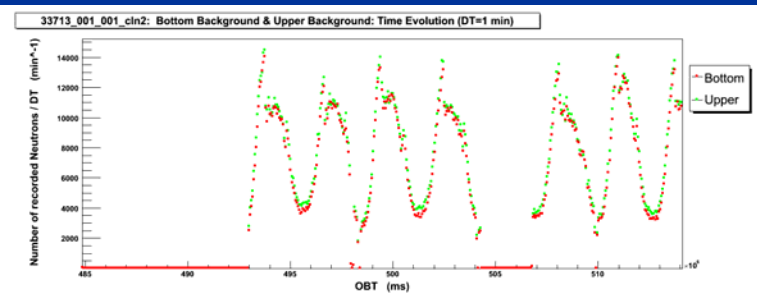
PROBABLY SOLAR NEUTRONS... Near the Earth $I_n(22-27 \text{ MeV}) \sim 810 \text{ n/m}^2\text{s}...$

06 July 2012. SF X1.1 23:08 UT

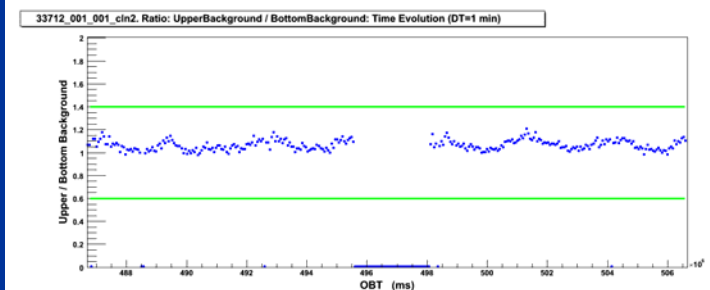
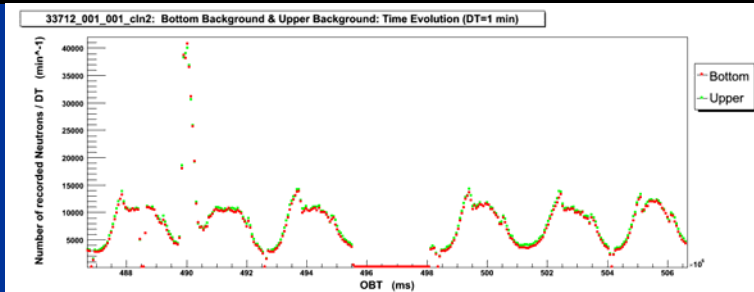
Area 1514, S13W59



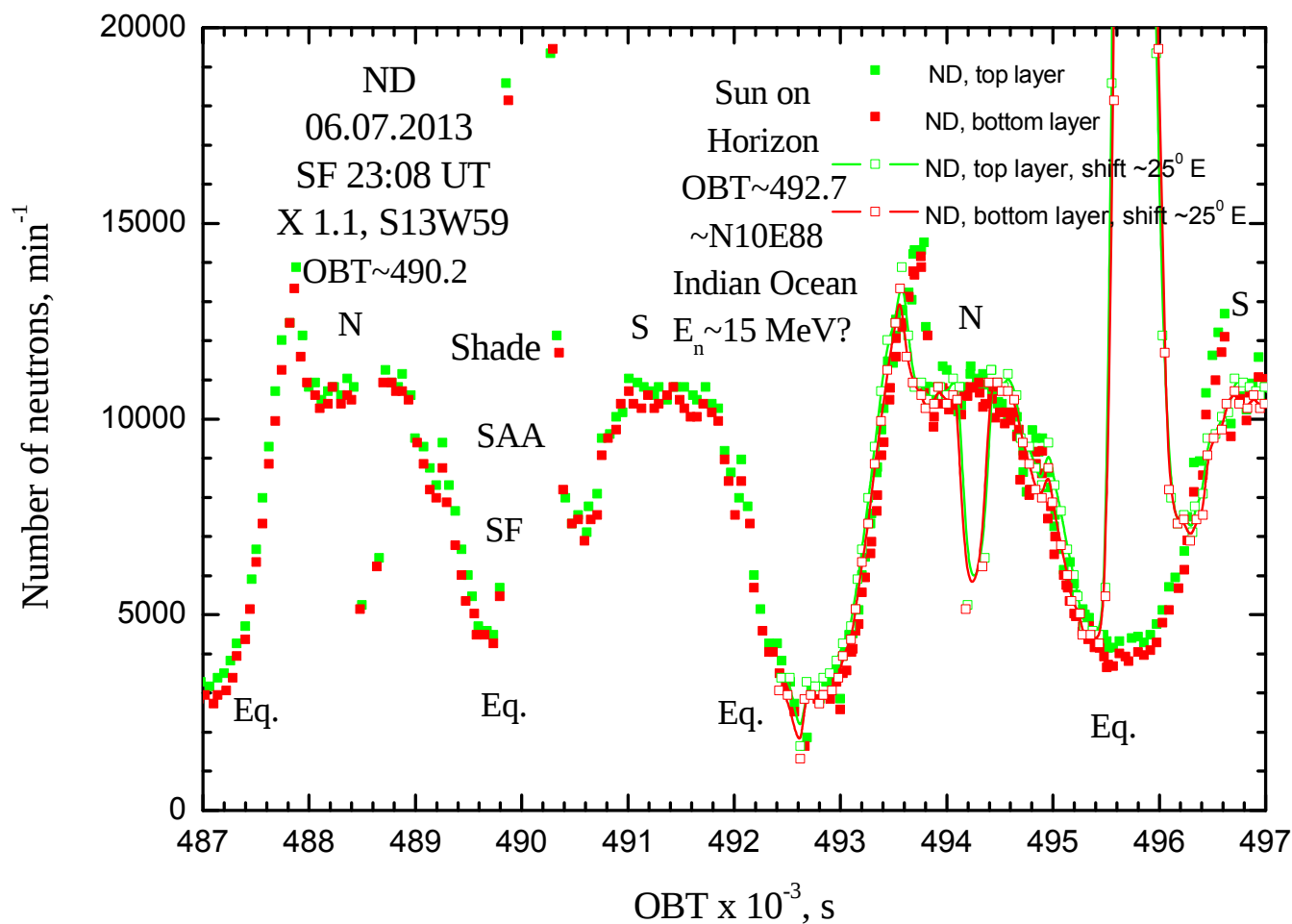
06.07.2012. QUICKLOOK Data



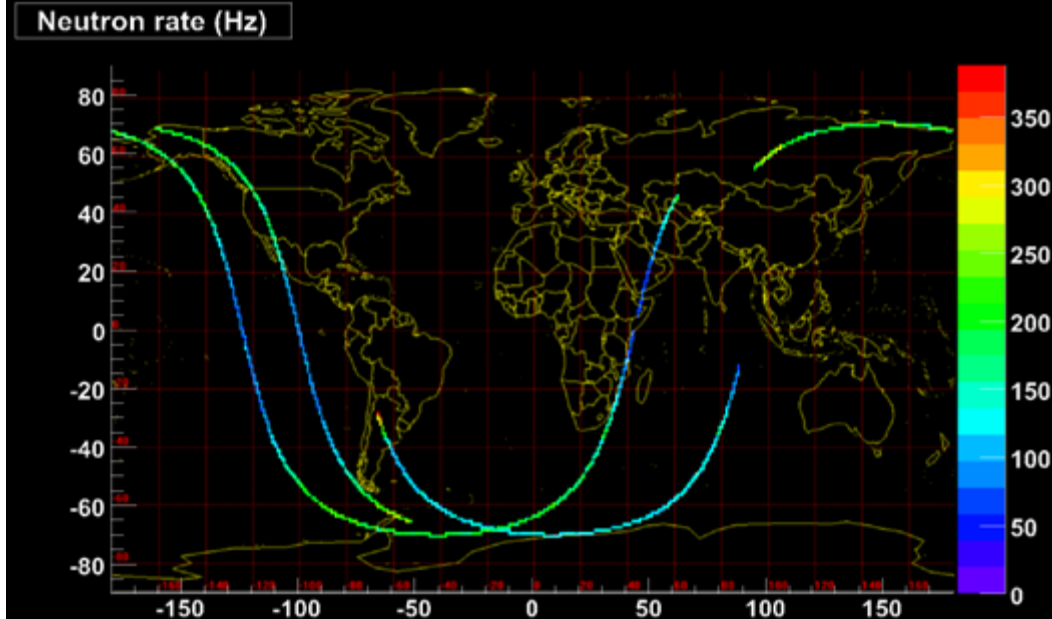
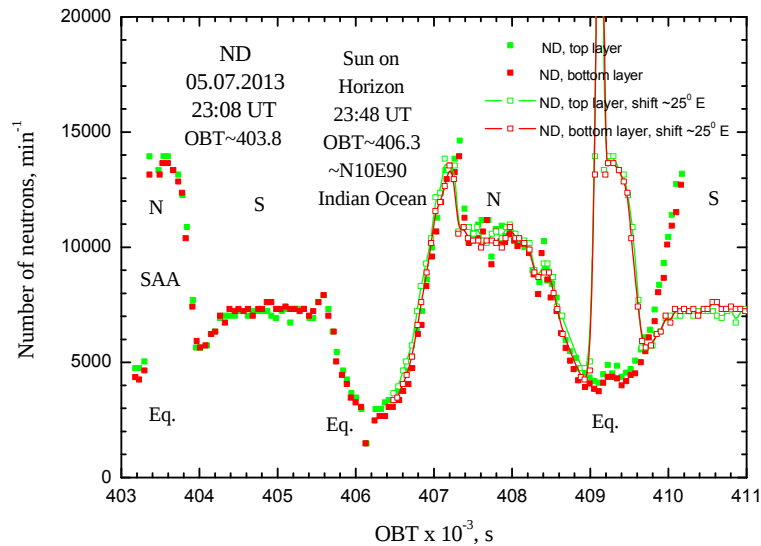
No
Pre-pulse
Near South
in S1-S3



