Changing SEP Climatology: What if Cycle 24 is the "New Normal"?

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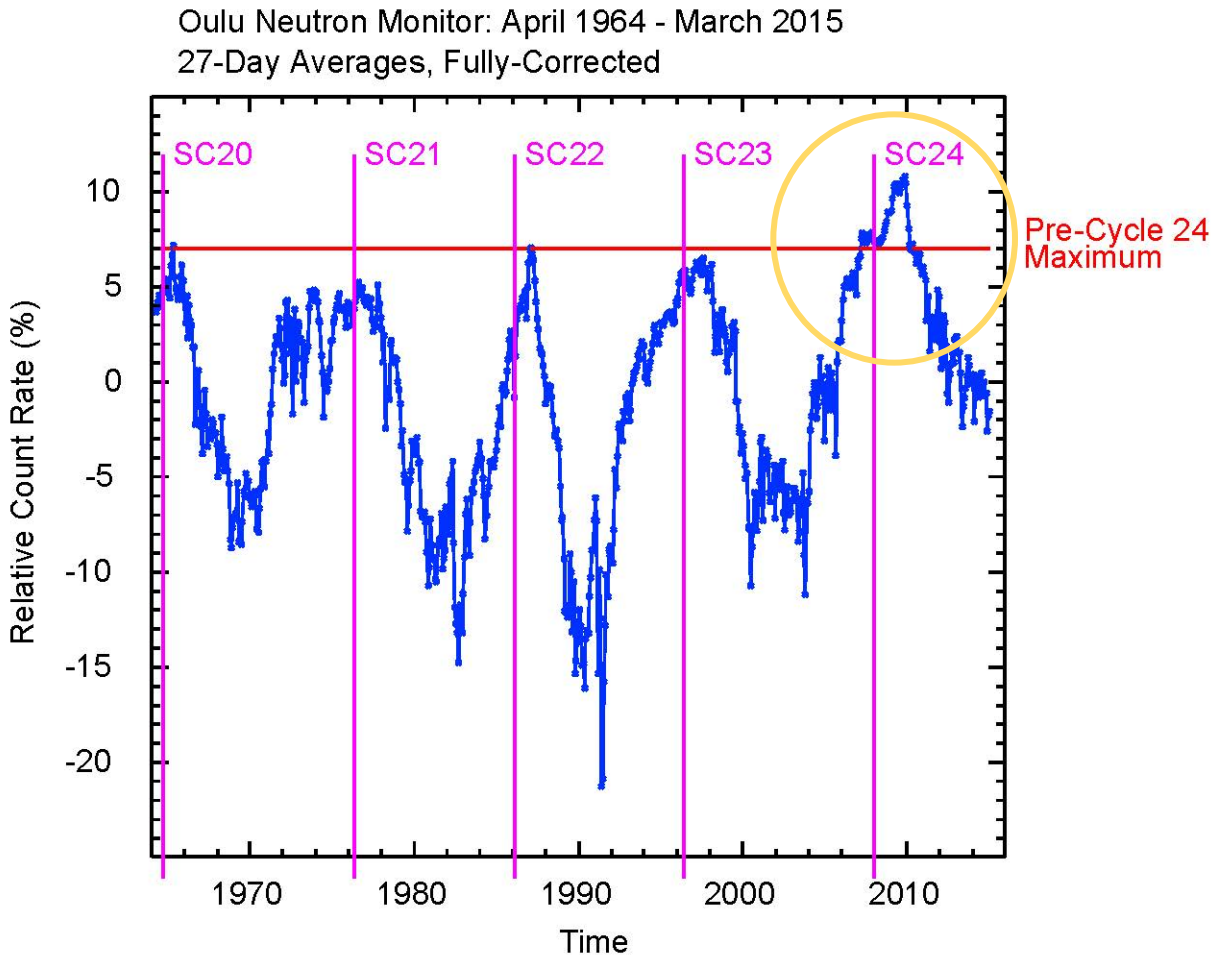
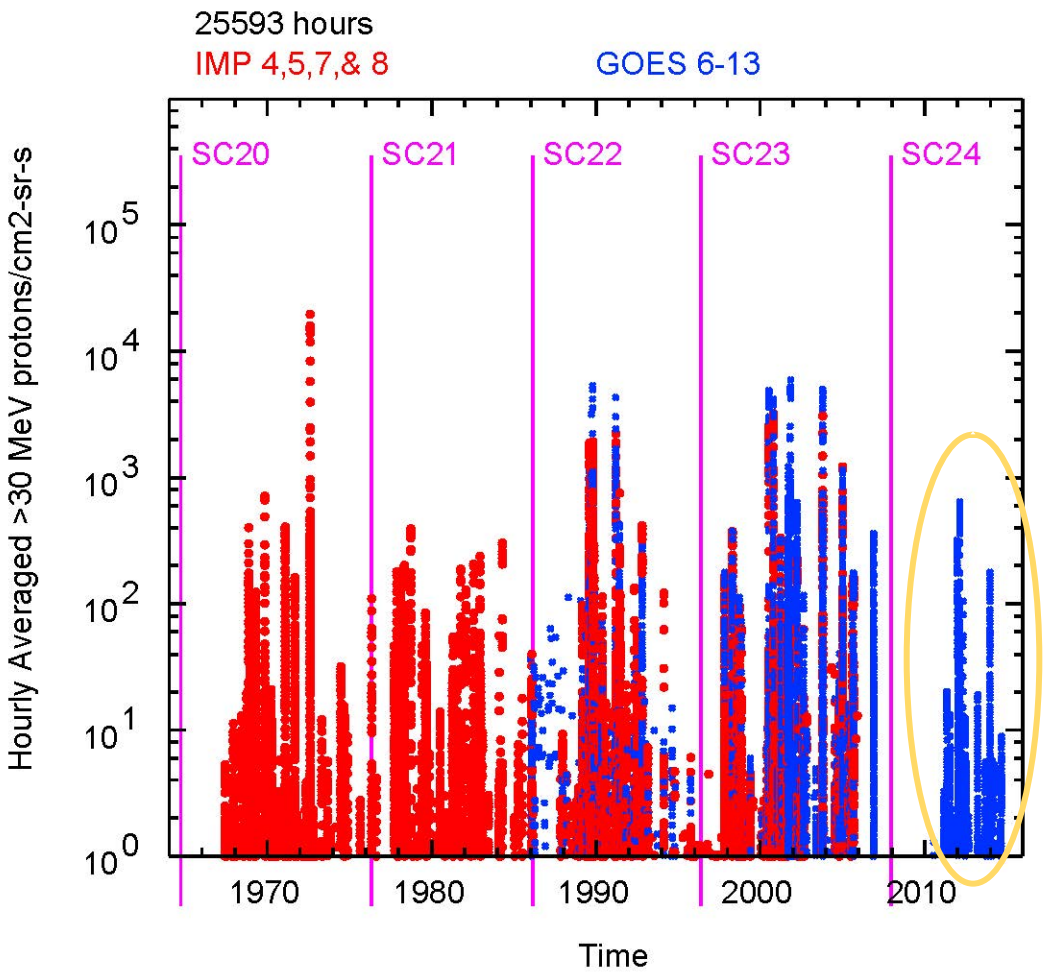
Motivation:

In the 2008-2010 minimum of solar activity, we saw a higher flux of Galactic Cosmic Rays (GCRs) at Earth than ever seen before in the Space Age.

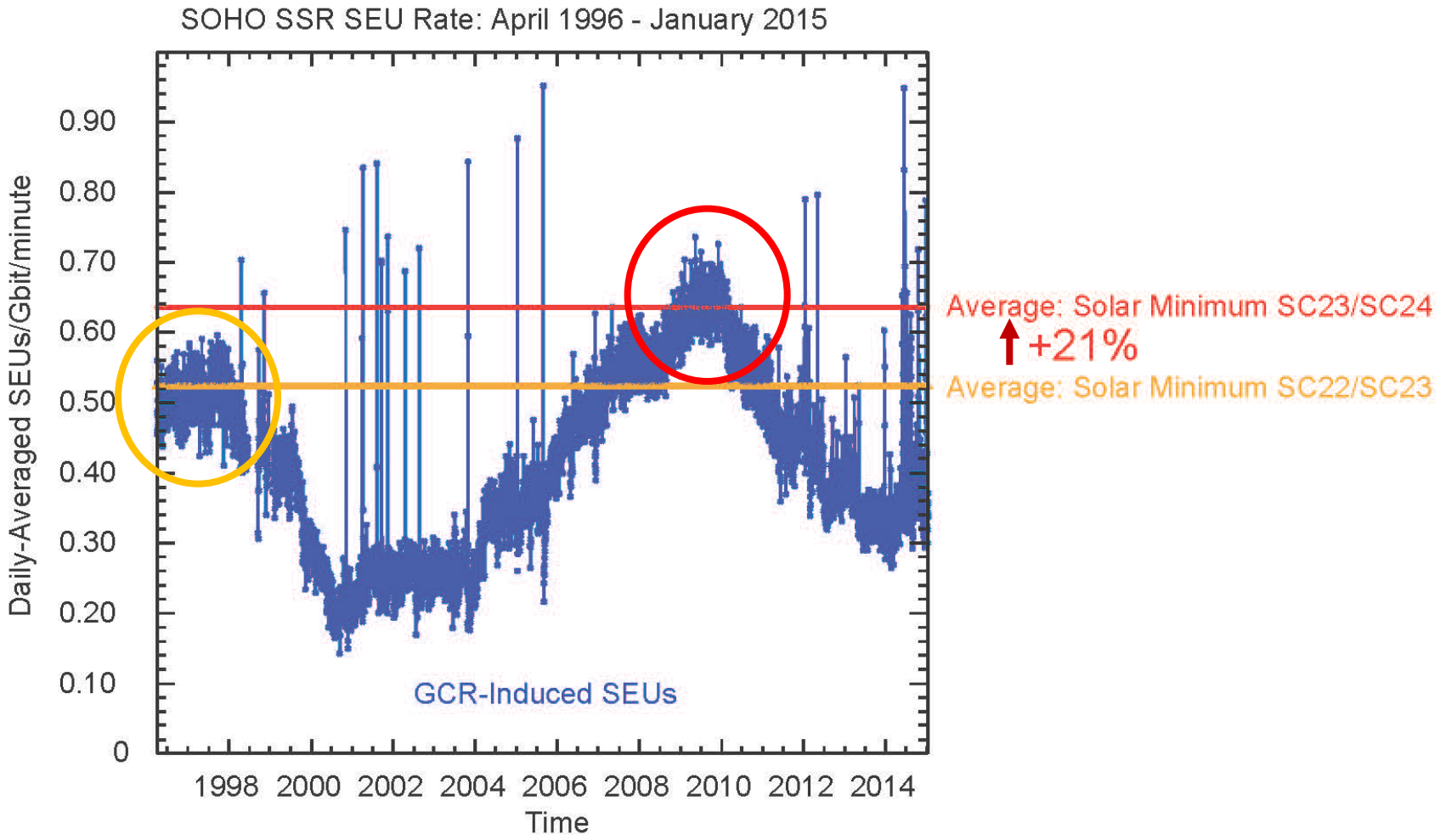
How do the SEP Events of Solar Cycle (SC) 24 differ from those of earlier Solar Cycles?
Do the differences between SC 24 and earlier SCs have implications for a manned mission to Mars?





SEUs in the SSR on SOHO at L1

(Single-Event Upsets in the Solid-State Recorder on the Solar and Heliospheric Observatory at the First Lagrangian Point)



But this is not the whole picture….

SOHO SEU data provided by Dr. Bernhard Fleck, ESA

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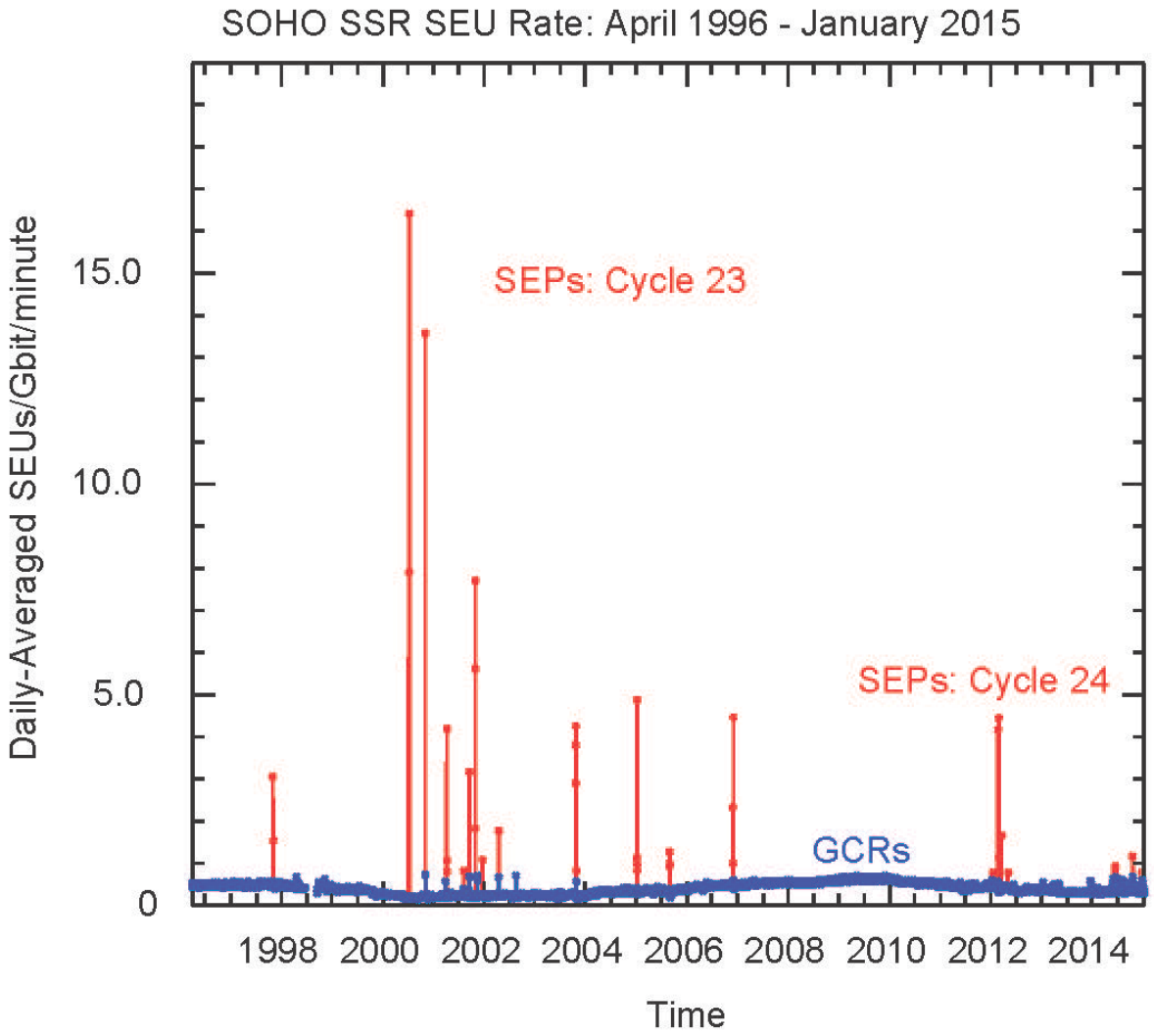


While the GCR-induced hazard has become more severe, the episodic SEP radiation hazard has become less severe and less frequent.

SOHO SEU data provided by Dr. Bernhard Fleck, ESA

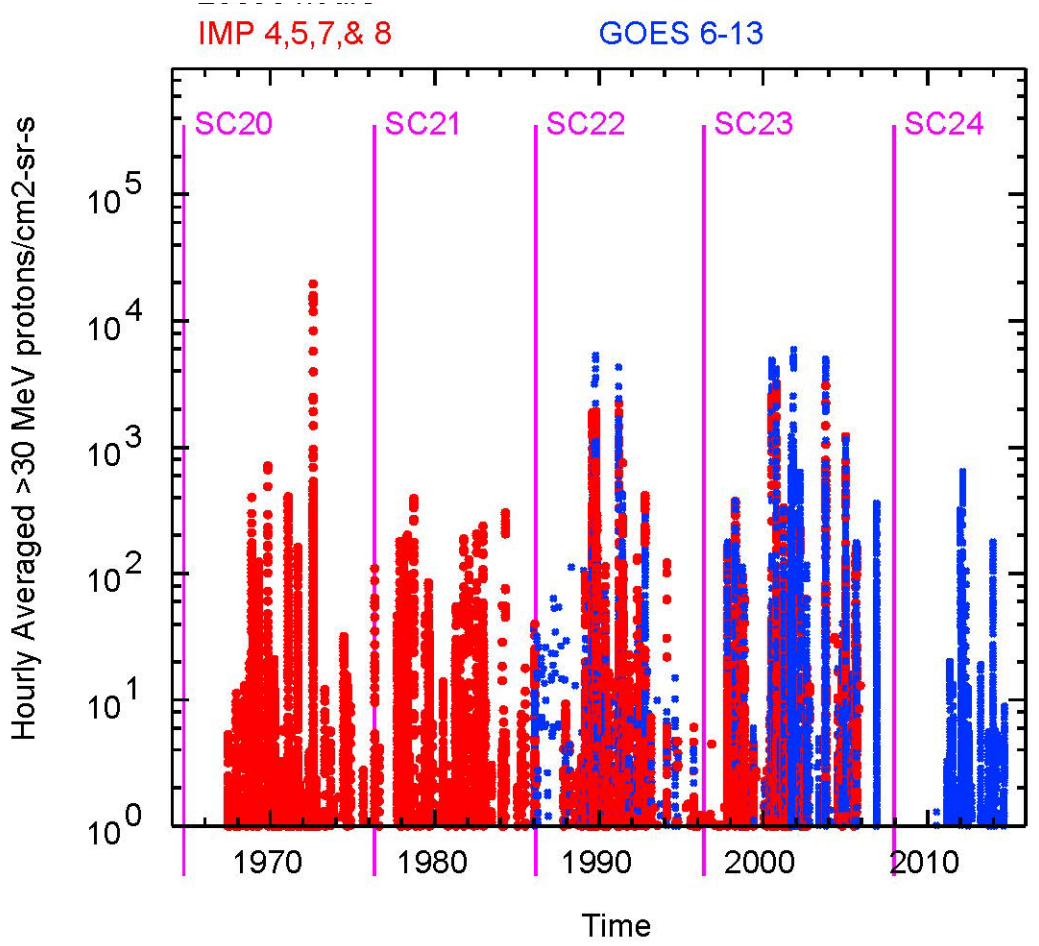
Outline

- Comparison of SEP productivity Cycle 24 vs. Cycles 20, 21, 22, and 23
- Speculation: What if Cycle 24 is the “new normal”?
- A Probabilistic Model of Solar Proton Events during Periods of Low Solar Activity (work in progress)
- Summary and Implications

Comment on SEP Proton-Energy Thresholds

- **Evaluating the SEP radiation hazard requires both the absolute normalization of the proton flux as well as its energy spectrum.**
- **Historically, certain energy thresholds have been used to *roughly* characterize the severity of the SEP hazard:**
  - **>10 MeV: relevant to solar panels and sensors; NOAA uses this threshold to identify 'events'.**
  - **>30 MeV: relevant to biological effects and electronics (single-event effects (SEEs))**
  - **>100 MeV: relevant to storm-shelter design**
    - **But for shelter-design calculations, the spectrum is needed up to ~1000 MeV.**

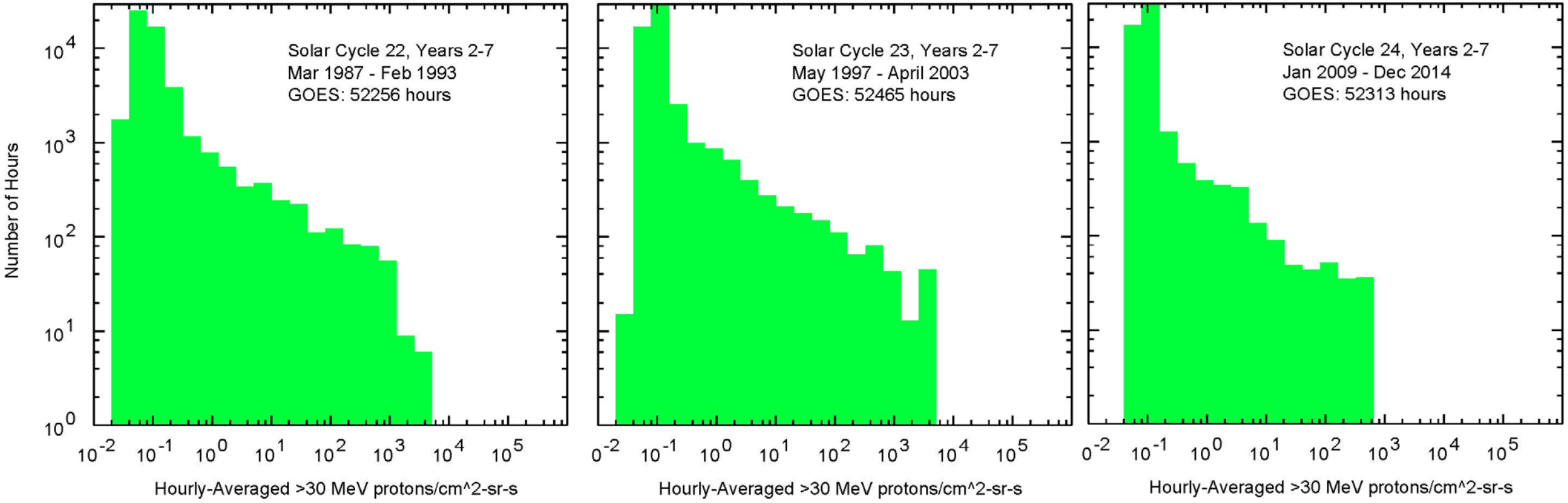
Comparison of SEP productivity Cycle 24 vs. Cycles 20, 21, 22 and 23



Threshold set at >1 pfu in this plot so as to avoid solar-quiet hours, dominated by GCRs.

~76,000 hours of SEP data

>30 MeV SEP Production in the Years 2-7 of the Solar Cycle
(Hourly-averaged fluxes in p/cm^2-sr-s)



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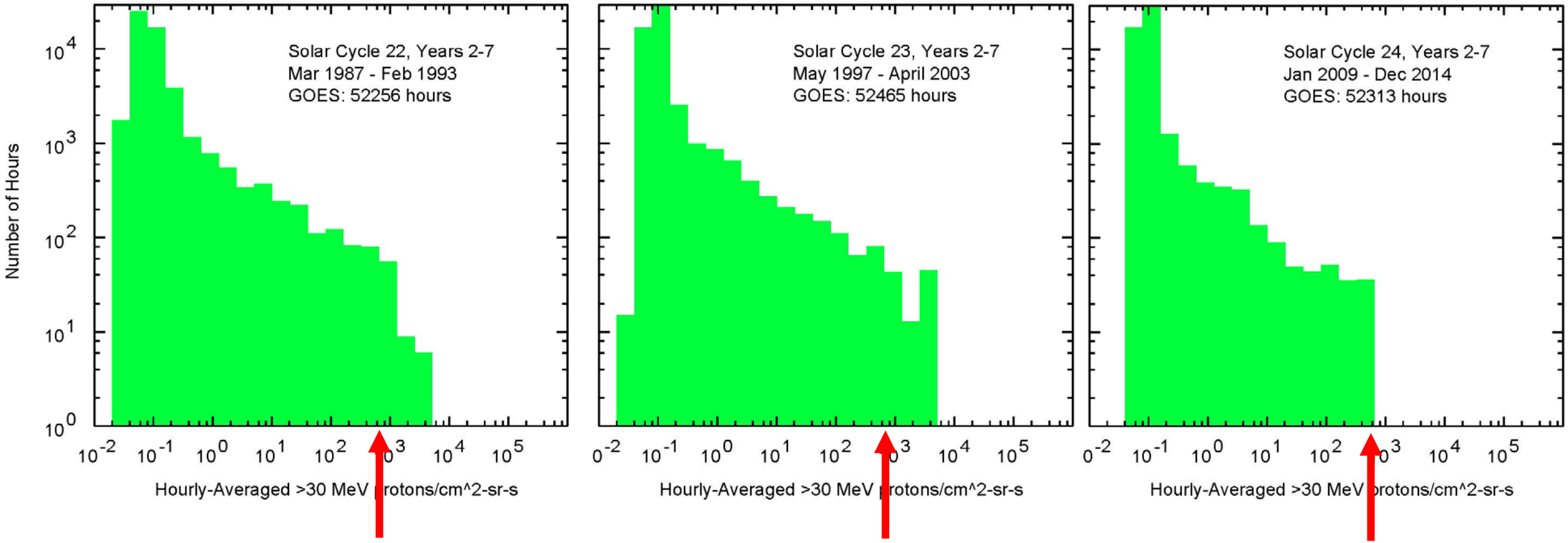

In Cycle 22, the Cycle 24 Max is exceeded in 73 hrs

In Cycle 23, the Cycle 24 Max is exceeded in 112 hrs

Max Flux in Cycle 24: 643 p/cm^2-sr-s

An interesting question: when, in the course of an event, do these hours with big fluxes occur? See back-up slides.
And what about the 2012 July 23 event observed by STEREO-A? See back-up slides.

>30 MeV SEP Production in the Years 2-7 of the Solar Cycle
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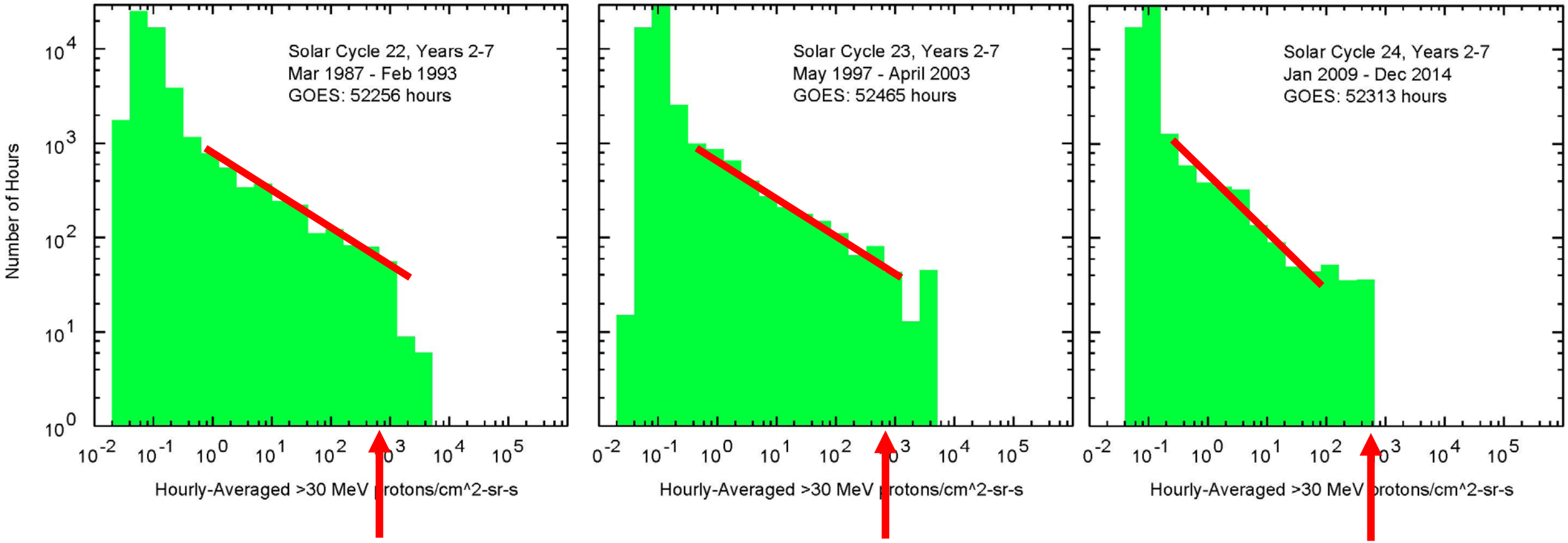


In Cycle 22, the Cycle 24 Max is exceeded in 73 hrs

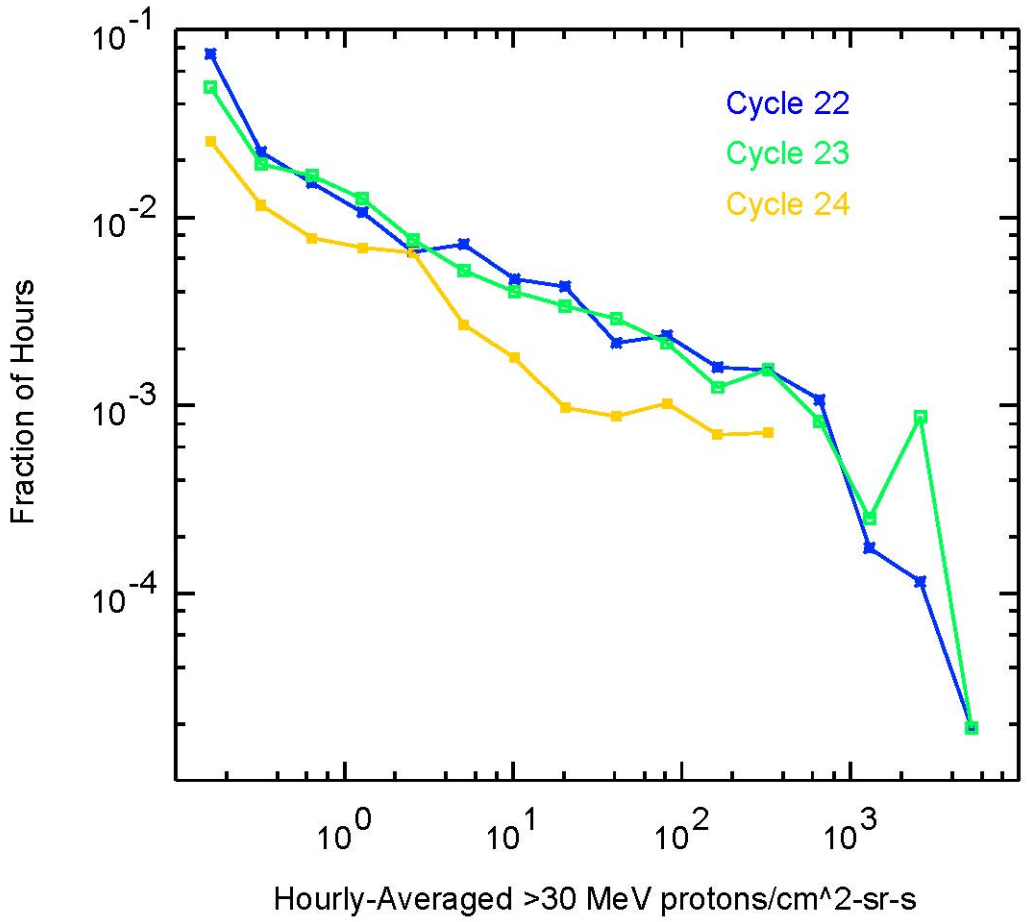
In Cycle 23, the Cycle 24 Max is exceeded in 112 hrs

Max Flux in Cycle 24: 643 p/cm^2-sr-s

In Cycle 24, the slope of the flux distribution is also steeper than in Cycles 22 & 23.

Let's look at this more quantitatively…

>30 MeV SEP Production in the Years 2-7 of the Solar Cycle (Hourly-averaged fluxes in p/cm^2-sr-s)



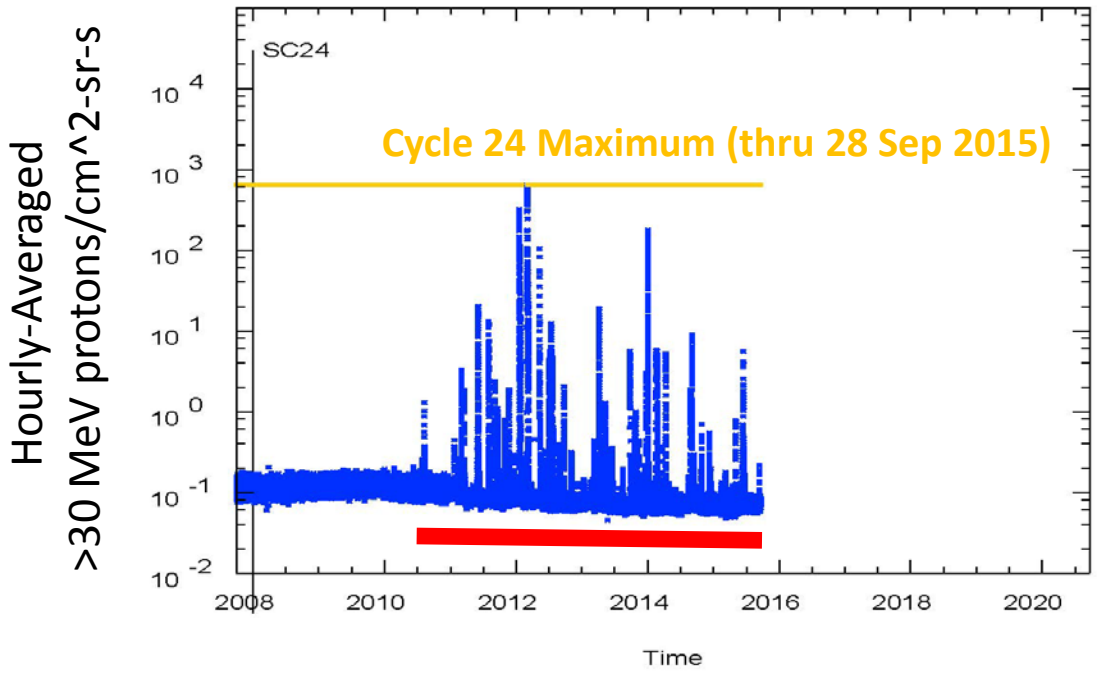
At every flux level, SC 24 has fewer hours at that level than either SC 22 or 23 by a factor of 2-4.