06.07.2012. QUICKLOOK Data Digitization



05.07.2012. QUICKLOOK Data Digitization



SN: 06.07.2012 OBT~492500-492920 ND(b&t): 42077-44482=2504±294, **-5.41±0.66%**

GM: 05.07.2012 OBT~406600-406720 ND(b&t): 12853-14435=-1582±165, **-10.96±1.14%**

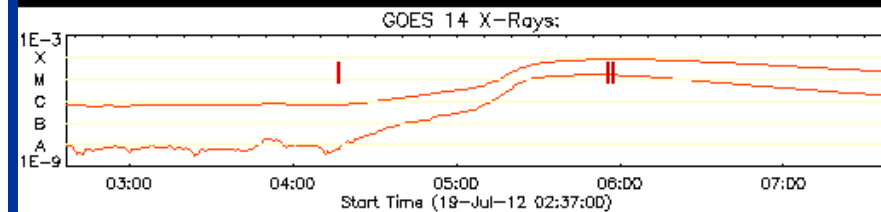
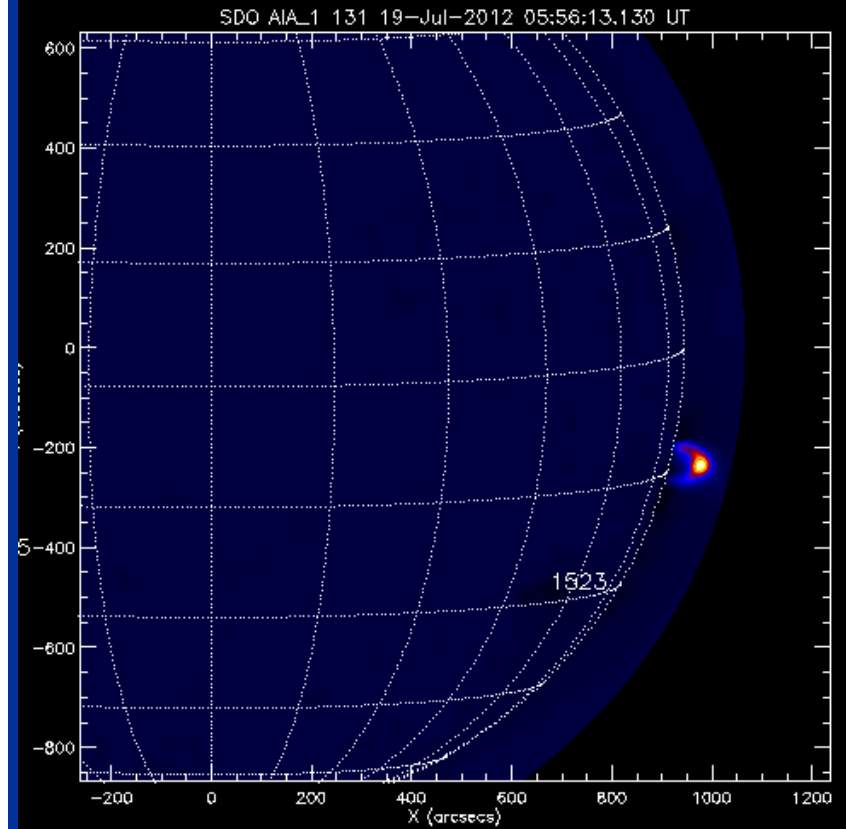
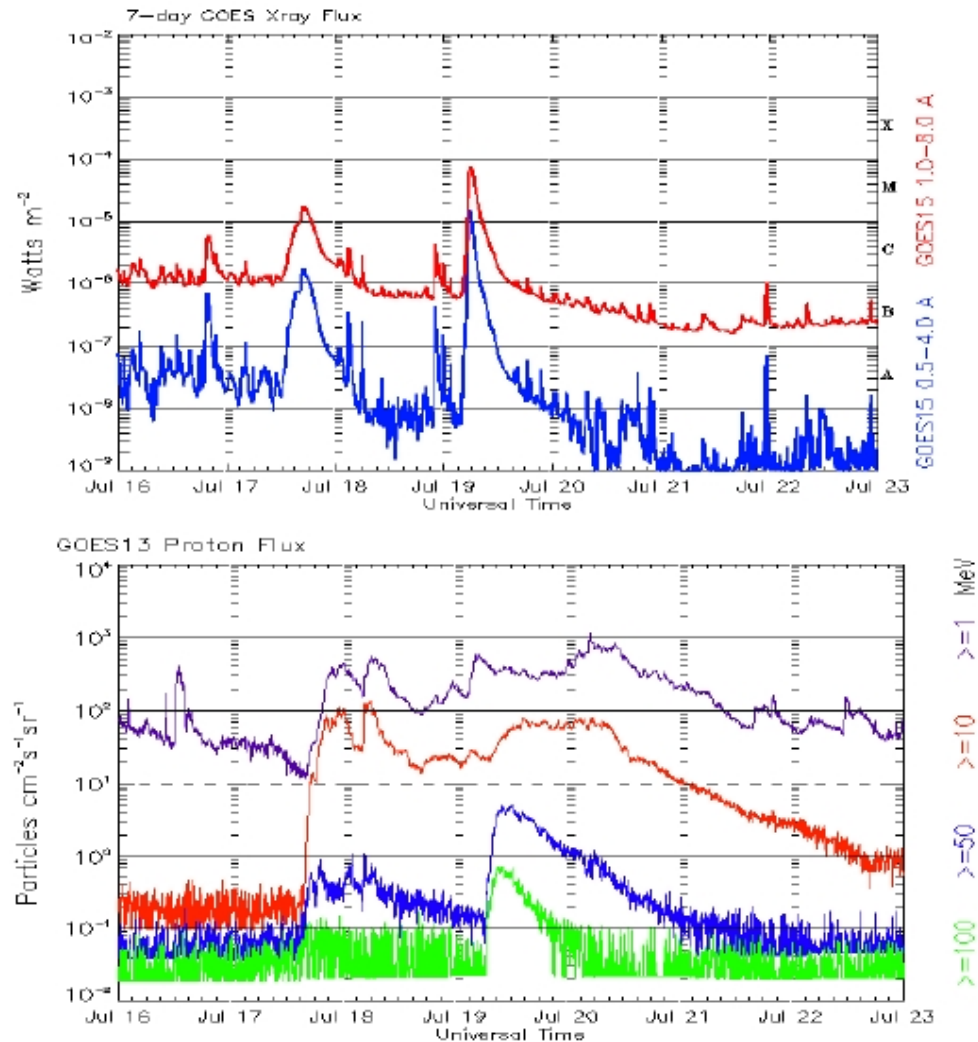
(GM: Cut-off shift ~ 15.9-16.8GV). **NB.** Quality of QL data for 16.05.2012 is so so...

Total Effect SN-GM: +5.55±1.32% for 49-56 min after SF, E_n ~11-15 MeV

PROBABLY SOLAR NEUTRONS... Near the Earth I_n (~11-15 MeV)~1600 $\text{n/m}^2\text{s}$...

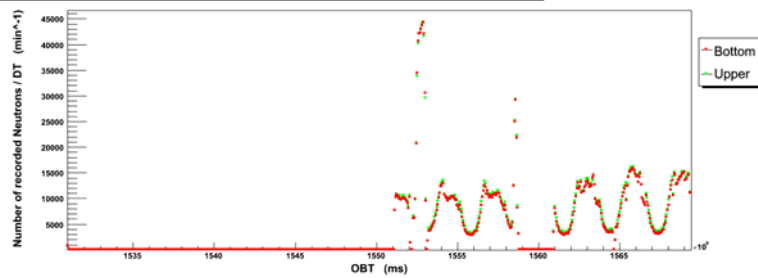
19 July 2012. SF M7.7 05:58 UT

Area 1520, S13W88

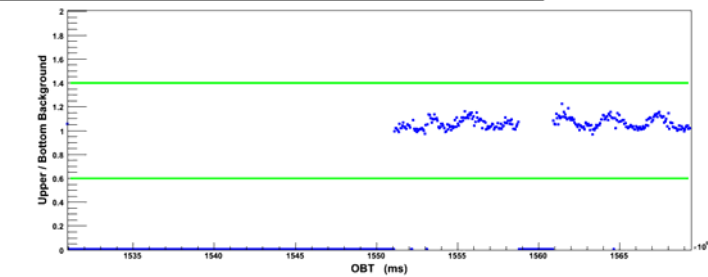


19.07.2012. QUICKLOOK Data

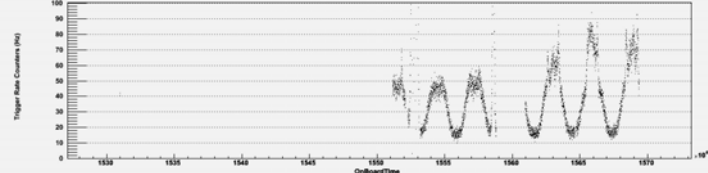
33896_001_001_cln2: Bottom Background & Upper Background: Time Evolution (DT=1 min)



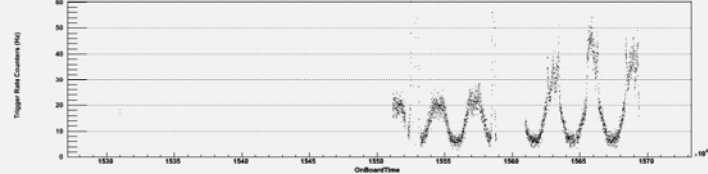
33896_001_001_cln2: Ratio: UpperBackground / BottomBackground: Time Evolution (DT=1 min)



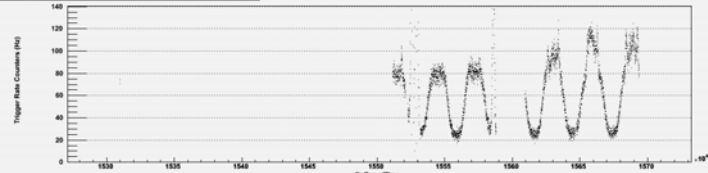
Trigger Rate Counters (S11 OR S12) AND (S21 OR S22) AND (S31 OR S32)



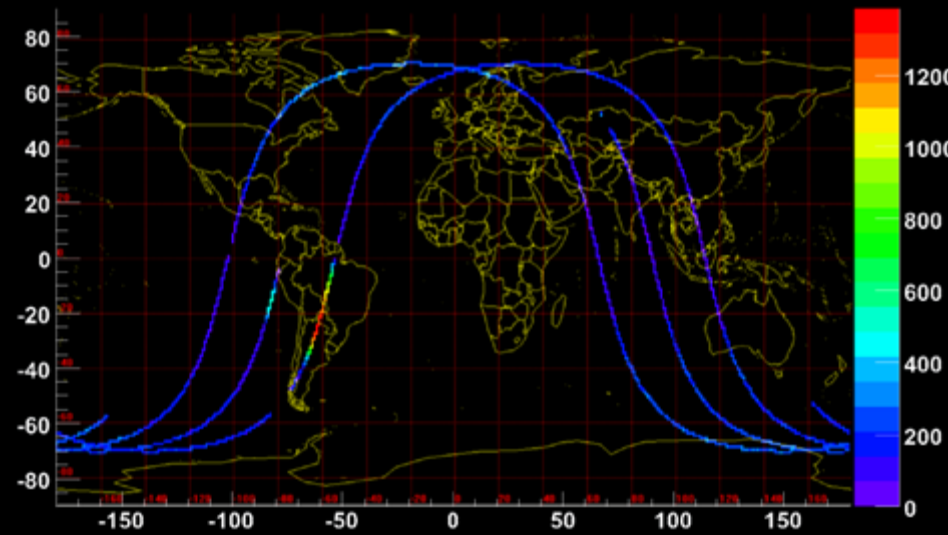
Trigger Rate Counters (S11 AND S12) AND (S21 AND S22) AND (S31 AND S32)



Trigger Rate Counters (S21 OR S22) AND (S31 OR S32)



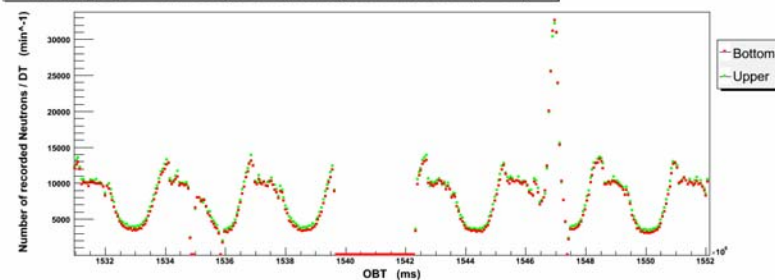
Neutron rate (Hz)



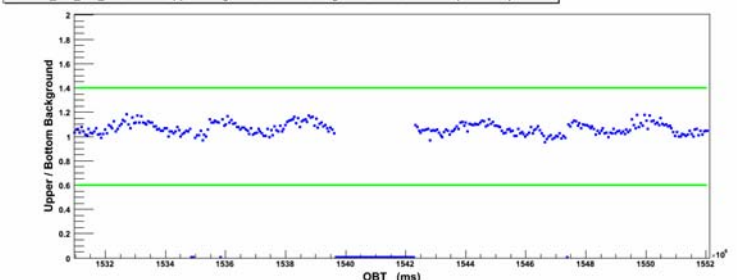
$n > p + e + \dots$?

Pre-pulse
Near South
in S1-S3

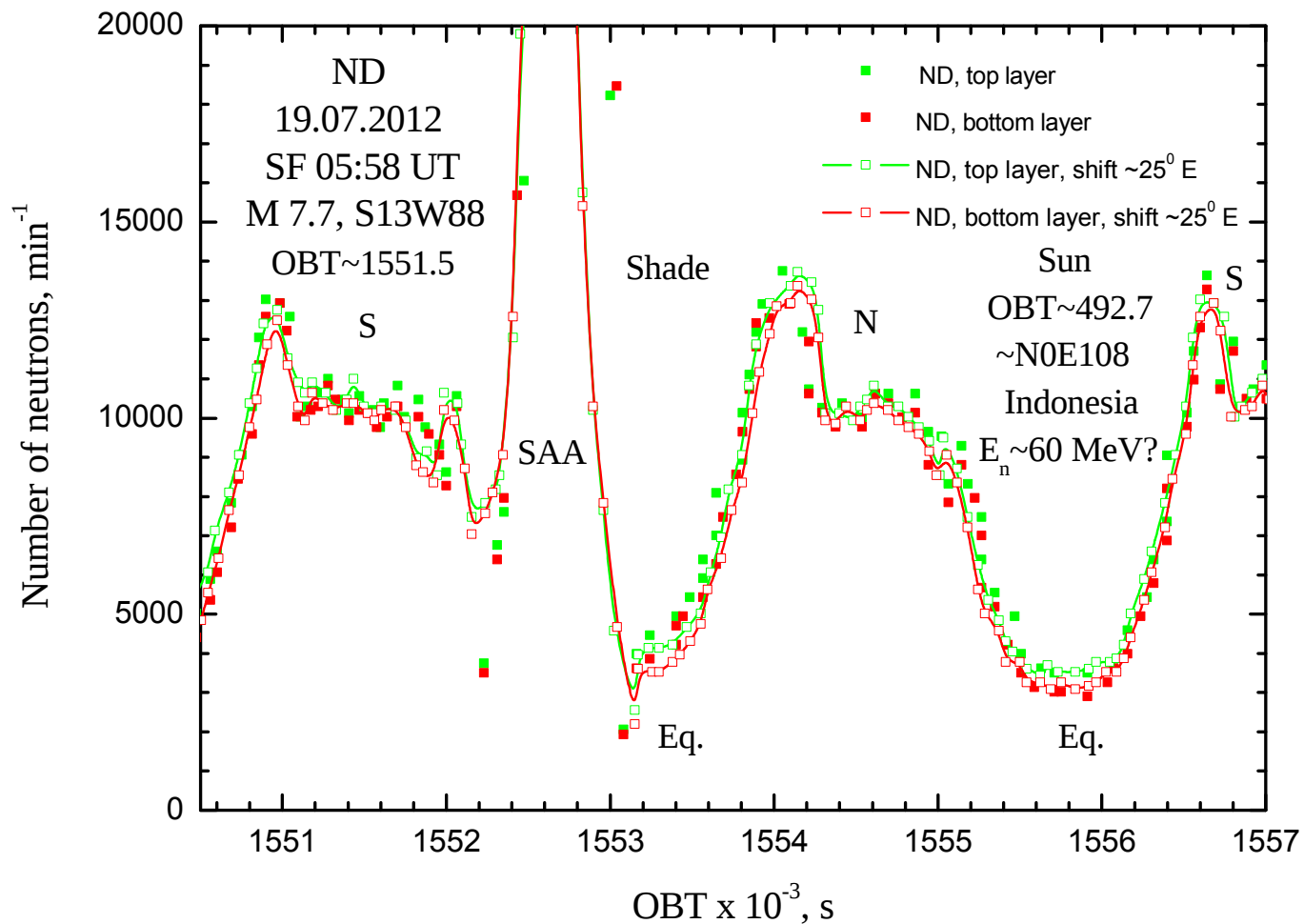
33896_003_001_cln2: Bottom Background & Upper Background: Time Evolution (DT=1 min)



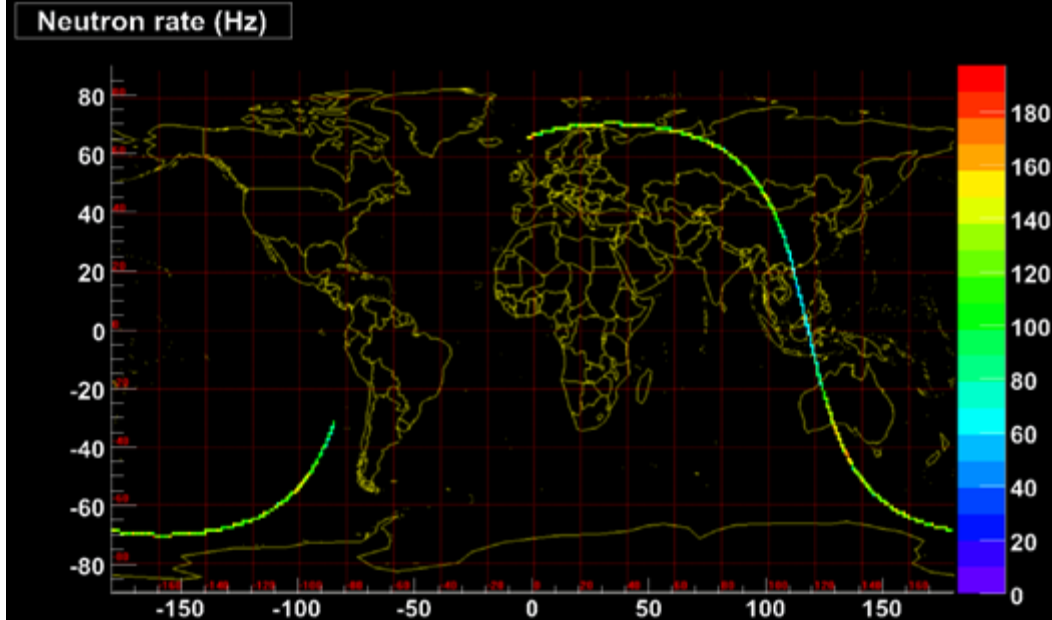
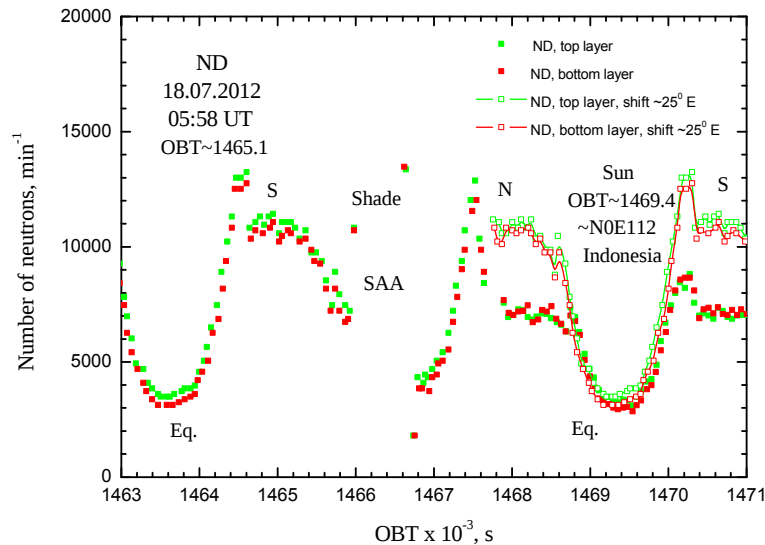
33896_003_001_cln2: Ratio: UpperBackground / BottomBackground: Time Evolution (DT=1 min)