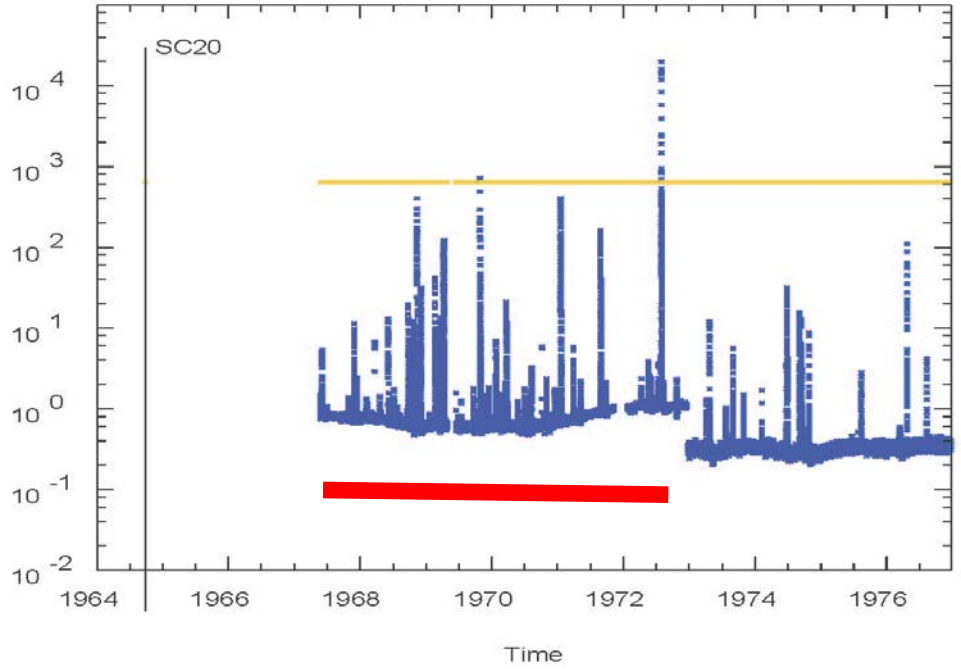
In SC 24, the highest SEP fluxes (top ~0.2%) are completely missing.

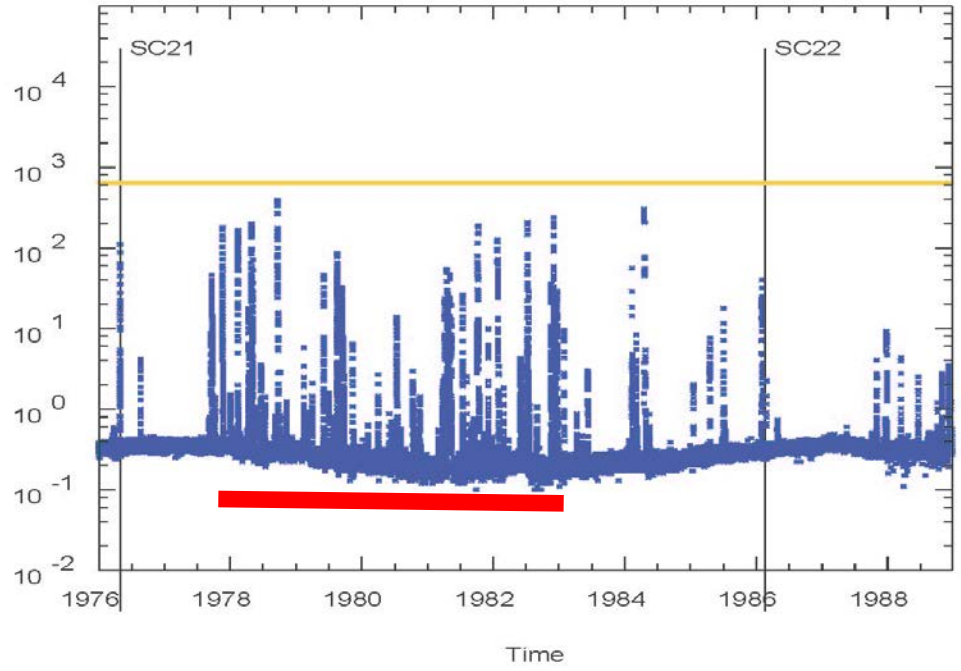
The same behavior is seen at other energies:
See backup slides at>10 and >100 MeV

In terms of the SEP radiation, SC 24 (at least so far) has been much less severe than SCs 22 & 23.

Cycle 24 compared to Cycles 20 & 21





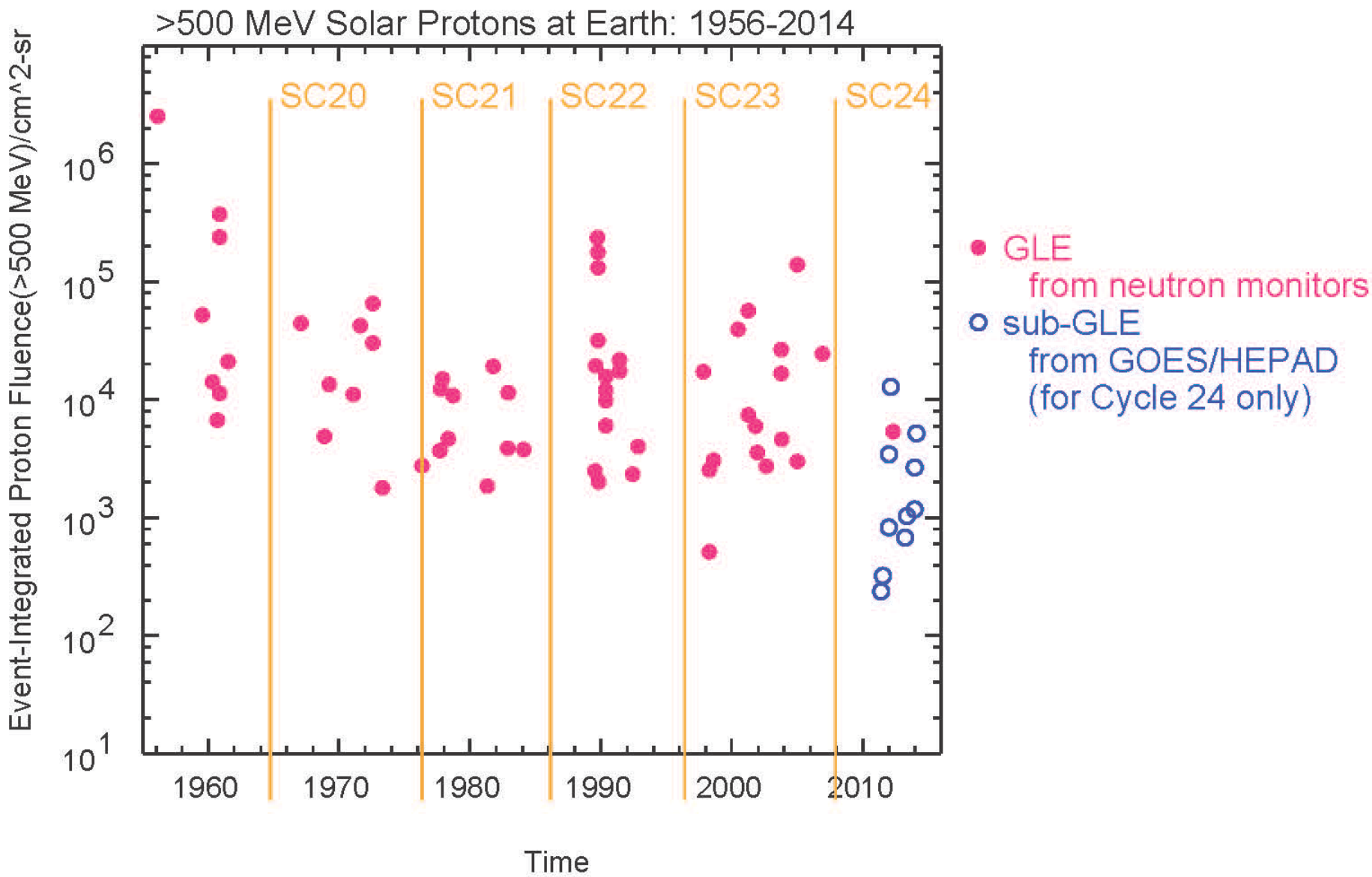


At >30 MeV, differences between Cycle 24 and Cycles 20 and 21 are less impressive than the differences with Cycles 22 and 23.

But at this late stage, Cycles 21 and 22 were still producing events 10x -100x larger than those so far seen in Cycle 24.

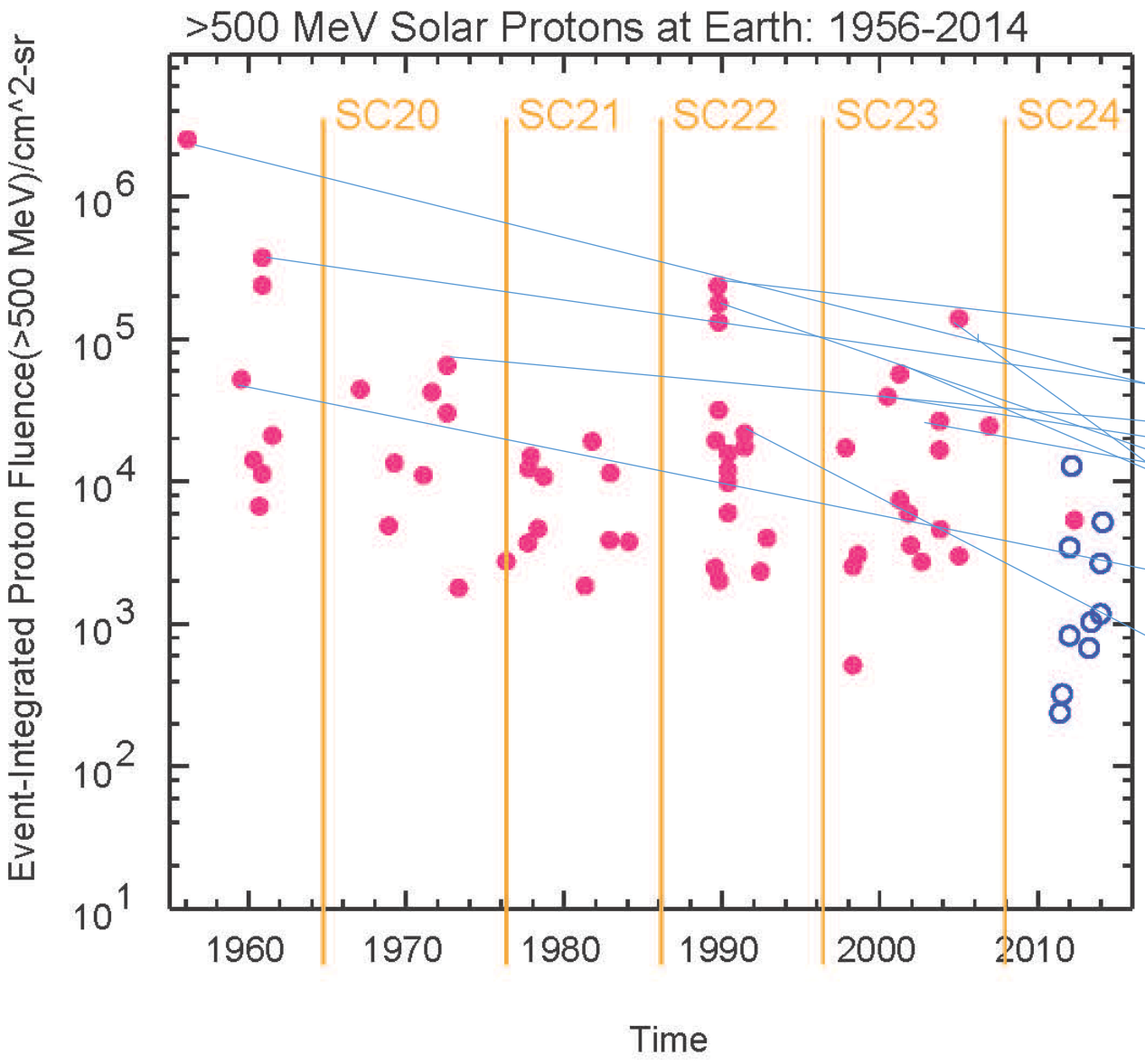
It will be important to watch how SC24 continues to evolve.

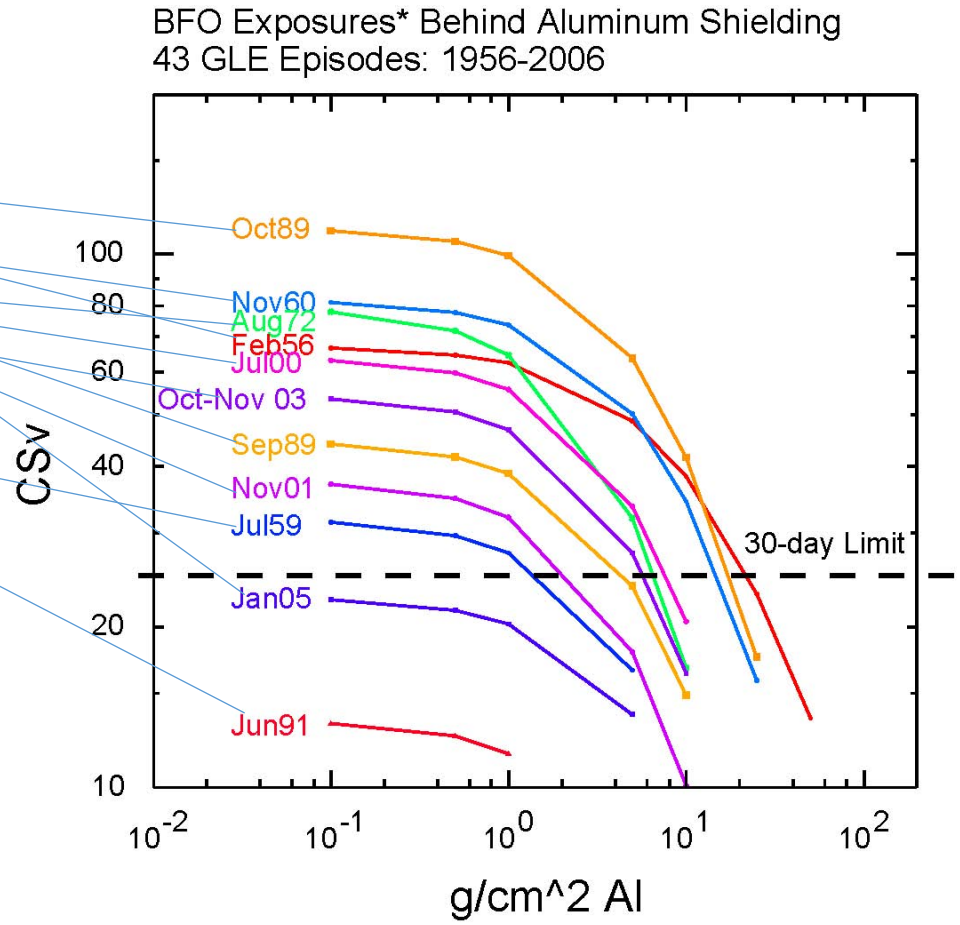
What about higher energies?



What about higher energies?

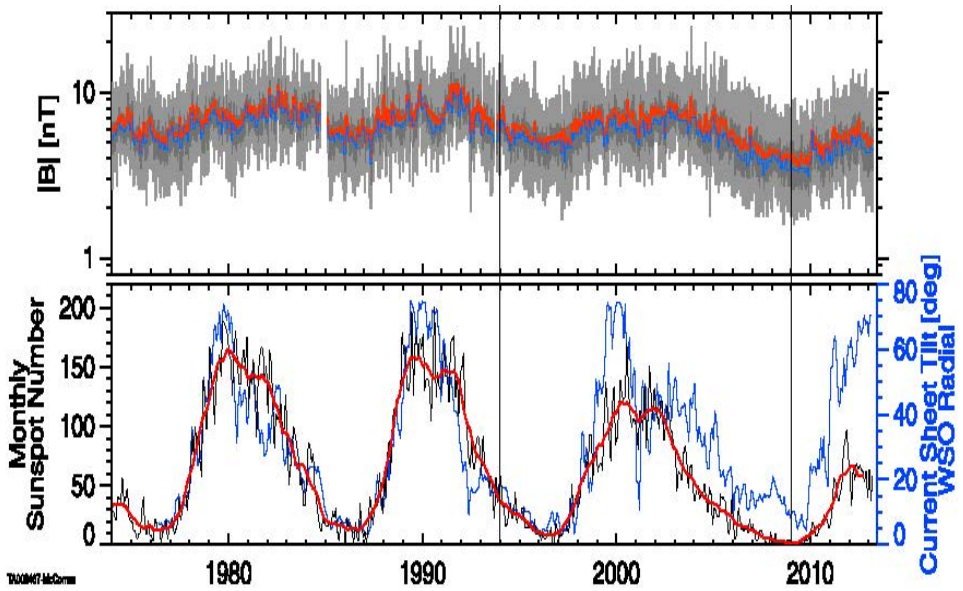
- IF *these very big GLEs have disappeared from the Sun's repertoire, the required storm-shelter shielding will be greatly reduced. (Note the big 'IF'.)*





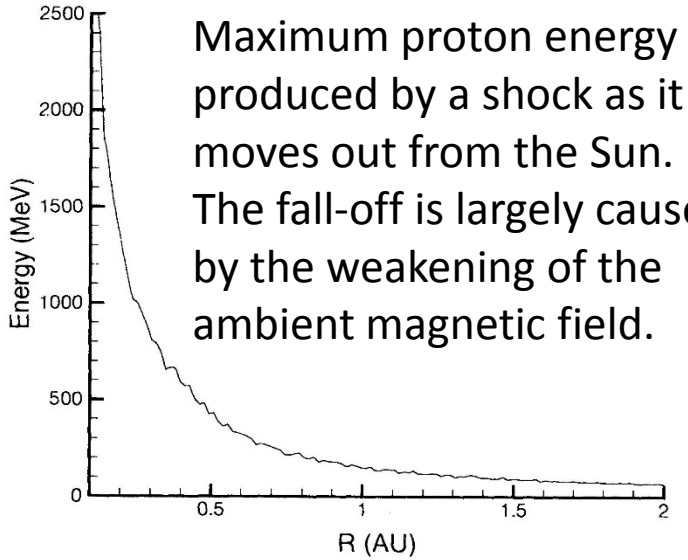
*Body self-shielding approximated as 8 g/cm^2 water

What's the physics behind the reduced SEP productivity? *We can speculate…*



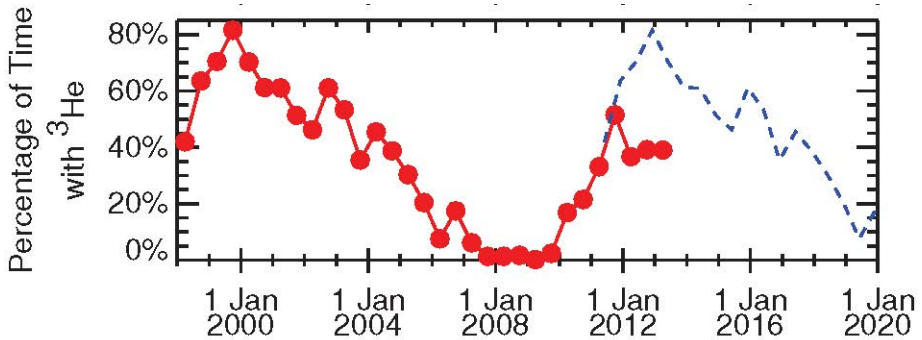
McComas et al., ApJ 779:2 (2013)

Compared to previous solar maxima, the mean interplanetary magnetic in the ecliptic at 1 AU has fallen by ~30%.



Maximum proton energy produced by a shock as it moves out from the Sun. The fall-off is largely caused by the weakening of the ambient magnetic field.

Zank et al., JGR 105, 25709 (2000)



Wiedenbeck & Mason, ASP Conf 484 (2014)

Compared to SC 23, there are fewer potential suprathermal seed particles available in SC 24.

These factors – weakened magnetic field and fewer suprathermals – together may explain why SEP production is down.

Other ideas: Gopalswamy et al. *Earth, Planets and Space* 66:104 (2014)

Speculation: What if Cycle 24 is the “new normal”?

***Prediction is very difficult, especially if it’s about the future*.**

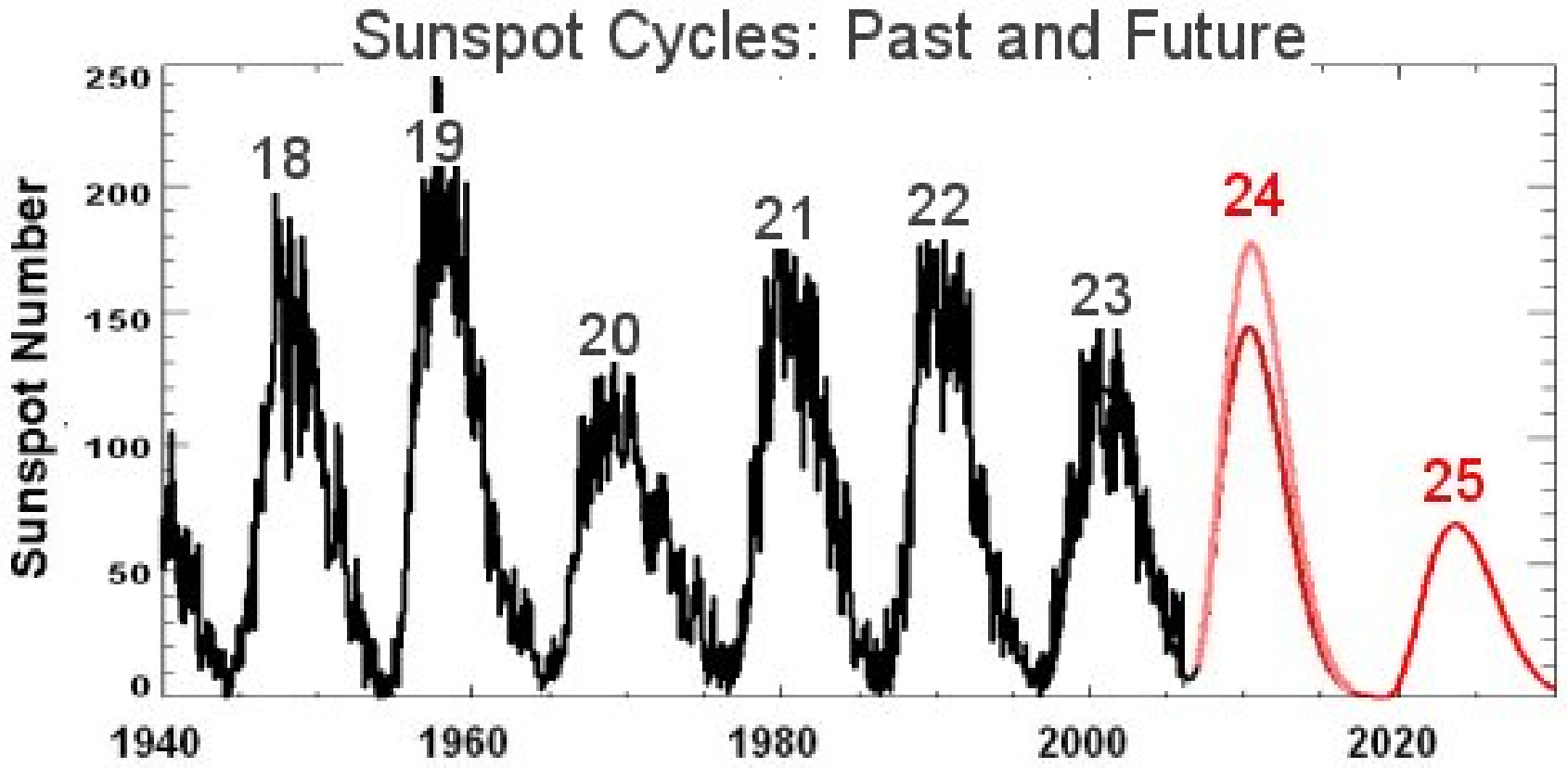
Neils Bohr

It’s tough to make predictions, especially about the future.

Yogi Berra

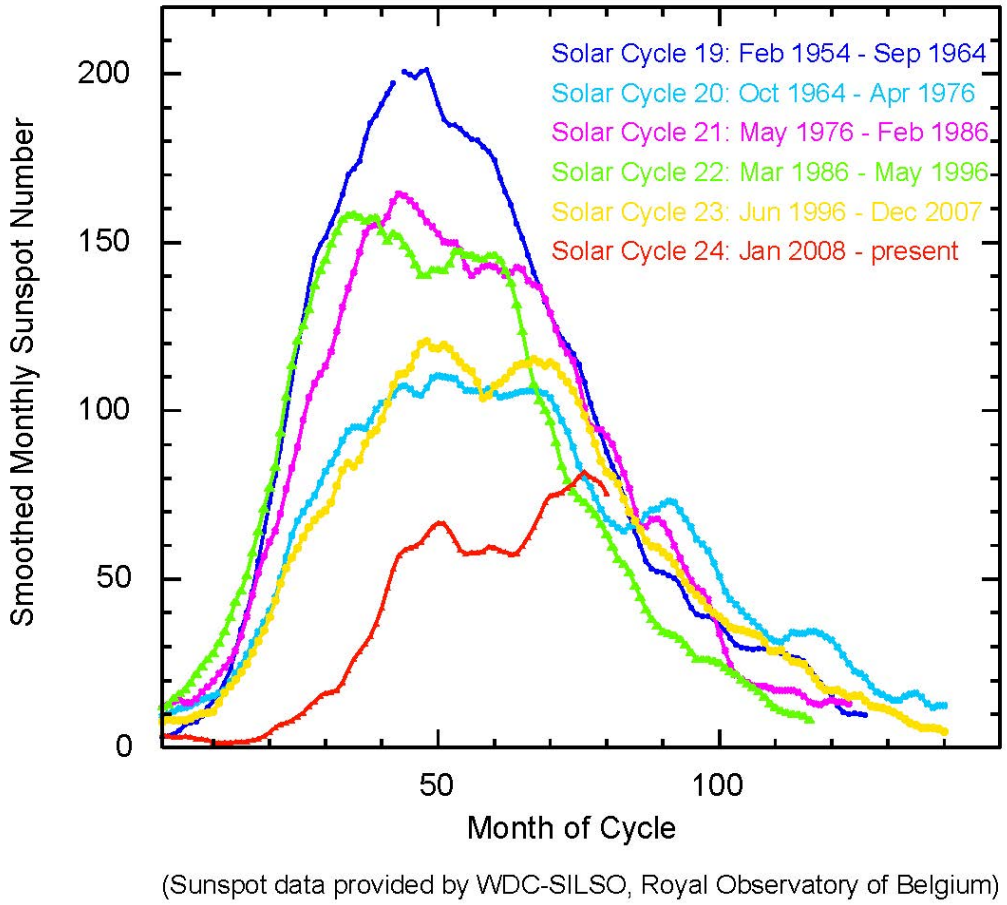
The speed of light is greater than the speed of the sound. That’s why people often look intelligent until they talk.

NASA Science News: "Solar Cycle 25, peaking around 2022, could be one of the weakest in centuries."



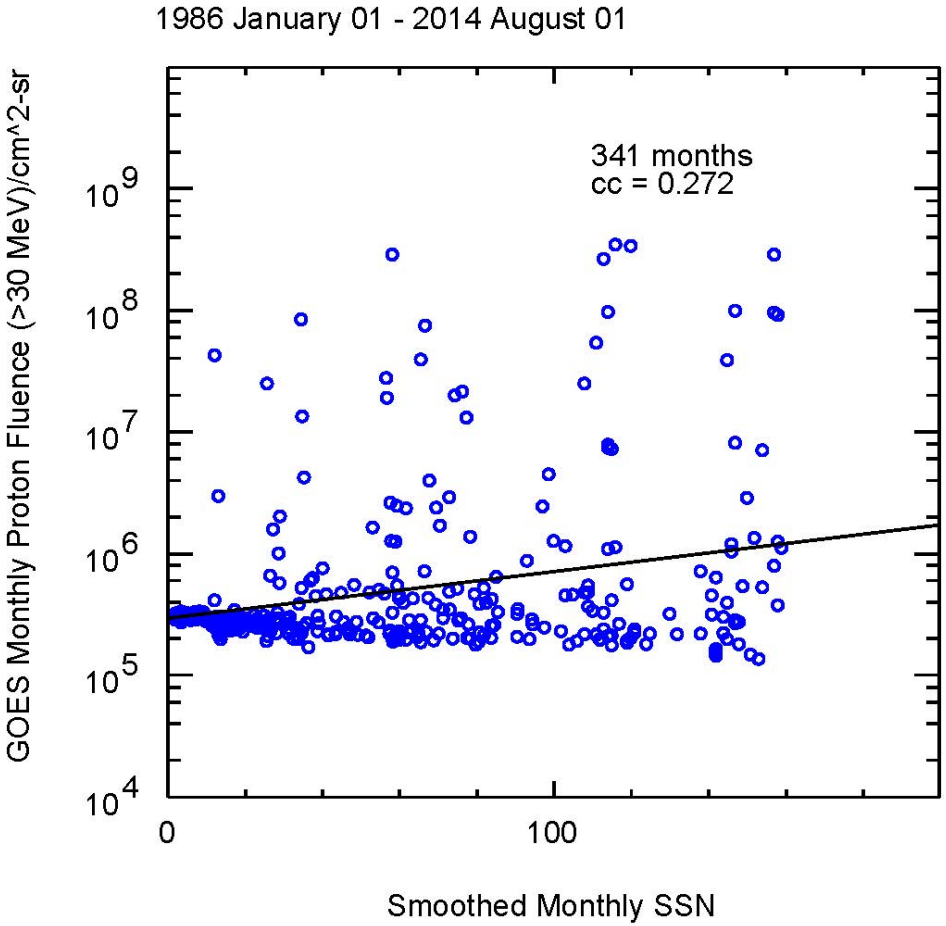
- **Caveat**: The solar-research community does not have an impressive track record for predicting the sunspot cycle.
- **However**, there is a growing consensus that Cycle 25 will likely be even weaker than Cycle 24.

Sunspot Number (SSN) serves as a general measure of solar activity, for which we have a long historical record.



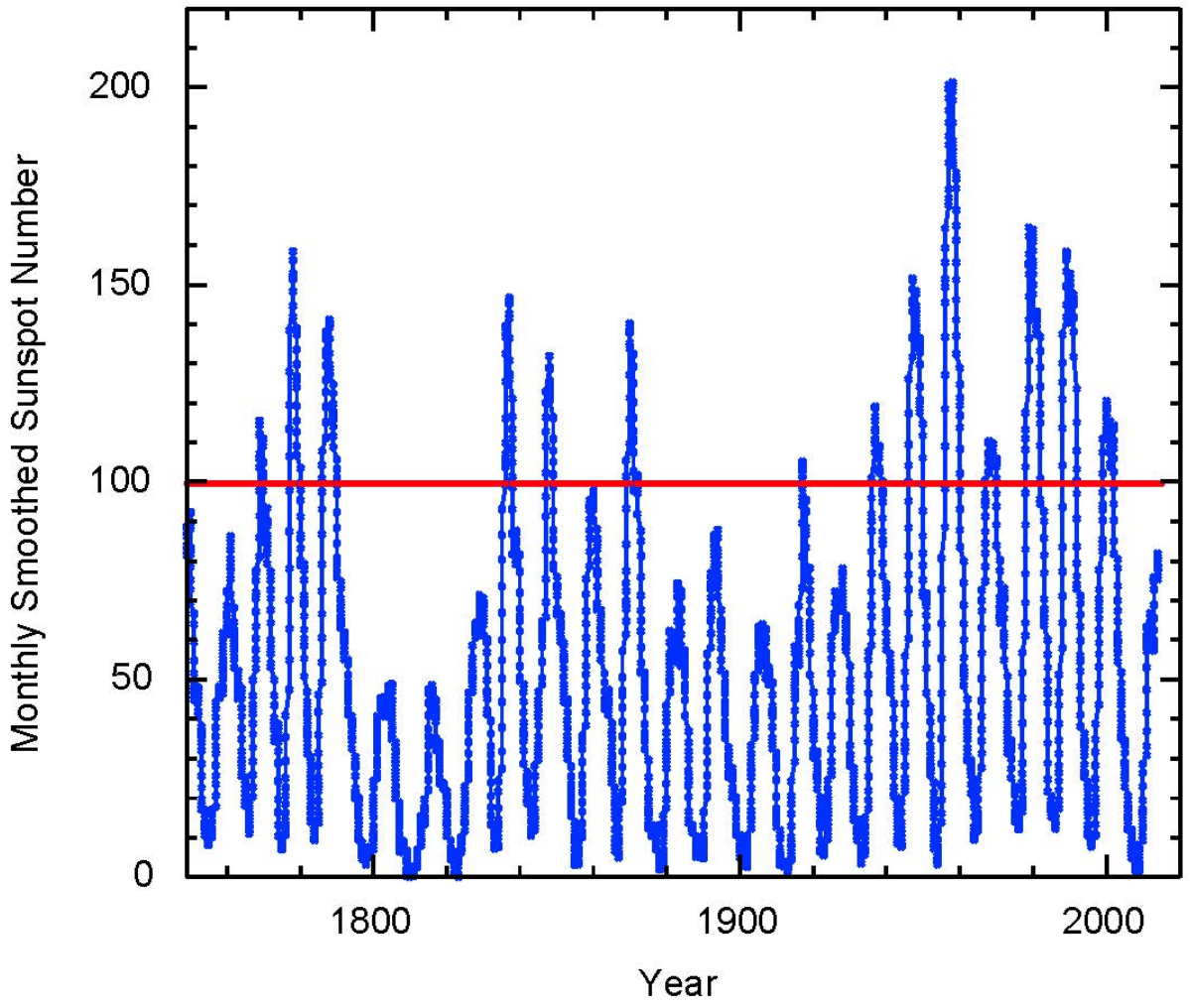
- **Sunspot Numbers in the Space Age, 1954-present**
  - **Cycles 24 is smaller – and unique**

But a **BIG CAVEAT**:
SSN is **not** a good predictor of SEP production



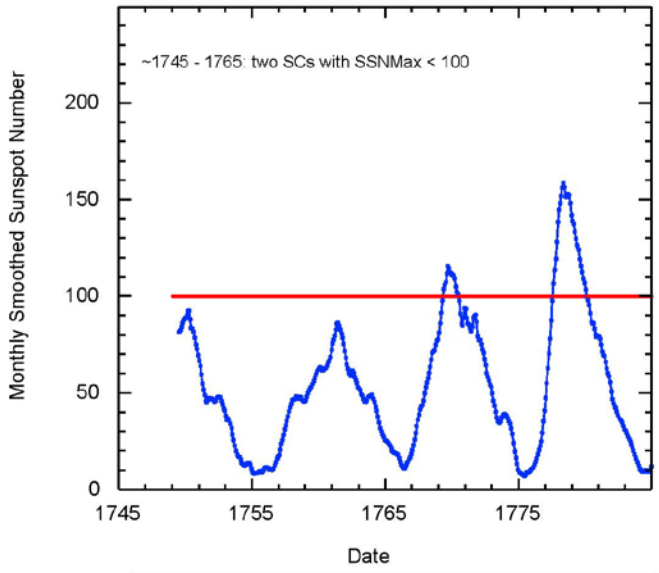
- **Nevertheless, let us boldly speculate where no one has ever speculated before…**