19.07.2012. QUICKLOOK Data Digitization



18.07.2012. QUICKLOOK Data Digitization



SN:19.07.2012 OBT~1555510-1555810 ND(b&t):33539-33607=68±259, -0.20±0.77%

GM:18.07.2012 OBT1469170-1469470 ND(b&t):32175-33690=-1515±257,-4.50±0.76%

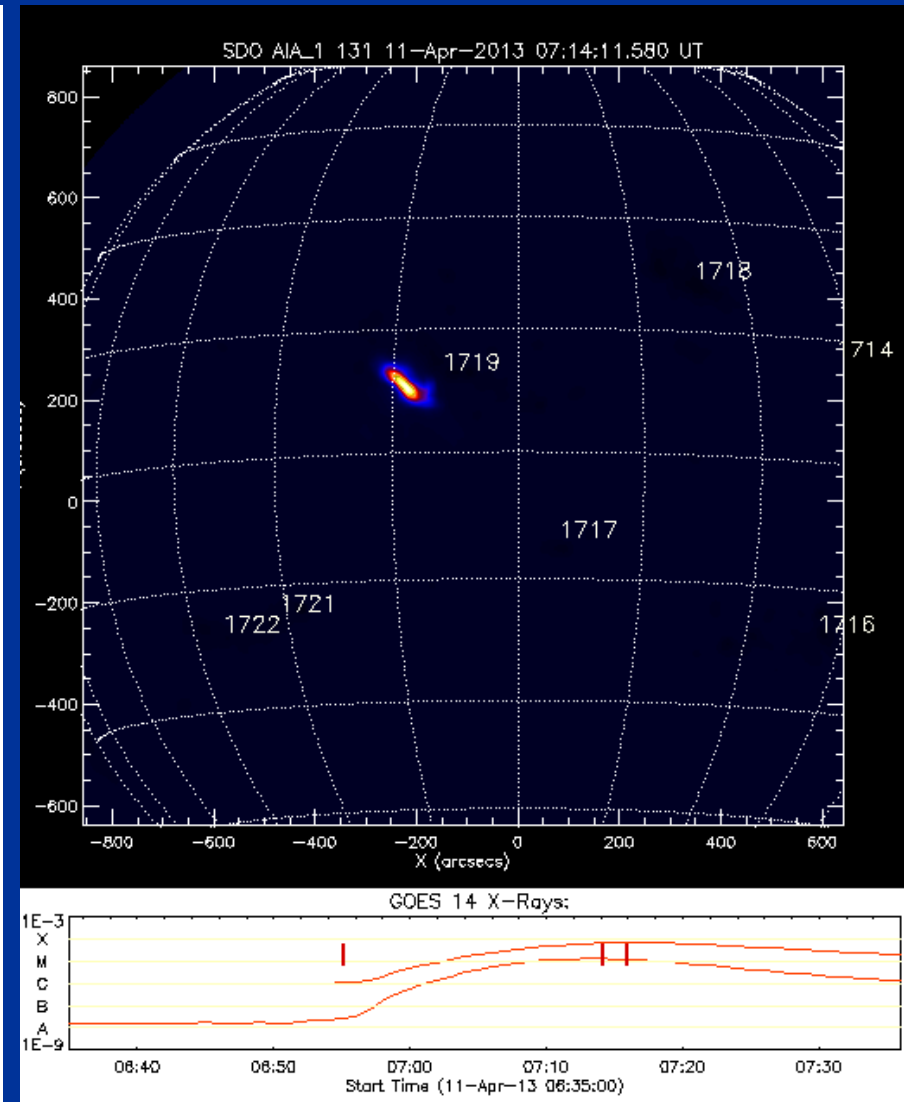
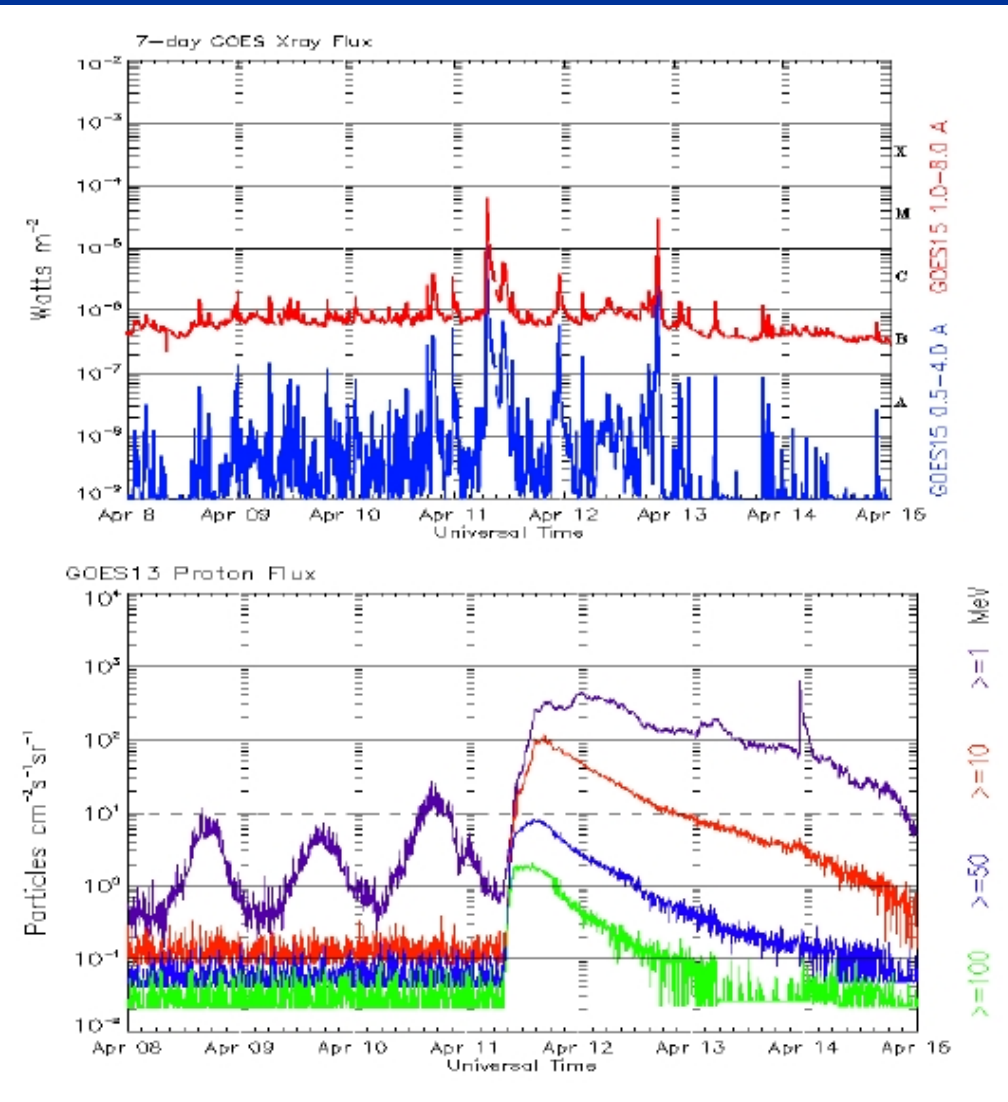
(GM: Cut-off shift ~ 15.9-16.8GV).