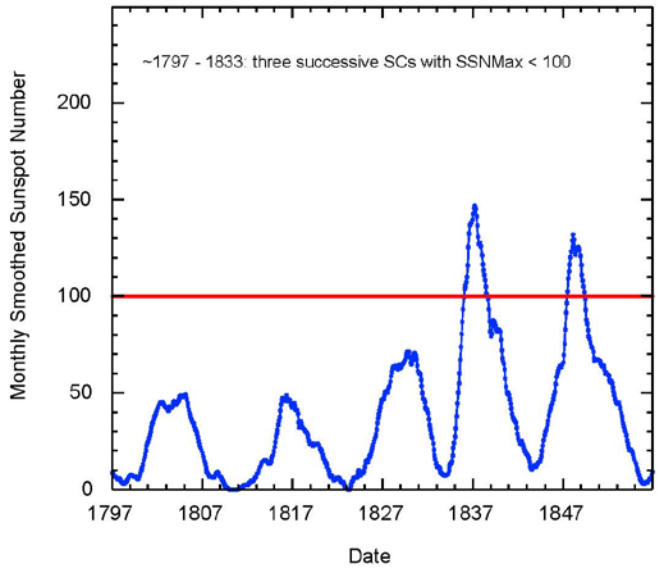
- **Cycle 24 is not yet over, but SSN is declining from a maximum of 82 in April 2014.**
- **Let's examine previous Cycles with maximum SSN < 100.**

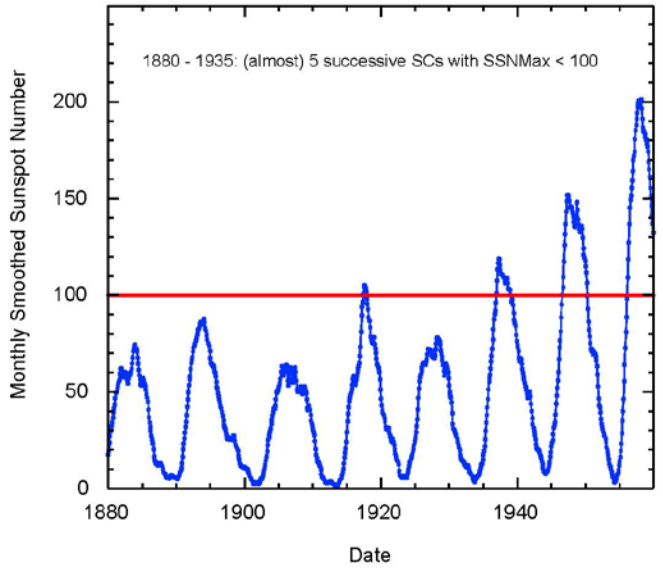


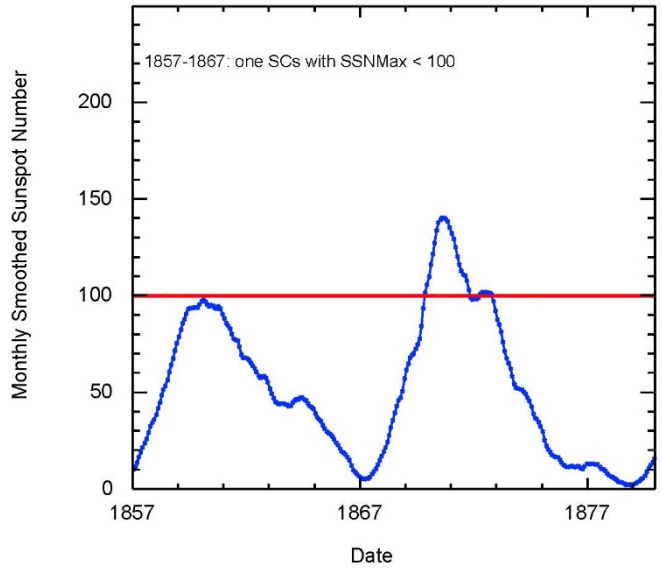
Sunspot numbers provided by WDC-SILSO, Royal Observatory of Belgium, Brussels

- **Cycle 24 is not over yet, but SSN is declining from a maximum of ~82 in April 2014.**
- **Let's examine previous Cycles with maximum SSN < 100.**









- In three cases (above), the appearance of an SC with SSNMax < 100 presaged an extended period of time (20-50 years) with comparably low sunspot numbers.
- However, there is also an example (left) of a single, isolated SC with SSNmax <100; after that, sunspot numbers returned to higher values.
- And, of course, there's also the Maunder Minimum: No sunspots: 1645-1715

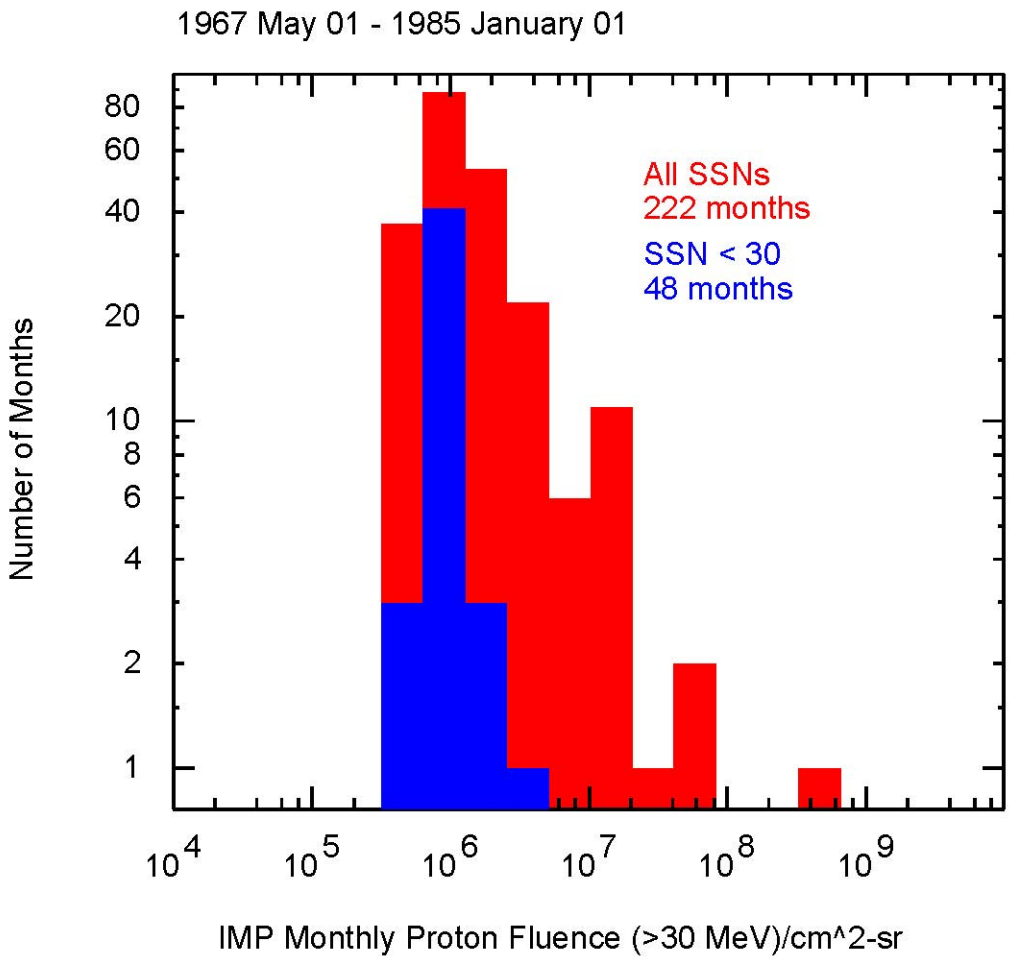
Work in Progress:

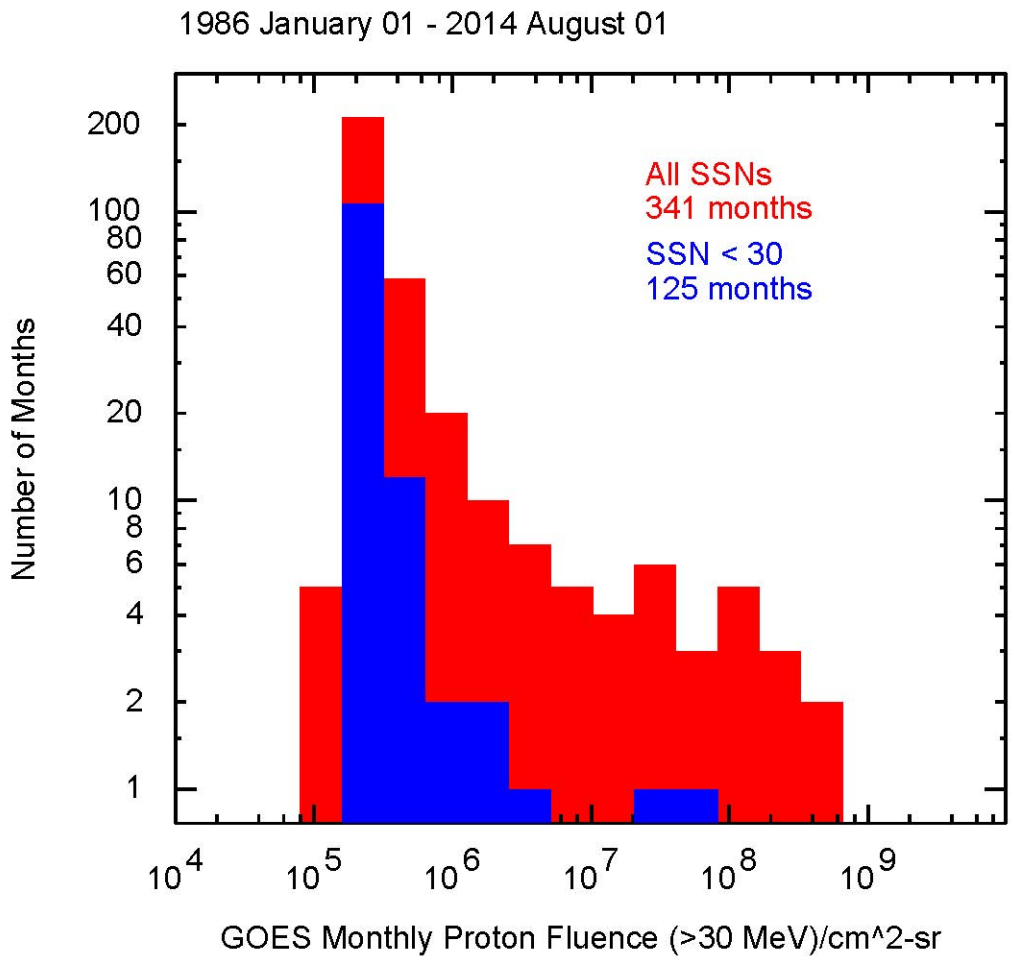
A Probabilistic Model of Solar Proton Events during Periods of Low Solar Activity

Tylka, Atwell, Dietrich, Rojdev, & Matzkind

For status report, see also: “Sub-GLE Solar Particle Events and the Implications for Lightly-Shielded Systems Flown During an Era of Low Solar Activity”, Atwell, Tylka, Dietrich, Rojdev, and Matzkind, *ICES 2015*

From IMP (1967-1985) and GOES (1986-2014):

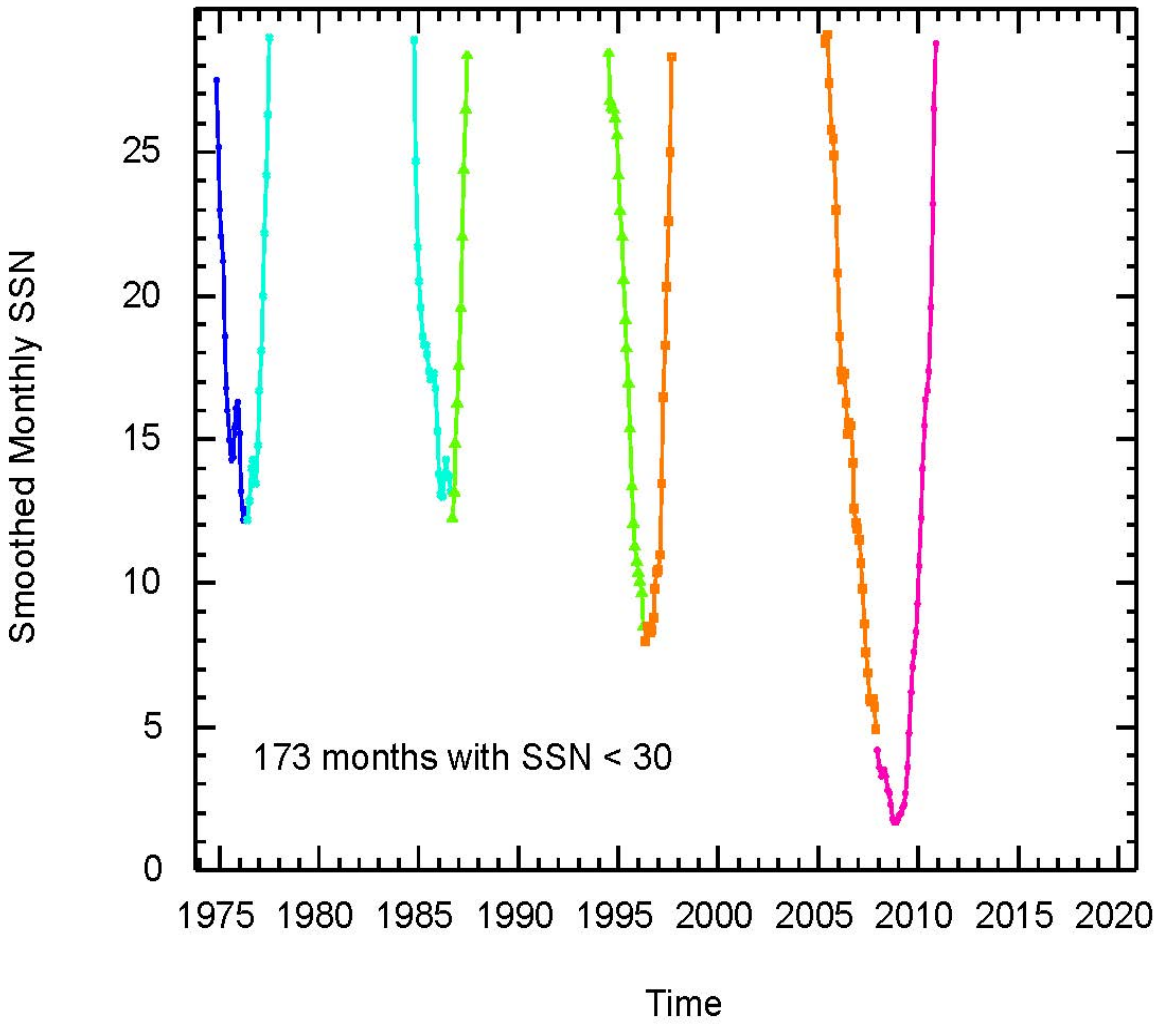




Although SEP production is not strongly correlated with SSN, the SEP hazard is clearly less severe and less probable when the SSN is low. (Here, we show SSN < 30.)

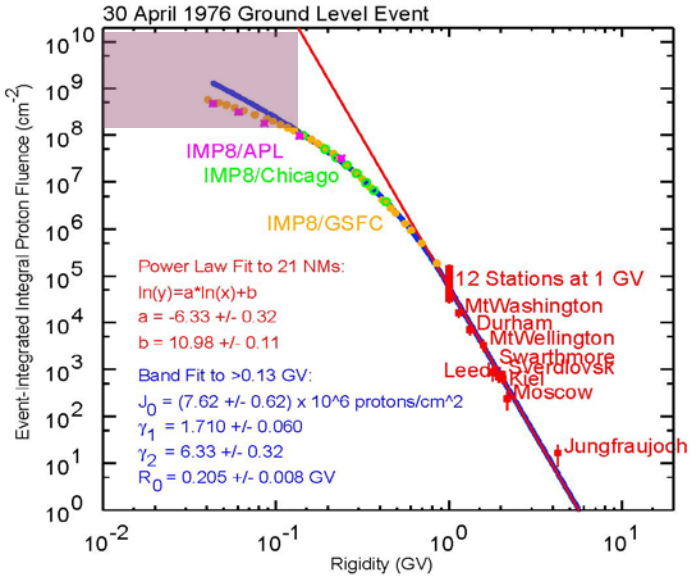
Solar Proton Events during Periods of Low Solar Activity

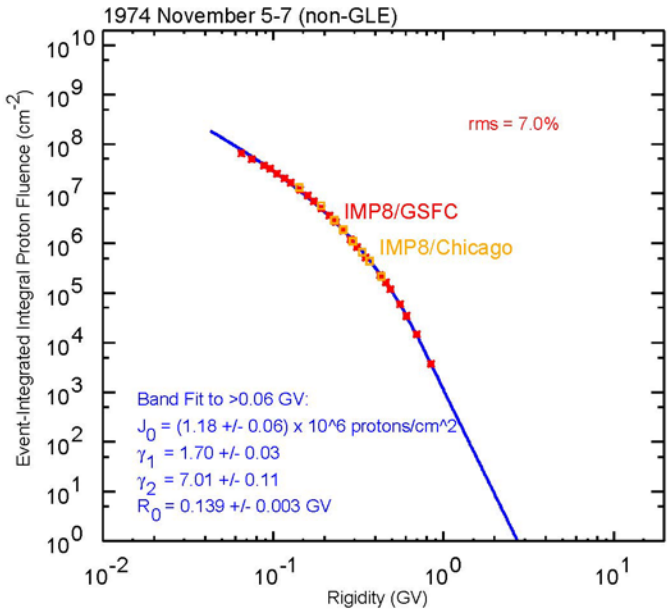
- We surveyed the nearly-continuous record energetic proton data (primarily from IMP8 and GOES) in 173 months since November 1974 in which the smoothed monthly sunspot number was less than 30 (SSN < 30).

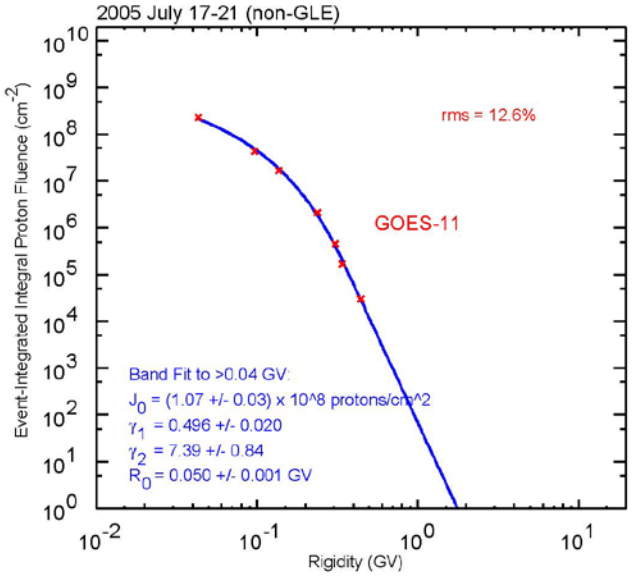


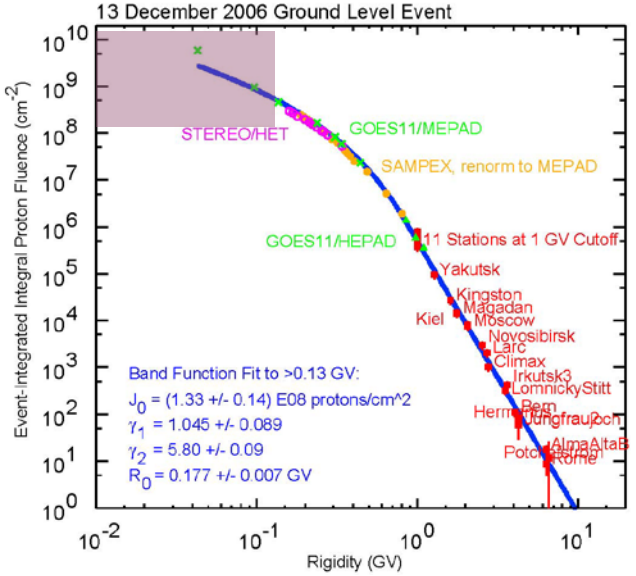
Solar Proton Events during Periods of Low Solar Activity

- We identified 34 events in which the >30 MeV proton fluence was at least twice the contemporaneous background (GCRs + instrumental).
- We derived the event-integrated proton spectrum for each of these events and fitted to a Band function.



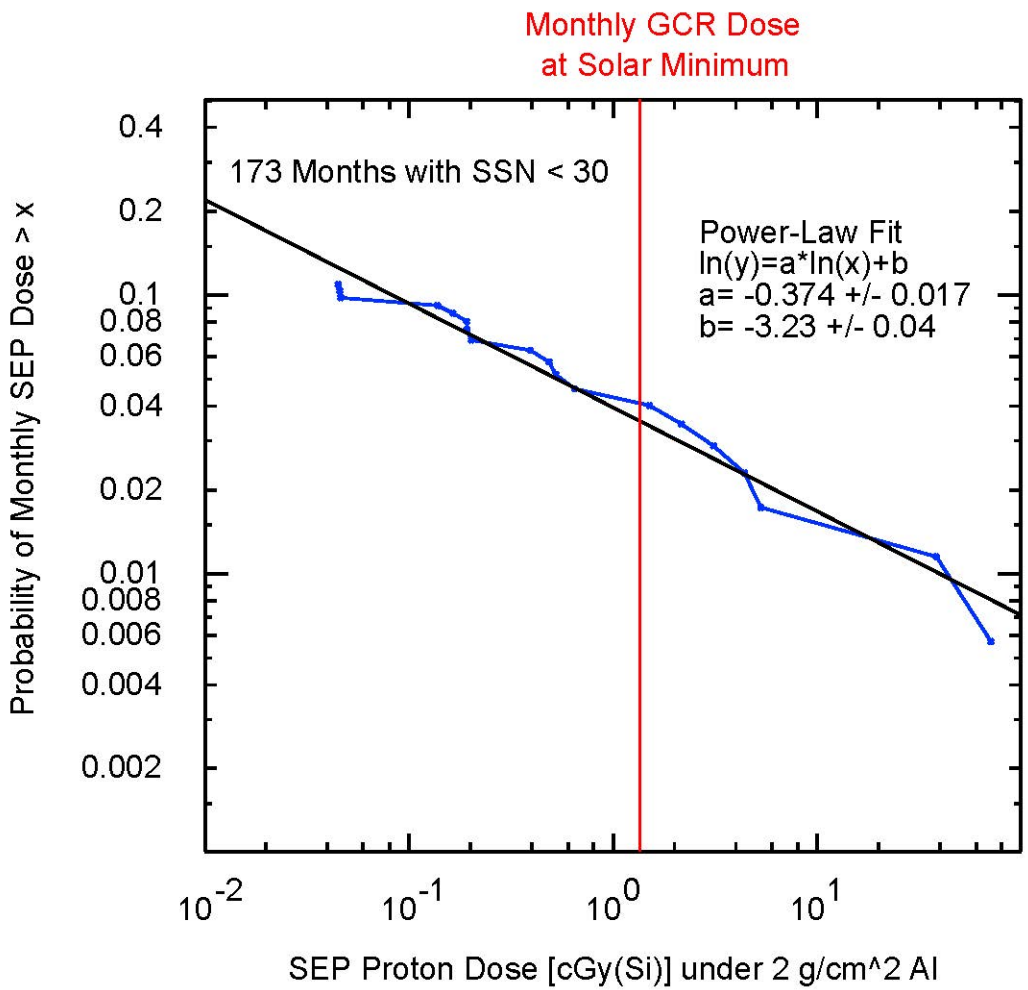






Solar Proton Events during Periods of Low Solar Activity

- Using NASA Langley's HZETRN code, we used these spectra to calculate dose-depth curves for these events.
- Results were binned into monthly dose values. Only 19 out of 173 months had measureable SEP-induced dose.
- We derived the dose probability distribution.
- The results are relevant for missions planned for the SSN < 30 timeframe.



Note: the biggest SEP events in the historical record have monthly dose values > 100 cGy(Si).

Solar Proton Events during Periods of Low Solar Activity

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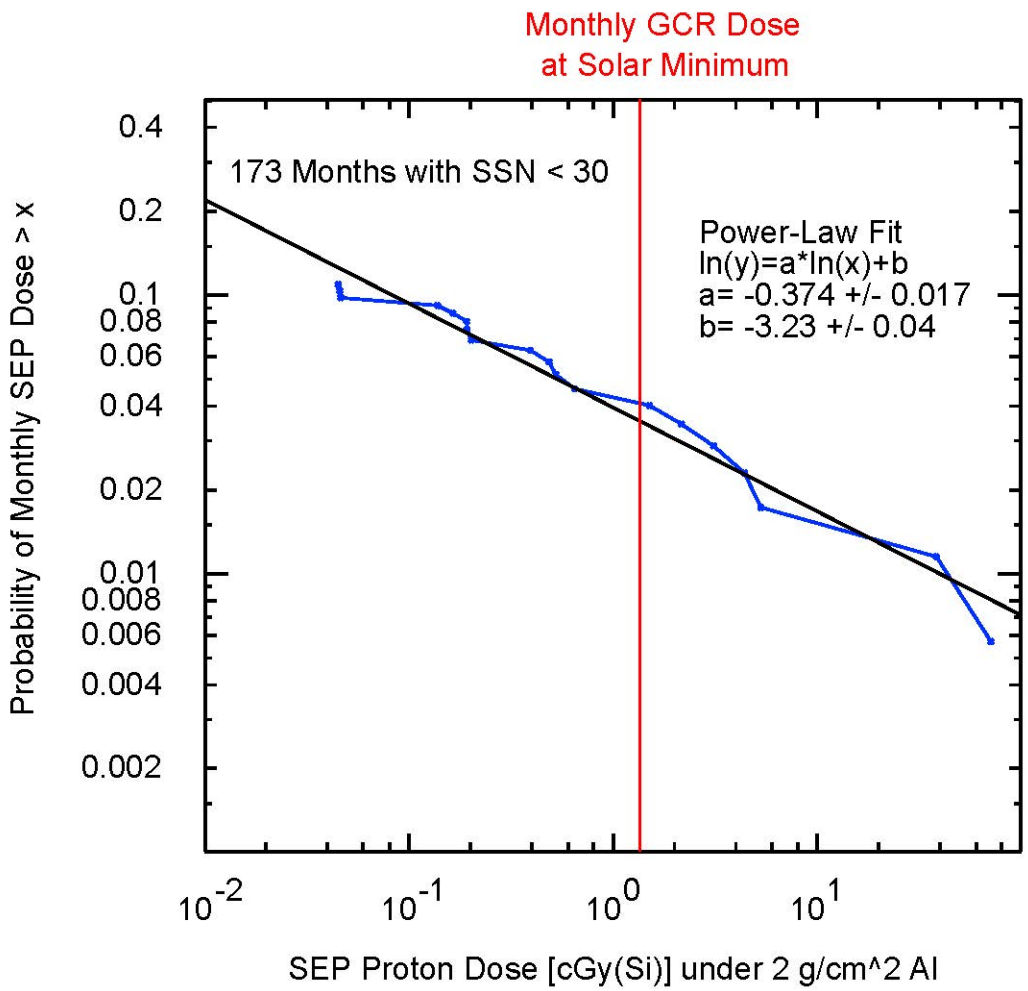
- Results were binned into monthly dose values Only 19 out of 173 months had measureable SEP-induced dose.
- We derived the dose probability distribution.
- The results are relevant for missions planned for the SSN < 30 timeframe.
- Future work: larger library of SEP spectra, for SSN < 50.
- The results will be potentially relevant for missions extending at least well into the next decade.



Note: the biggest SEP events in the historical record have monthly dose values > 100 cGy(Si).

Summary

- Compared to Solar Cycles 22 & 23, the SEP radiation hazard is reduced in Solar Cycle 24, at least over the first 7 years of the cycles:
  - The probability of encountering any given flux level is less.
  - The largest fluxes of previous Solar Cycles (top ~0.2%) are absent.
  - These statements are true at all energies relevant to space-system design.
  - Differences with Solar Cycles 20 and 21 are most apparent at very high energies (>500 MeV), as evidenced by Solar Cycle 24's relative dearth of GLEs.

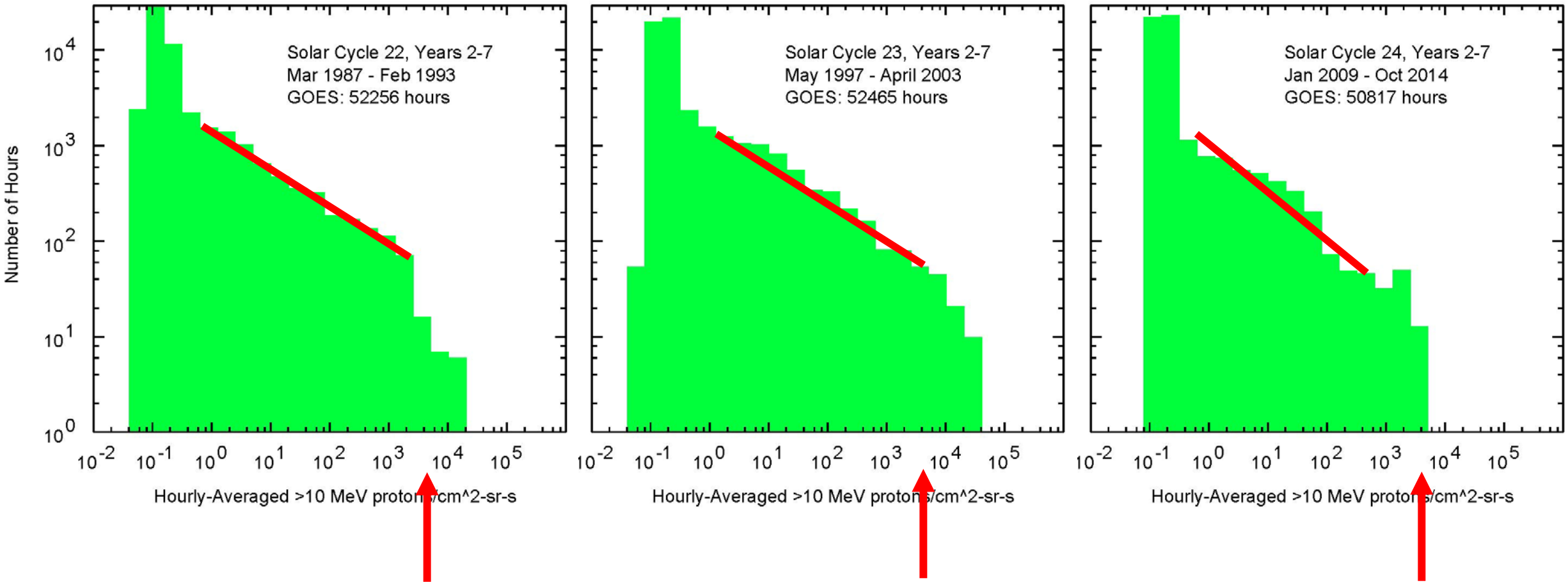
- IF Cycle 24 presages a new type of solar behavior, not seen before in the Space Age and that will continue for decades, the relative importance of the SEP radiation hazard will be reduced. (Note the 'big IF'.)

Implications

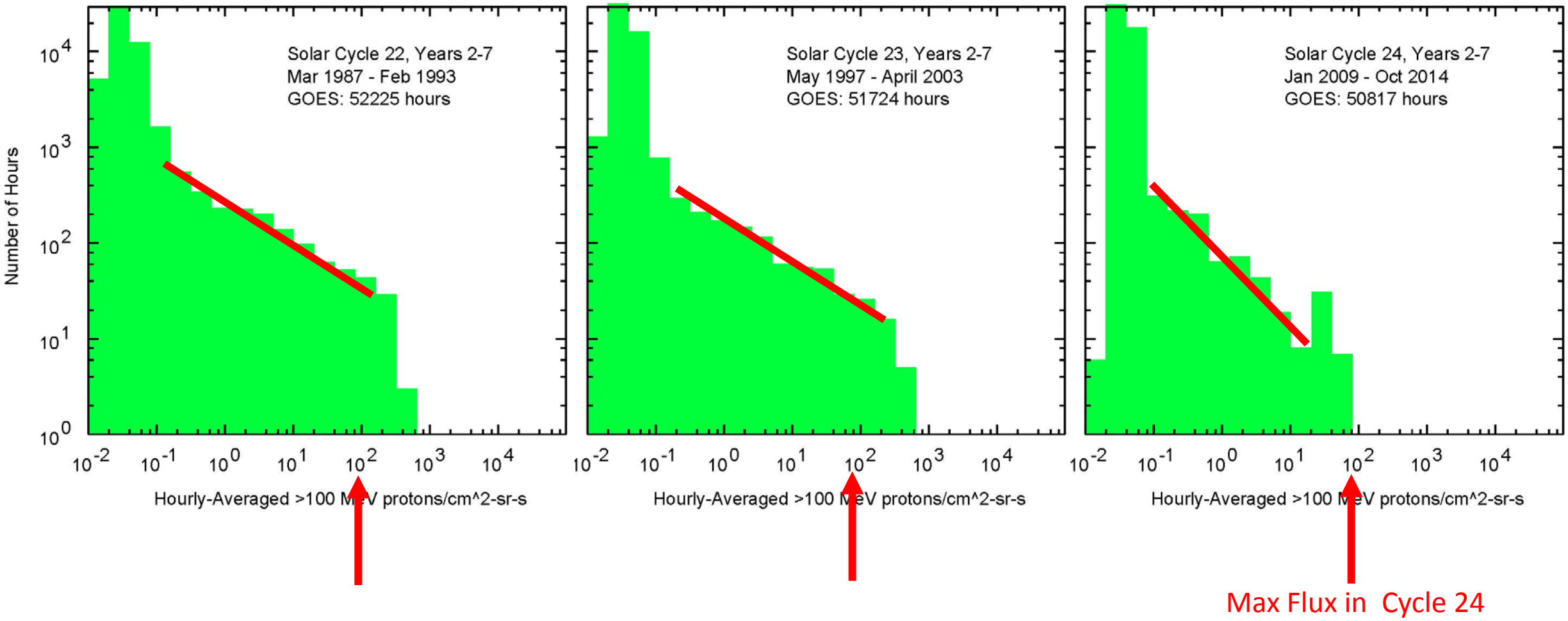
- ***For human exploration:*** these reductions in the SEP-radiation hazard, combined with the ***increase*** in the GCR-radiation hazard, suggest that solar maximum might present a better time-frame for long-duration human missions.
- ***For the robotic missions, with higher acceptable risk***: existing SEP radiation-hazard models, based on the very severe "worst-case" events observed in Cycles 19-23 are likely too conservative.
  - This concern is particularly acute for small, low-cost missions, where the spacecraft offers little inherent shielding and the budget does not support rad-hard parts.