Total Effect SN-GM: +4.30±1.08% for 75-80 min after SF, E_n ~5.2-5.9 MeV

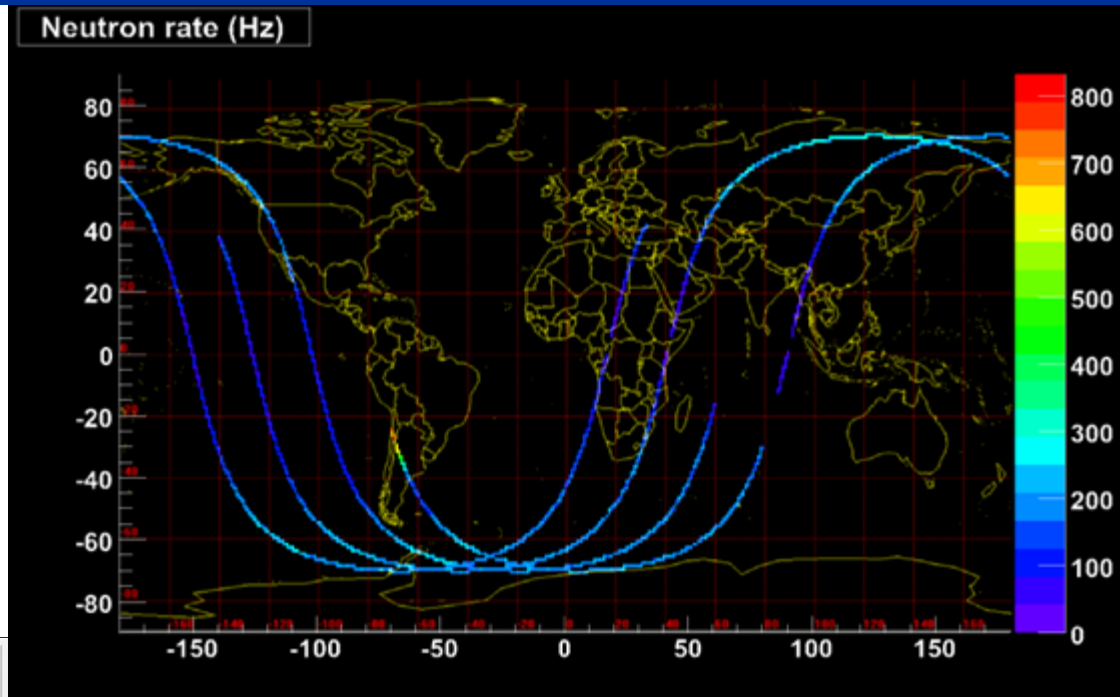
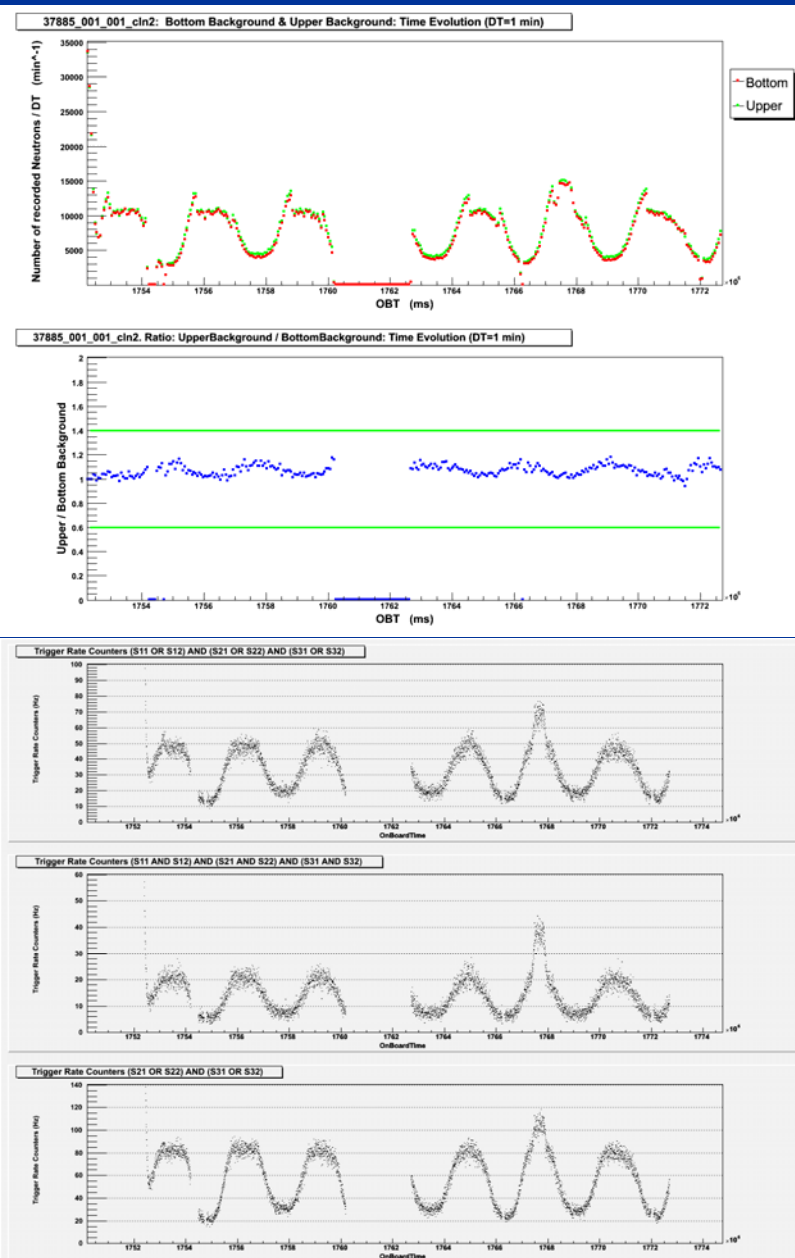
PROBABLY SOLAR NEUTRONS... Near the Earth I_n(~6 MeV)~1300 n/m²s...

11 April 2013. SF M6.5 07:16 UT

Area 1719, N07E13

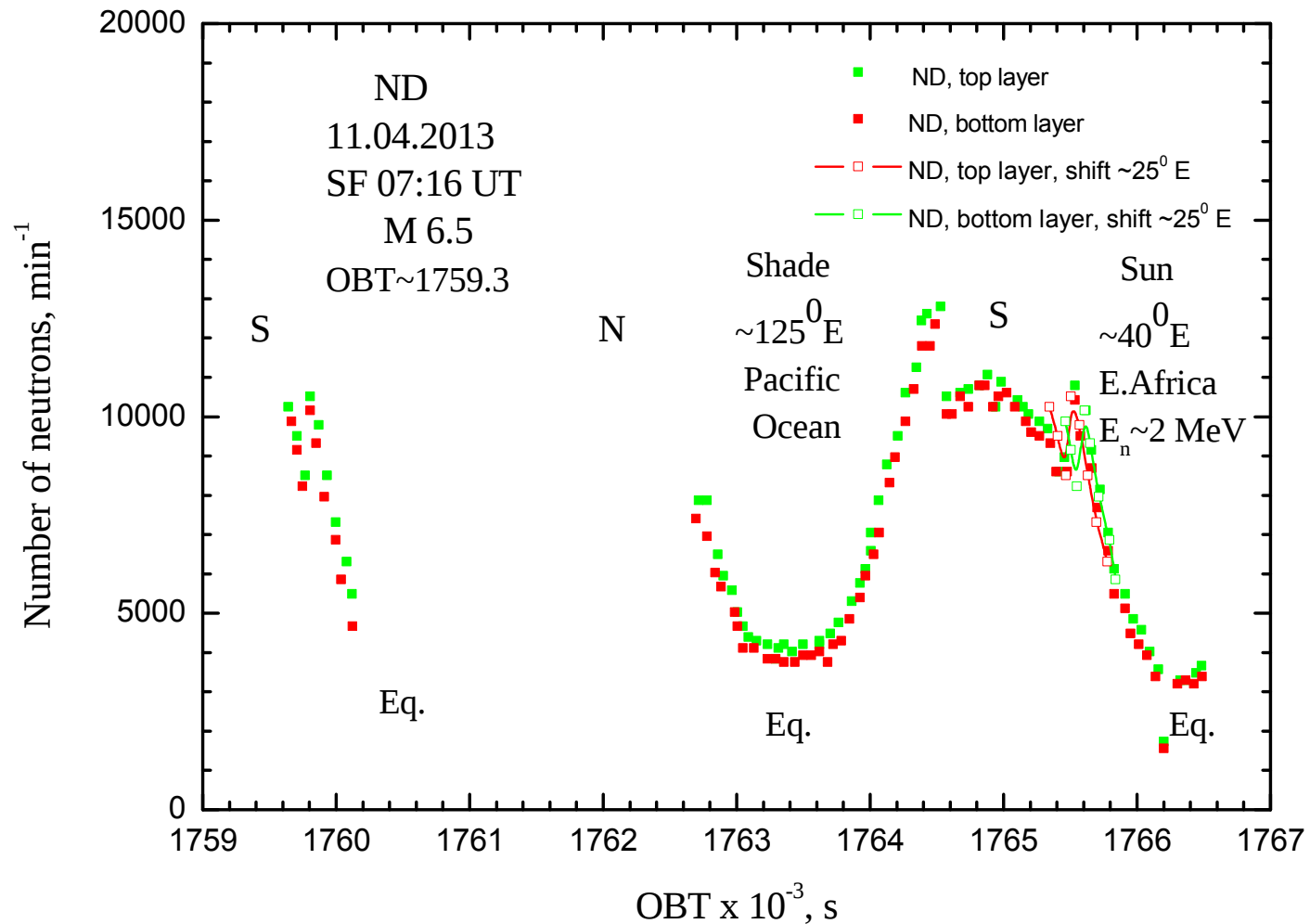


11.04.2013. QUICKLOOK Data

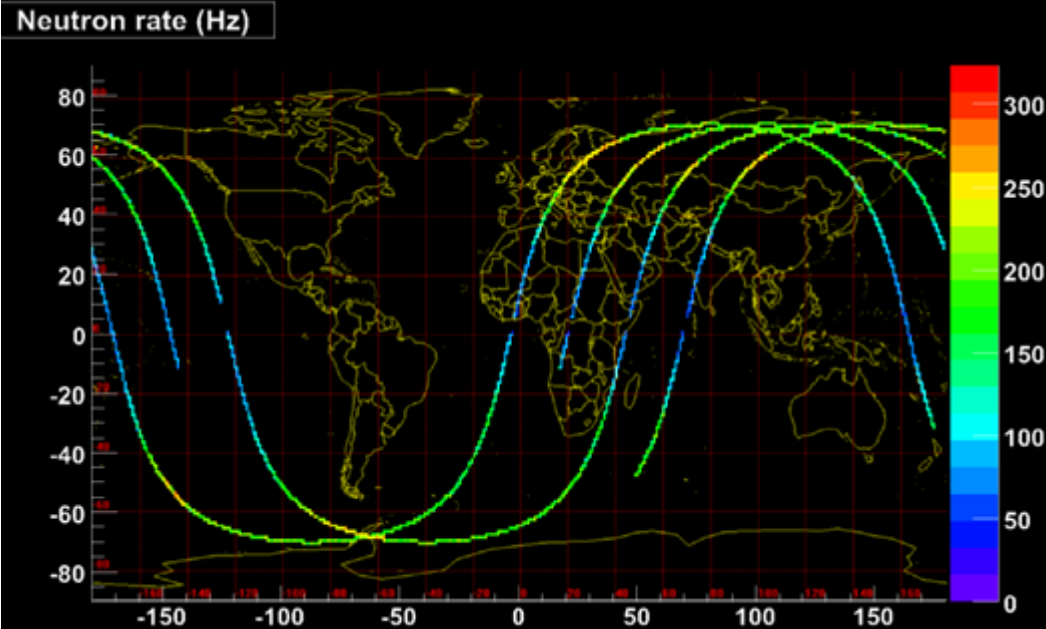
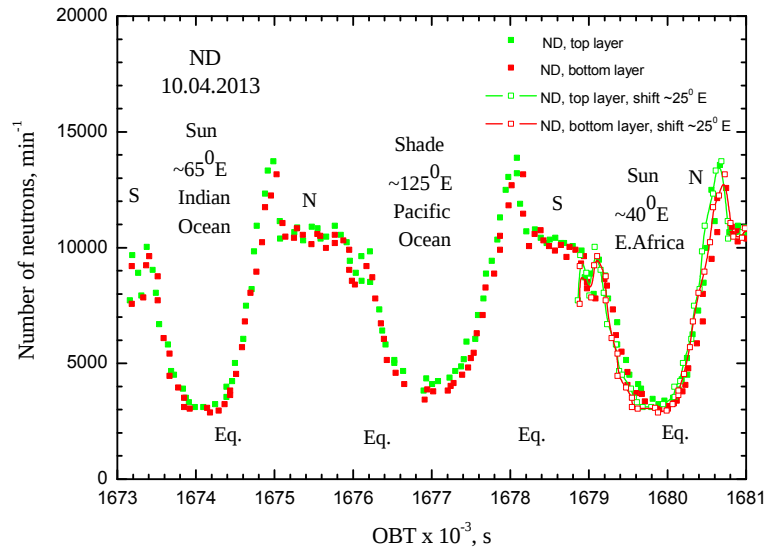


No
Pre-pulse
Near North
in S1-S3

11.04.2013. QUICKLOOK Data Digitization



10.04.2013. QUICKLOOK Data Digitization

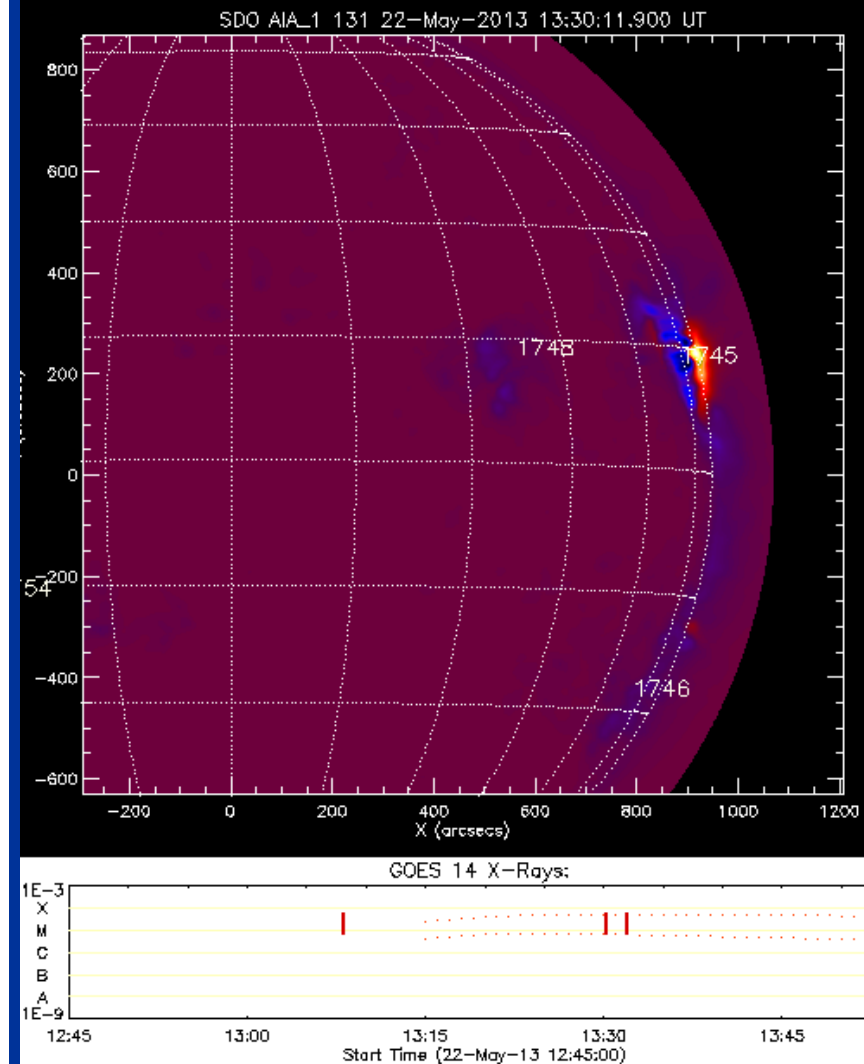
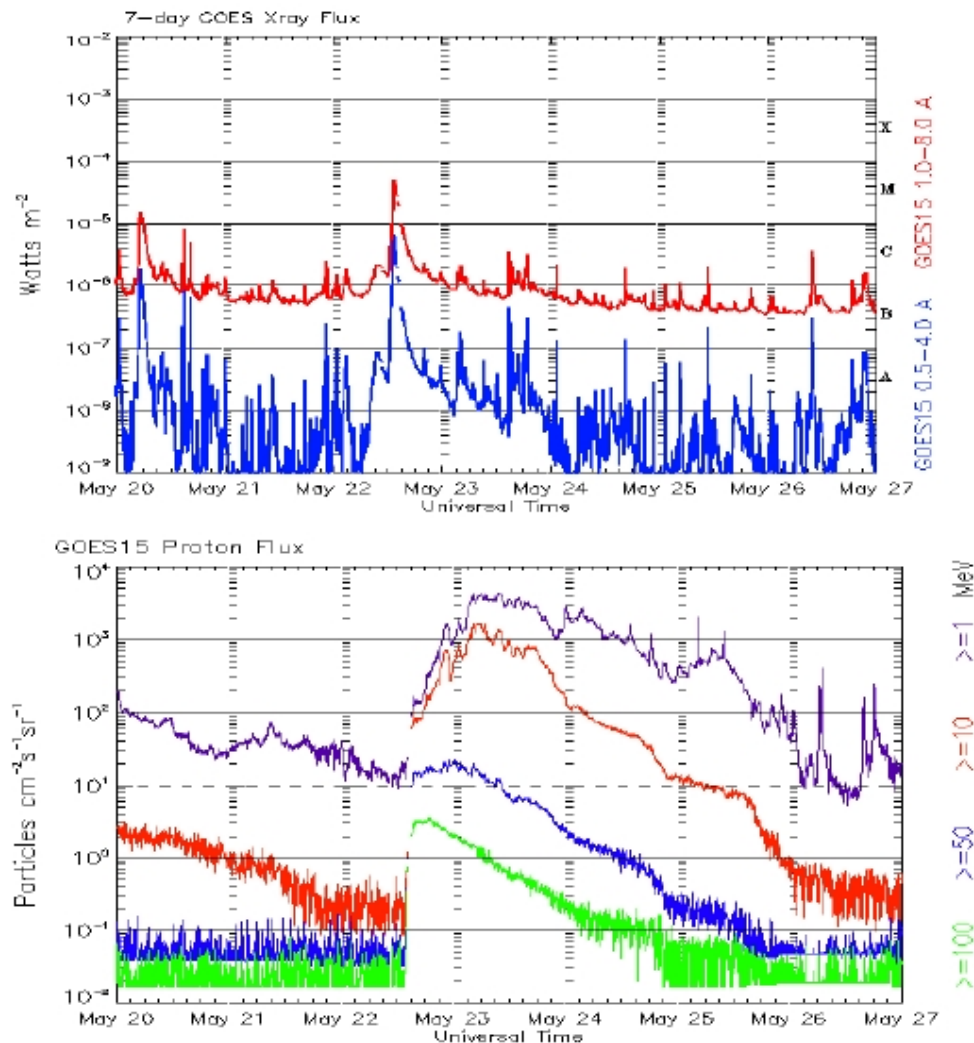