Backups

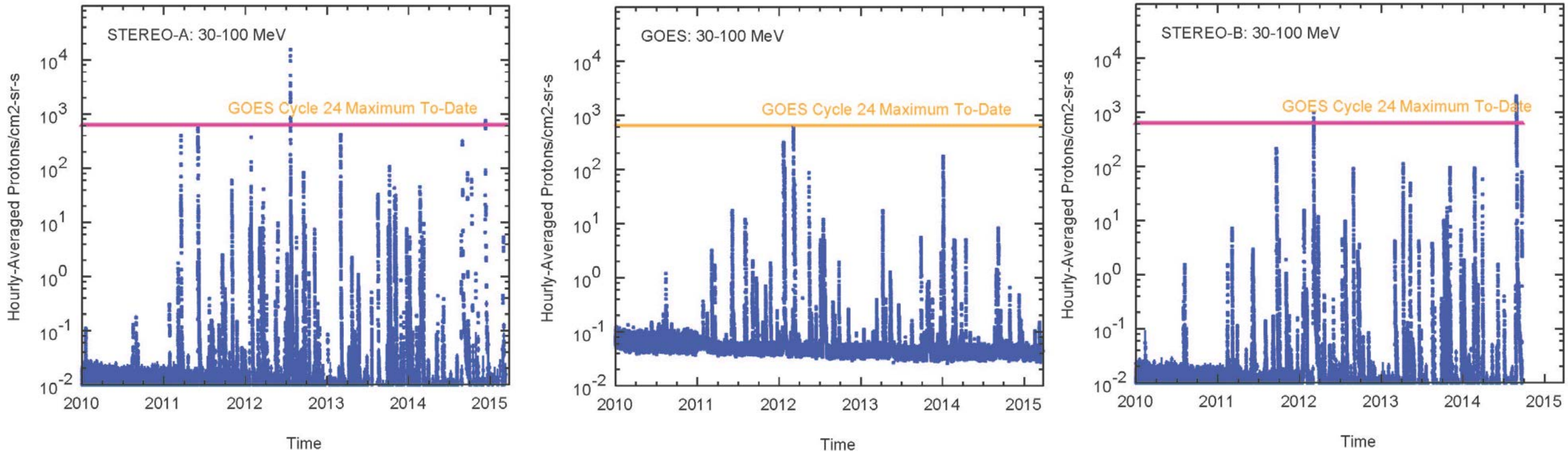
>10 MeV SEP Production in the Years 2-7 of the Solar Cycle
(Hourly-averaged fluxes in p/cm2-sr-s)



>100 MeV SEP Production in the Years 2-7 of the Solar Cycle
(Hourly-averaged fluxes in p/cm2-sr-s)



STEREO-A Observations of the 23 July 2012 Shock Event

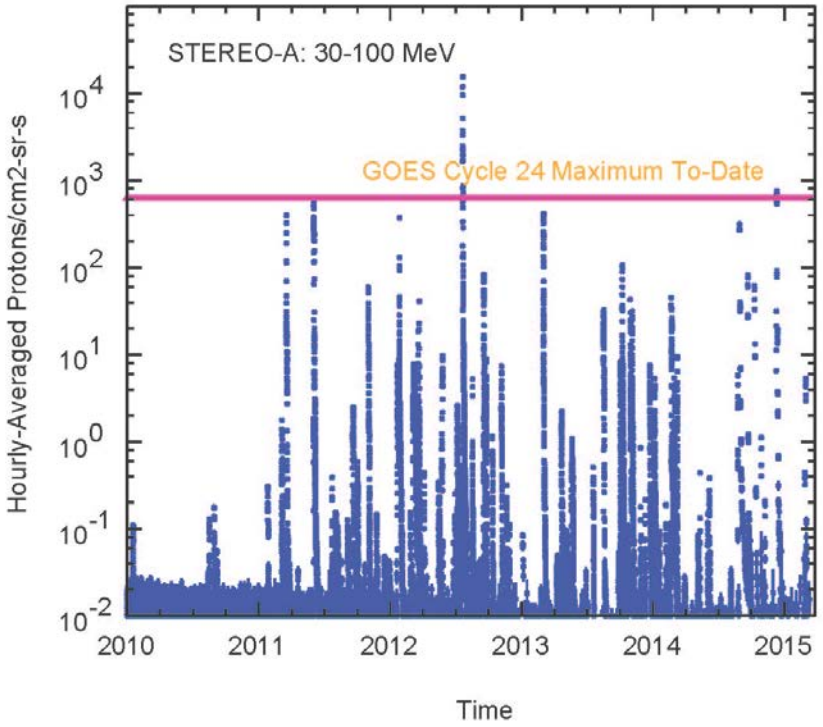


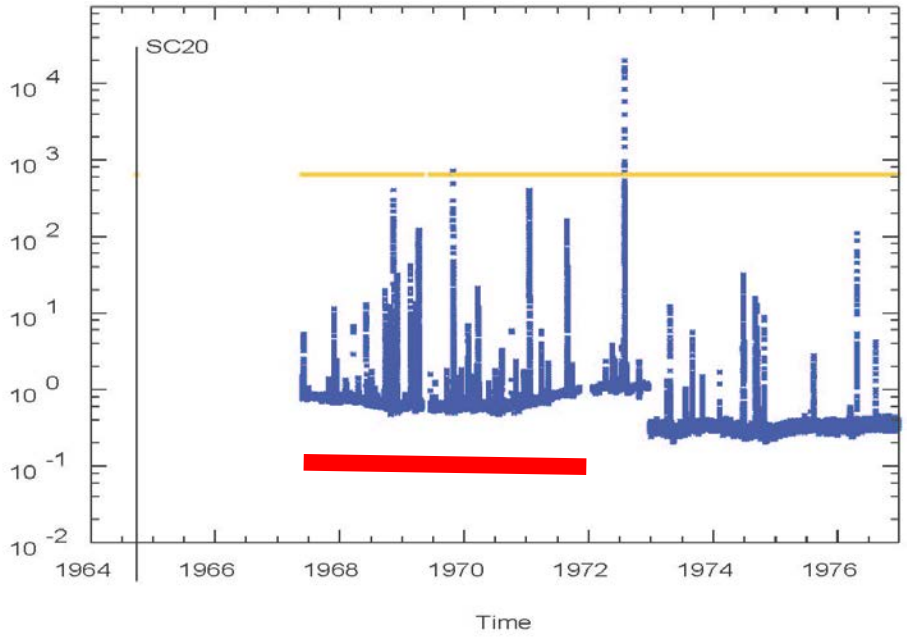
The July 23, 2012 shock event (Russell et al. ApJ 770:38, 2013) as observed at STEREO-A exceeded the maximum flux level seen so far in Cycle 24 at GOES.

However, STEREO-A exceeded the GOES/Cycle 24 maximum for only **13** hours. For comparison:
in the first 6-years of Cycle 22, the Cycle-24 maximum was exceeded for **73** hours.
In the first 6-years of Cycle 23, the Cycle-24 maximum was exceeded for **112** hours.

Even taking into account the STEREO-B observatons of 23 July 2012 event, Cycle 24 is still less hazardous than Cycles 22 & 23.

STEREO-A 23 July 2012 Shock Event vs. August 1972

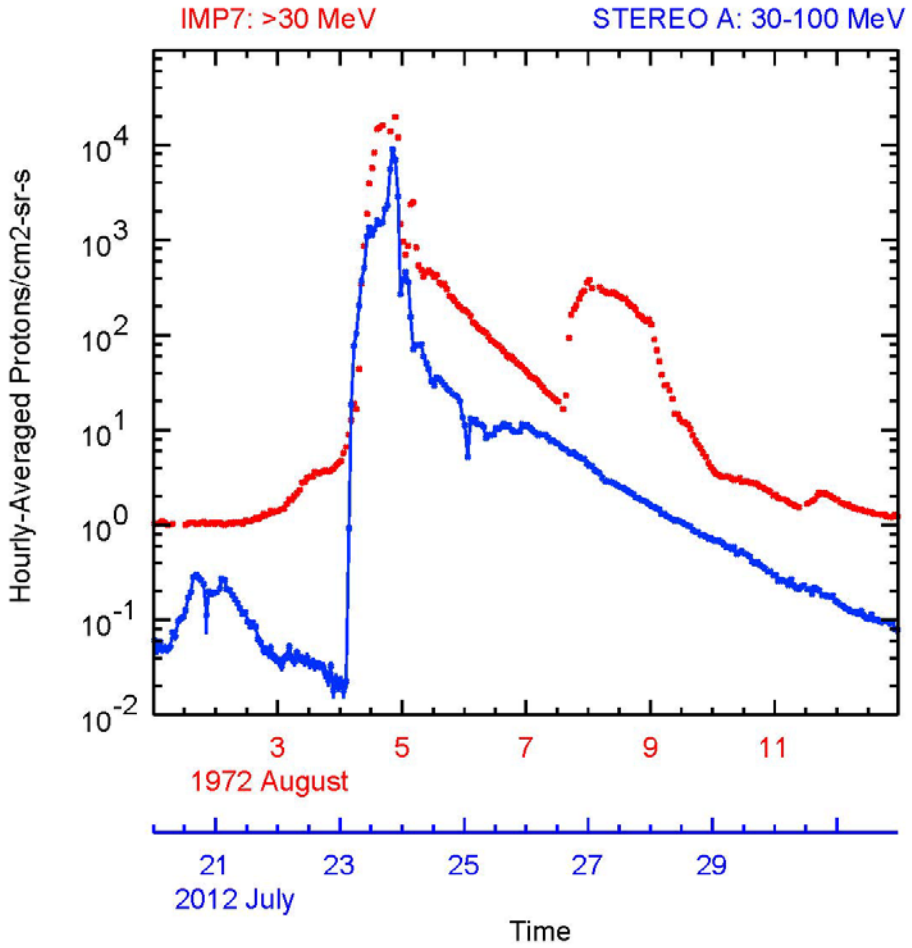




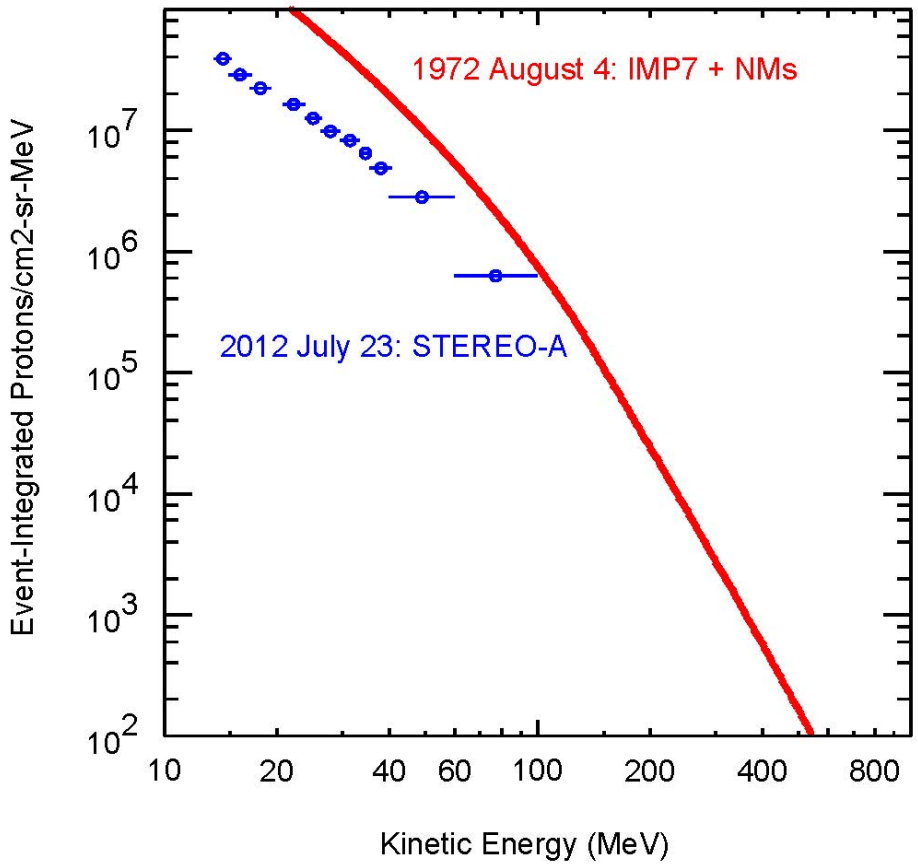
The July 2012 event (as observed at STEREO-A) is reminiscent of the the August 1972 events of Cycle 20. See the next slide for a more detaile comparison.