SN:11.04.2013 07:31-08:13 UT (OBT $\sim$ 1760200-1762700s) – NO QUICKLOOK DATA

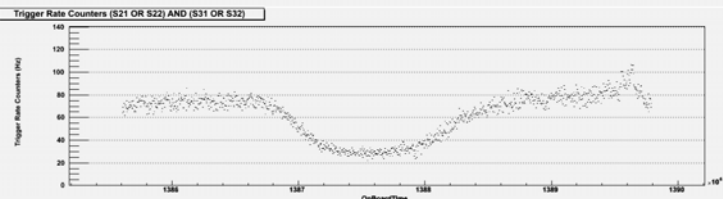
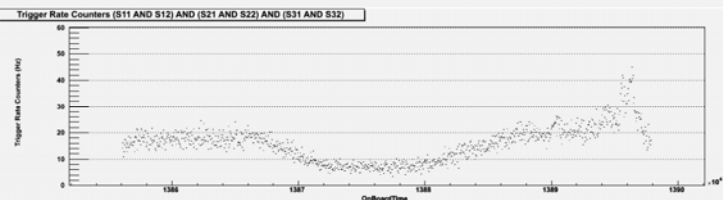
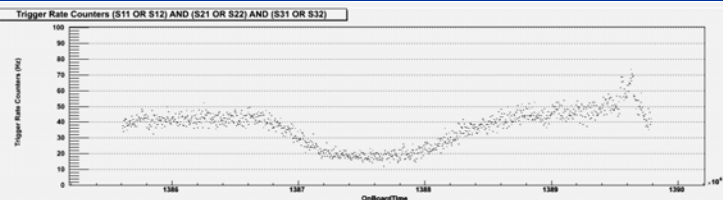
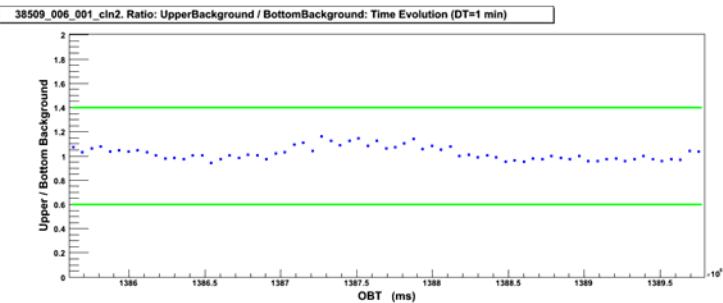
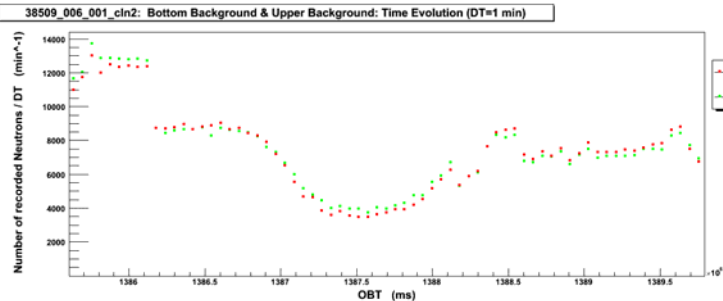
NO SOLAR NEUTRONS ?... No QUICKLOOK Data or Shade...

22 May 2013. SF M5.0 13:32 UT

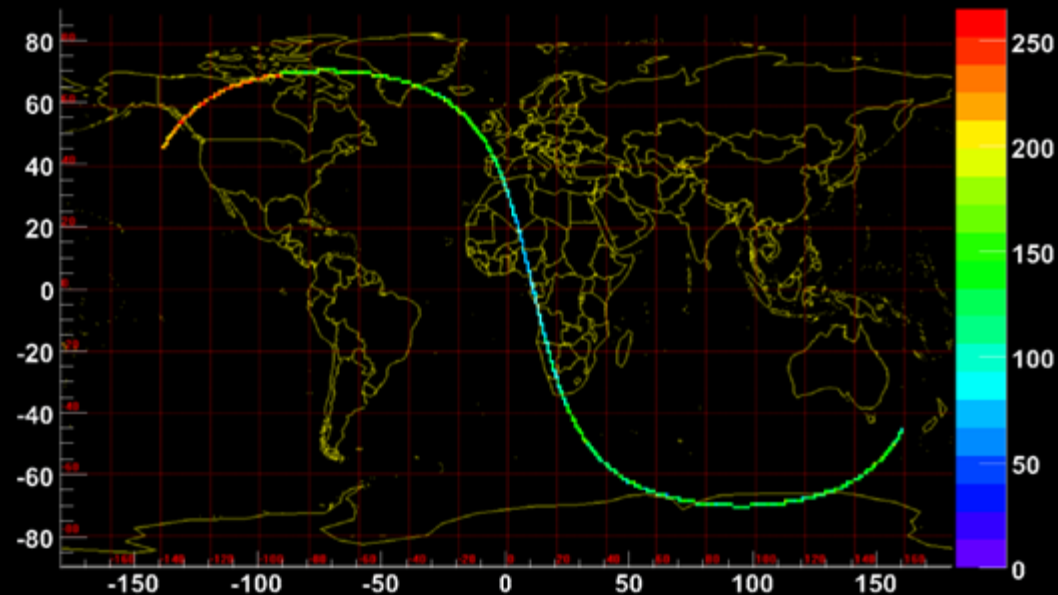
Area 1745, N14W87



22.05.2013. QUICKLOOK Data

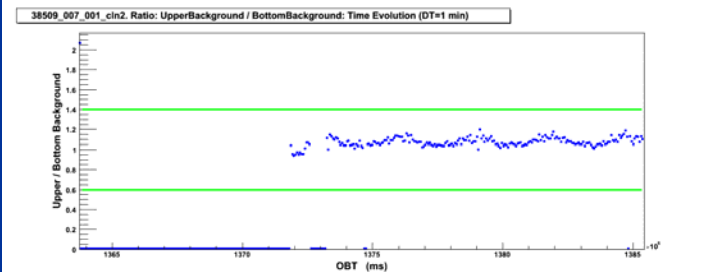
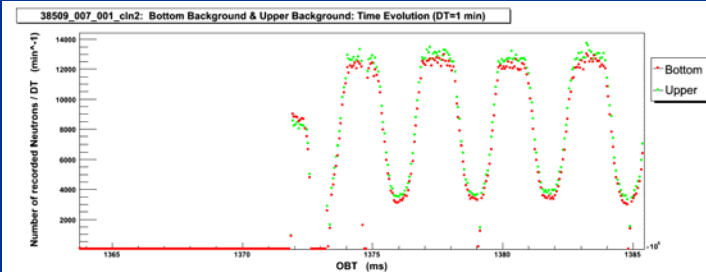


Neutron rate (Hz)

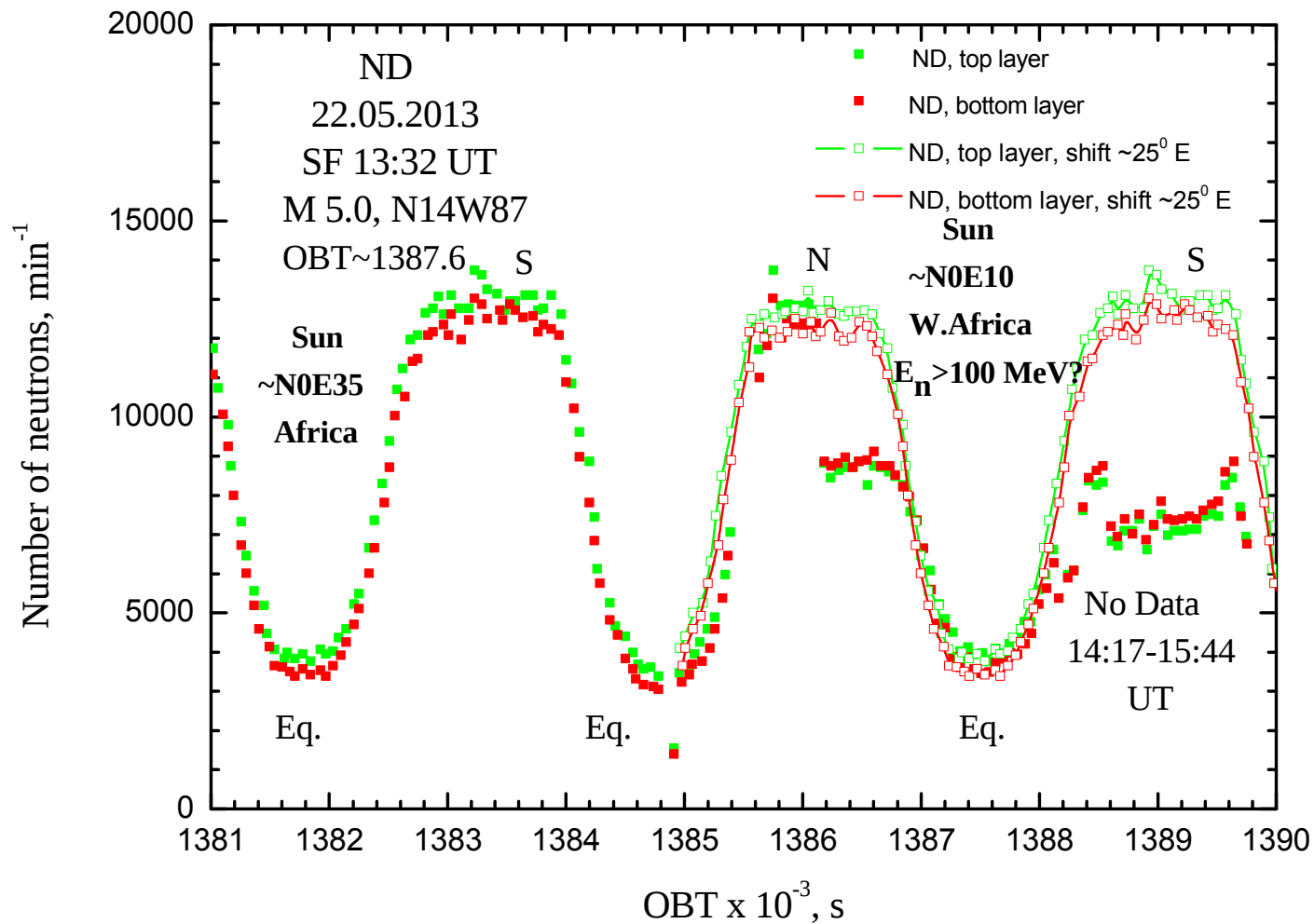


$n > p + e + \dots$?

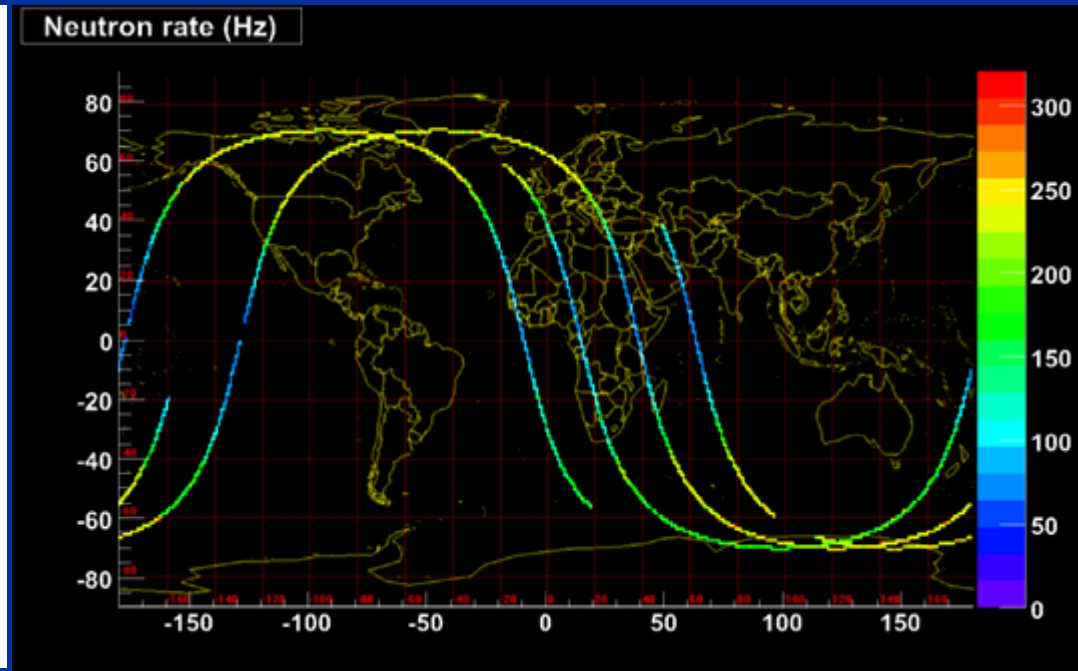
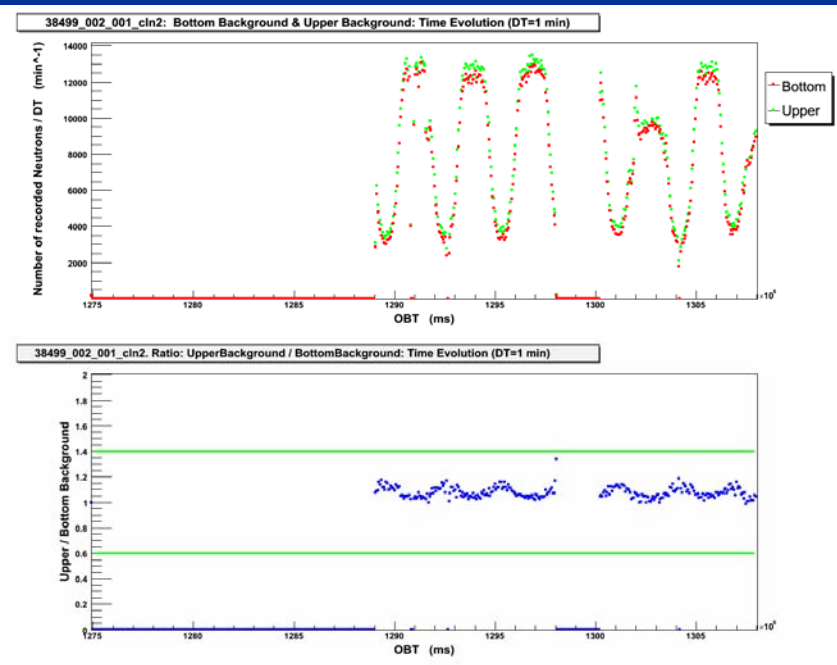
Pre-pulse
Near South
in S1-S3



22.05.2013. QUICKLOOK Data Digitization



21.05.2013. QUICKLOOK Data Digitization



SN:22.05.2013 OBT1387600-1388200 ND(b&t):92820-94113=-1273±432, -1.35±0.46%
GM:21.05.2013 OBT1301200-1301800 ND(b&t):99963-105890=-5927±454, -5.60±0.43%
(GM: Cut-off shift ~ 11.5-12.0GV).

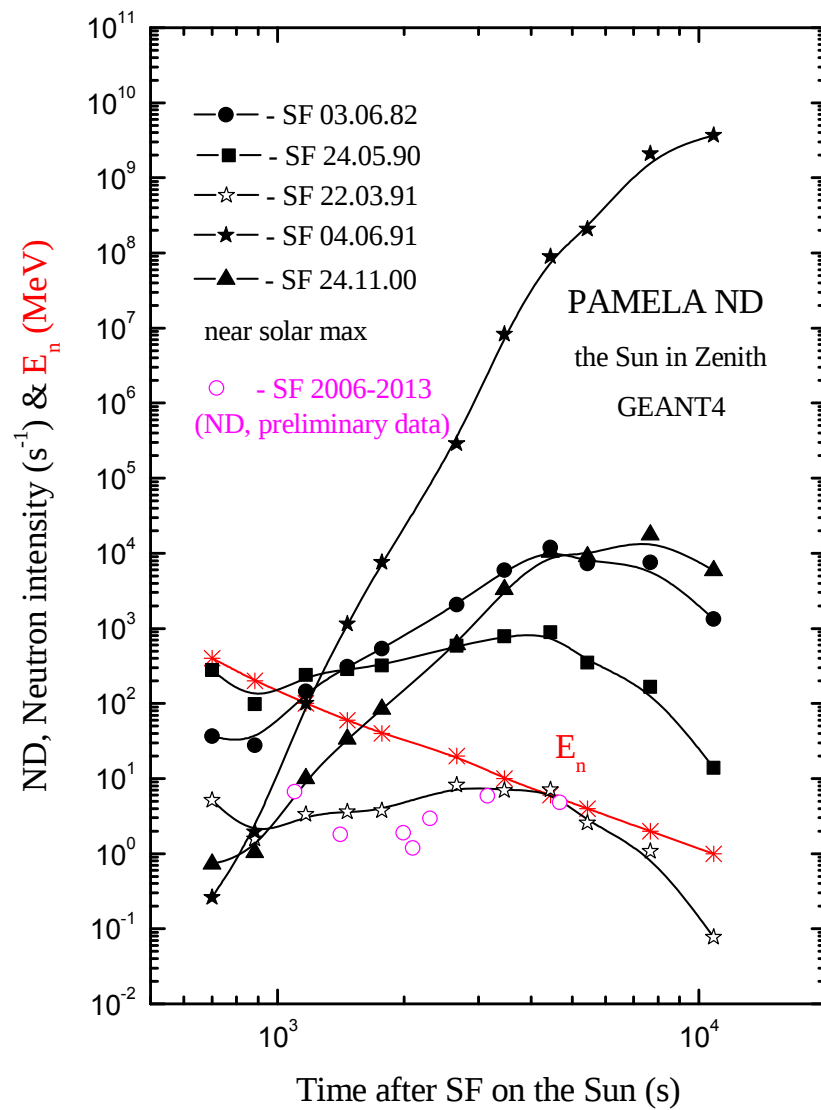
Total Effect SN-GM: +4.25±0.63% for 8-18 min after SF, $E_n \sim 100$ MeV

PROBABLY SOLAR NEUTRONS... Near the Earth $I_n(>100 \text{ MeV}) \sim 1800 \text{ n/m}^2\text{s}...$

Summary

Solar Flare	Class	Area	Energy	Effect	SN(GM)
13 December 2006	X3.4	S06 W24	$E_n \sim 38-96$ MeV	$+1.3 \pm 0.7\%$	Yes?
07 June 2011	M2.5	S22 W53	$E_n \sim 27-40$ MeV	$-1.8 \pm 0.8\%$	No
23 January 2012	M8.7	N18 W21	$E_n \sim 18-23$ MeV	$+1.5 \pm 0.8\%$	Yes?
27 January 2012	X1.7	N27 W71	$E_n \sim 23-38$ MeV	$+0.2 \pm 0.7\%$	No?
07 March 2012	X5.4	N17 E27	$E_n \sim ?$ MeV	No QL Data	No?
17 May 2012	M5.1	N11 W76	$E_n \sim 22-27$ MeV	$+1.9 \pm 0.9\%$	Yes?
06 July 2012	X1.1	S13W59	$E_n \sim 11-15$ MeV	$+5.6 \pm 1.3\%$	Yes?
19 July 2012	M7.7	S13W88	$E_n \sim 5-6$ MeV	$+4.3 \pm 1.1\%$	Yes?
11 April 2013	M6.5	N07E13	$E_n \sim ?$	No QL Data	No?
22 May 2013	M5.0	N14W87	$E_n \sim >100$ MeV	$+4.3 \pm 0.7\%$	Yes?

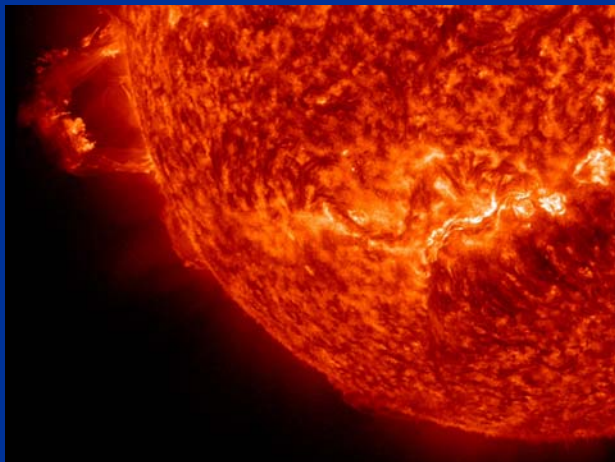
Solar neutrons spectra in ND.



CONCLUSION

- Probably Solar Neutrons (SN) should be generated more or less in each Solar Flash (SF)
- Analysis of the PAMELA QL Data for SF 2006-2013 show that Solar Neutrons probably were found recently in Solar Flares 13.12.2006, 23.01.2012, 17.05.2012, 06.07.2012, 19.07.2012 and 22.05.2013...
Lower limit of SN flux registration in ND $\sim 300 \text{ n/m}^2\text{s}$
- This work can be extended on more precise level using Level 2 data. For PAMELA people who study solar flares...
- P.S. During the nearest Solar Max PAMELA can have data complex for SCR spectra in time, ^1H , ^2H , ^3H , ^3He , ^4He isotopes and Solar Neutrons...

Best wishes from St. Petersburg :~)



Thanks