A More Detailed Comparison of 1972 August and 2012 July

Hour-by-hour Timelines at >30 MeV

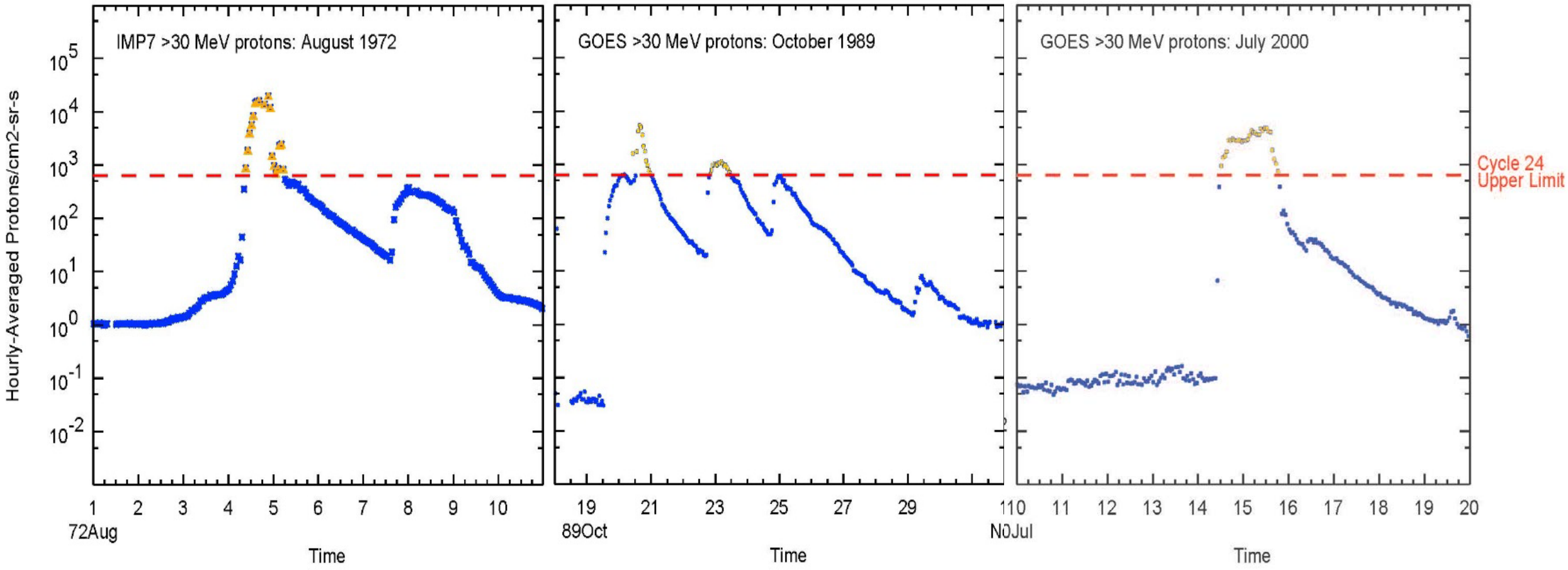


Event-Integrated Differential Proton Spectra



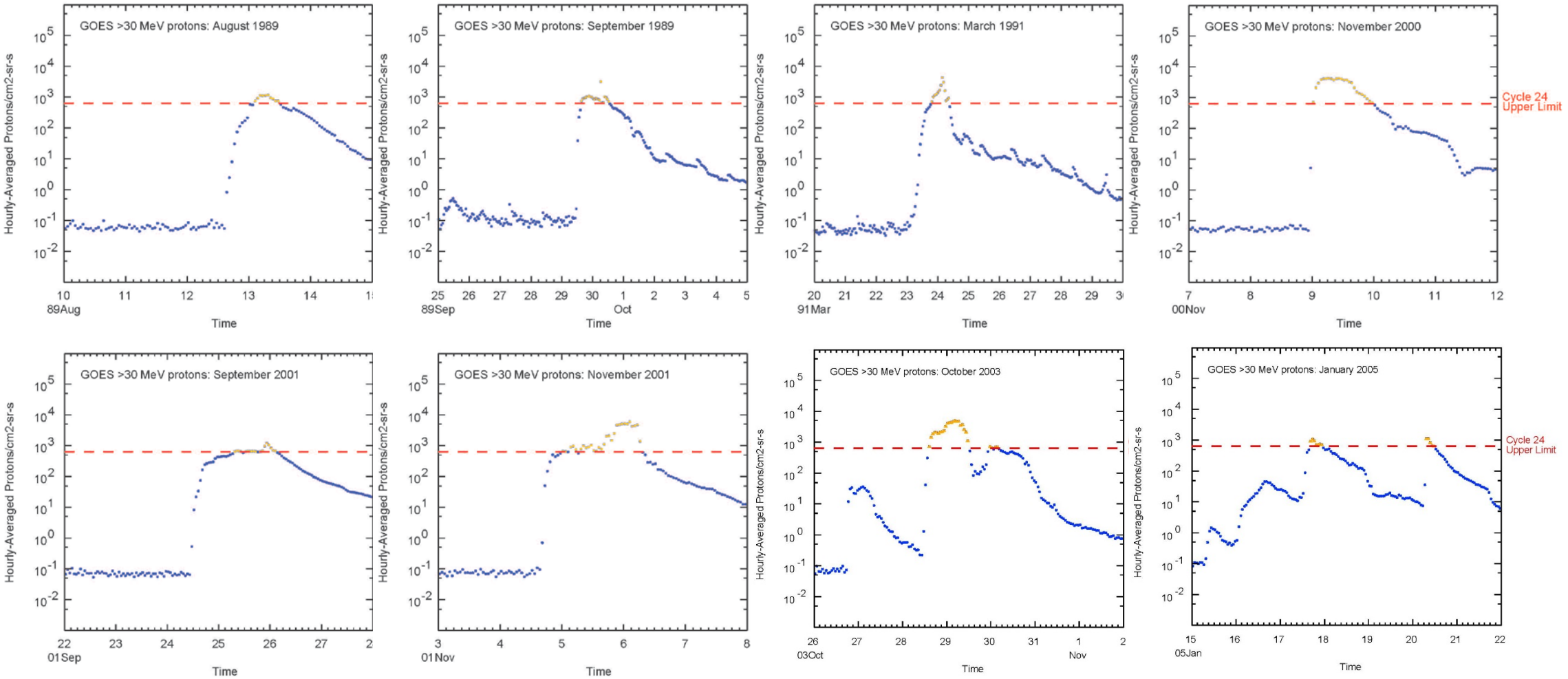
- Although superficially similar, 1972 August 04 had more hours with very high-intensity that 2012 July 23.
- 1972 August 04 was a GLE, as observed by terrestrial neutron monitors.
- However, STEREO-A provides no measurements above 100 MeV; hence we cannot say how the 2012 July 23 spectrum extended to higher energies.

Examples of "Big Hours": >30 MeV Intensity exceeds Cycle 24 Upper Limit

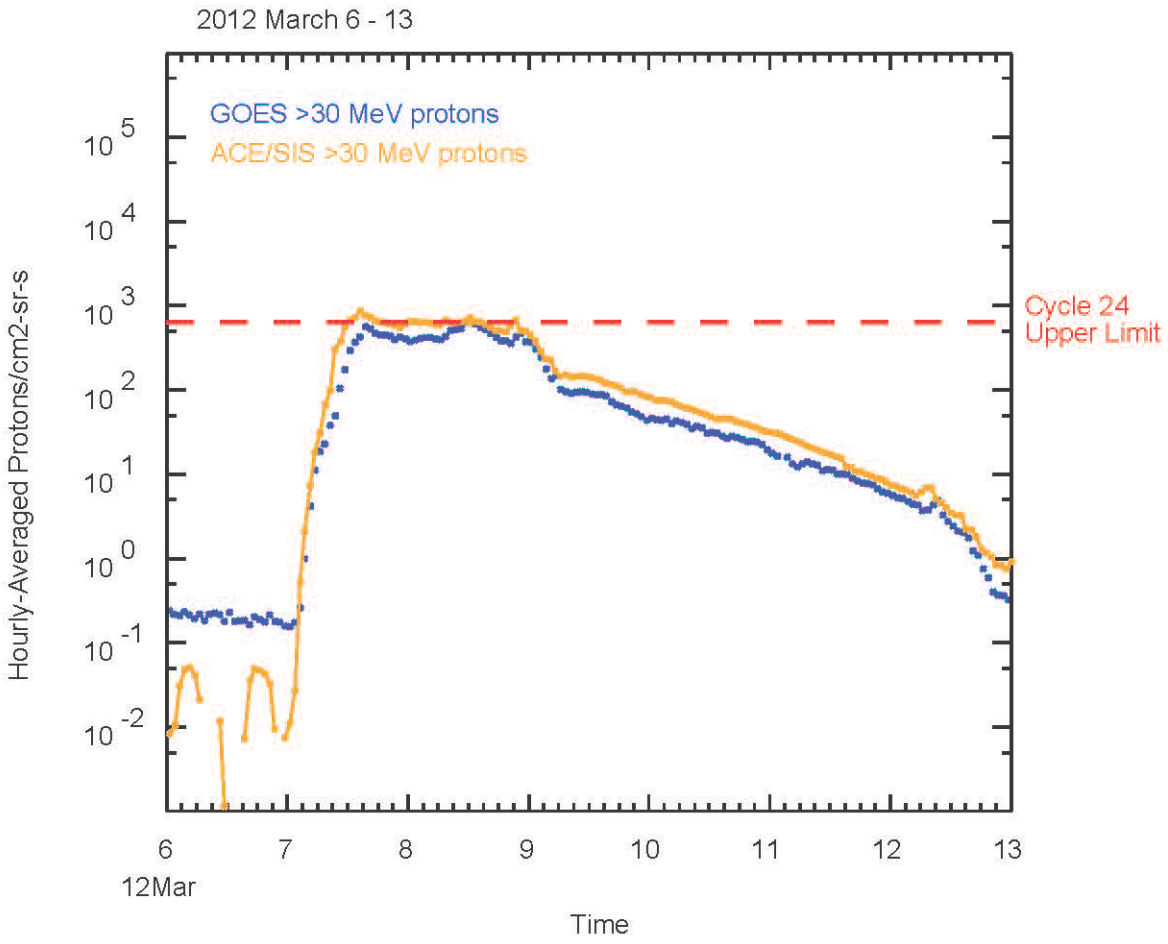


1. GOES can measure fluxes that are more than 10x greater than the maximum seen in Cycle 24. The Cycle 24 maximum is unlikely to be an instrumental artifact.
2. These 'severe hours' occur during events which are often used as "worst-case" SEP environments for design studies.
3. In some cases (like July 2000), the Cycle 24 upper limit is exceeded in less than 3 hours.

More Examples of "Big Hours": >30 MeV Intensity exceeds Cycle 24 Upper Limit



Highest >30 MeV Intensities seen in Solar Cycle 24



(GCR background has been subtracted.)

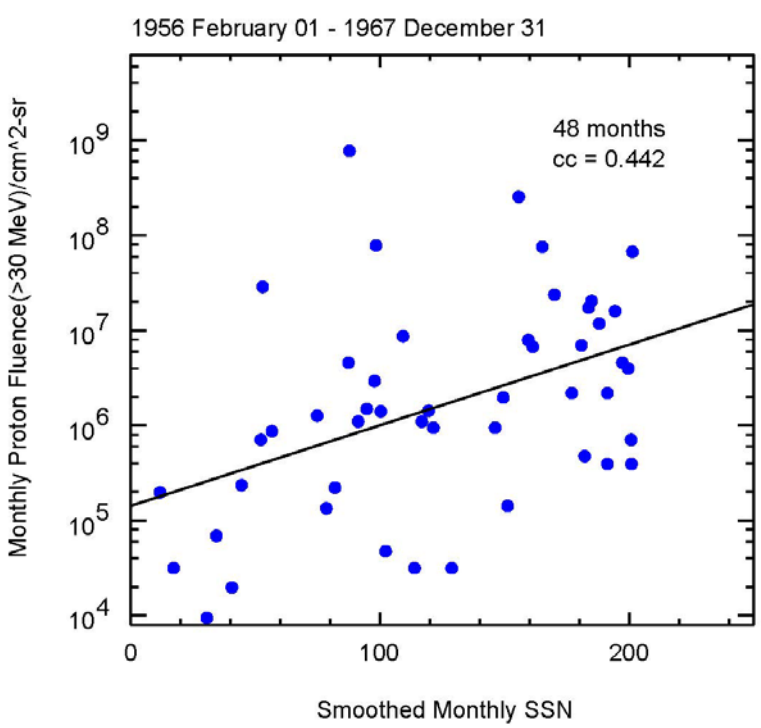
Could this be instrumental saturation? ***Very Unlikely:***

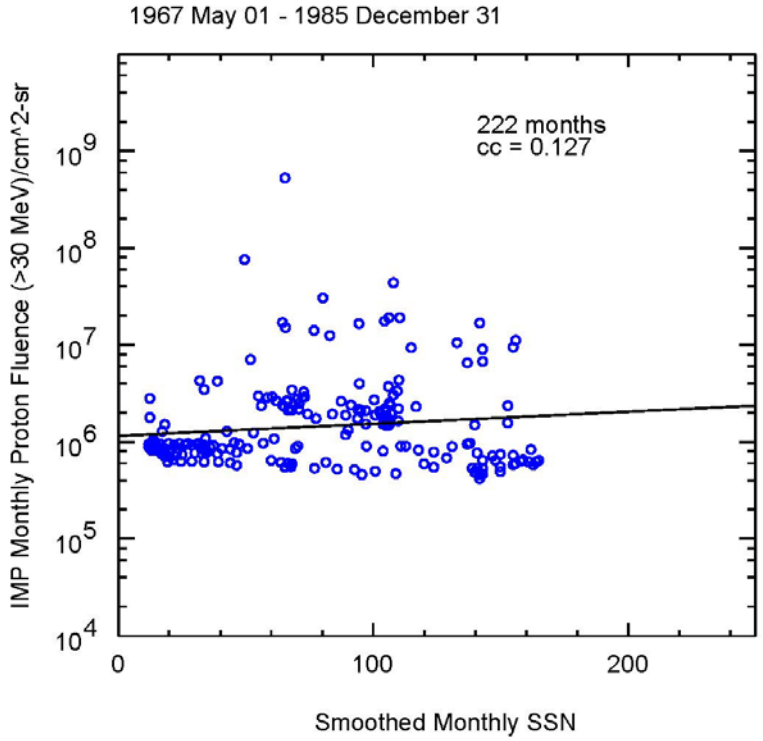
ACE/SIS intensities agree to within 30%

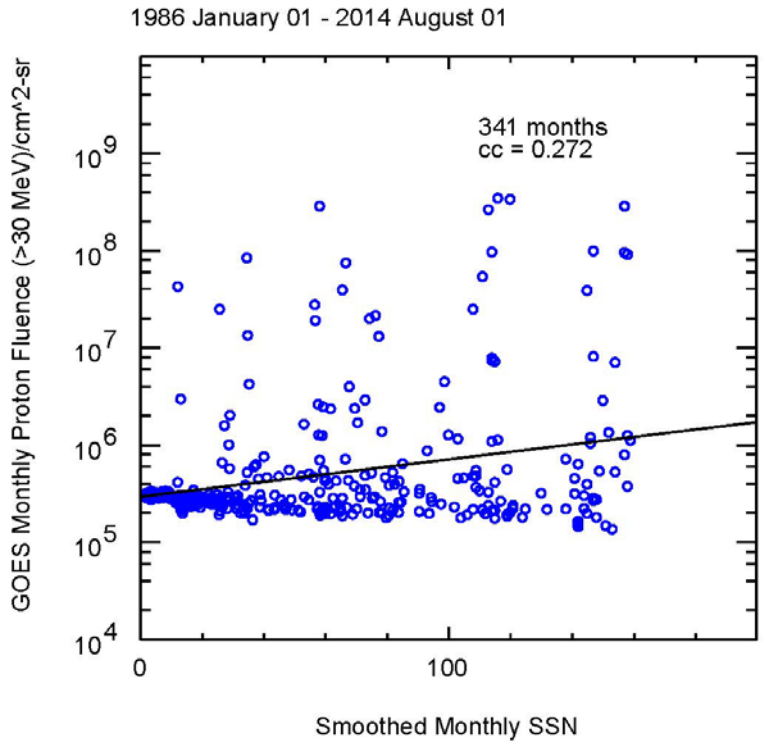
GOES design has demonstrated the ability to handle rates that are higher by at least a factor of 30.

ACE/GOES discrepancy to be investigated.

Monthly >30 MeV Proton Fluence vs. Smoothed Sunspot Number







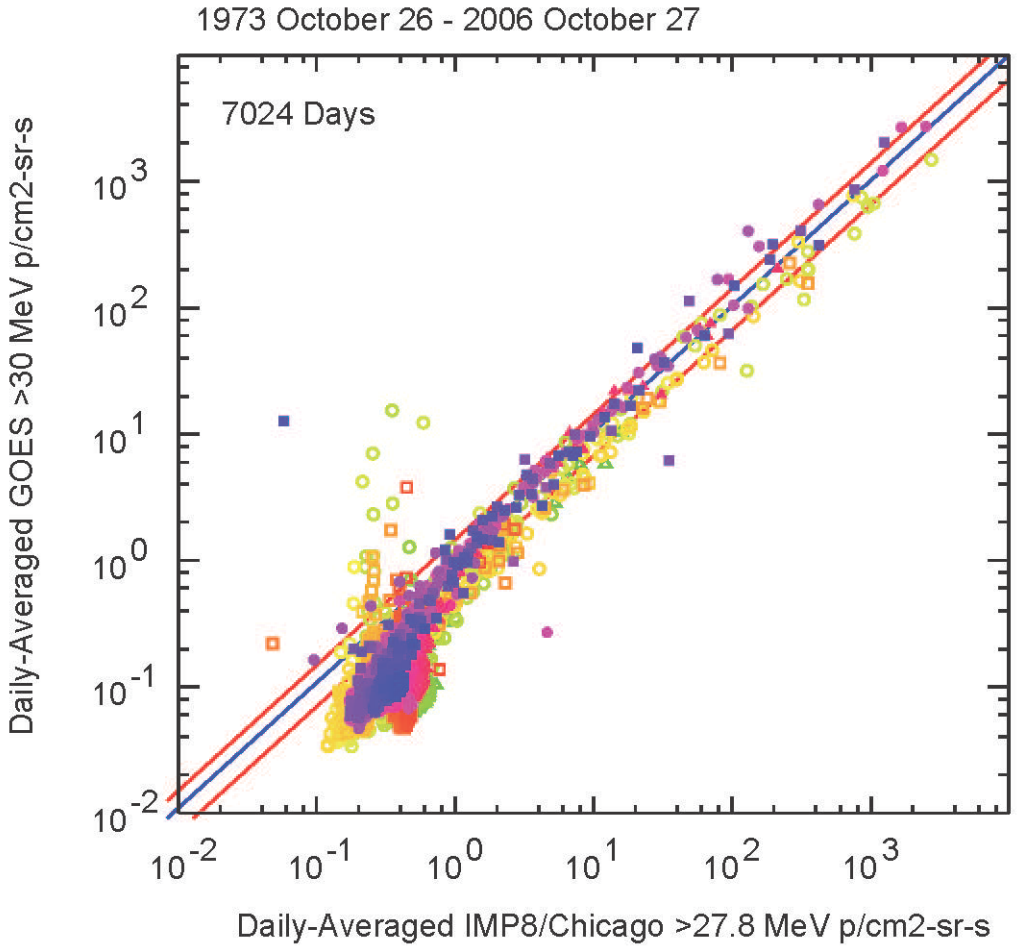
Numbers of SEP Events* in Solar Cycles 21 - 24

	Cycle 21		Cycle 22		Cycle 23		Cycle 24	
	Dates	# Events	Dates	# Events	Dates	# Events	Dates	# Events
Year 1	May 76-Apr 78	5	Mar 86-Feb 87	2	May 96-Apr 97	0	Jan 08-Dec 08	0
Year 2	May 77-Apr 78	5	Mar 87-Feb 88	2	May 97-Apr 98	3	Jan 09-Dec 09	0
Year 3	May 78-Apr 79	8	Mar 88-Feb 89	9	May 98-Apr 99	9	Jan 10-Dec 10	1
Year 4	May 79-Apr 80	6	Mar 89-Feb 90	22	May 99-Apr 00	5	Jan 11-Dec 11	7
Year 5	May 80-Apr 81	4	Mar 90-Feb 91	14	May 00-Apr 01	18	Jan 12-Dec 12	13
Year 6	May 81-Apr 82	8	Mar 91-Feb 92	16	May 01-Apr 02	24	Jan 13-Dec 13	7
Year 7	May 82-Apr 83	12	Mar 92-Feb 93	5	May 02-Apr 03	10	Jan 14-Dec 15	6
Sum		48		70		69		34
Year 8	May 83-Apr 84	6	Mar 93-Feb 94	3	May 03-Apr 04	10	Jan 15- Sep 15	3
Year 9	May 84-Apr 85	4	Mar 94-Feb 95	1	May 04-Apr 05	6		
Year 10	May 85-Feb 86	3	Mar 95-Feb 96	1	May 05-Apr 06	6		
Year 11	n/a	-	Mar 96-Apr 96	0	May 06-Apr 07	2		
Year 12	n/a		n/a		May 07-Dec 07	0		
Total		61		75		92		?

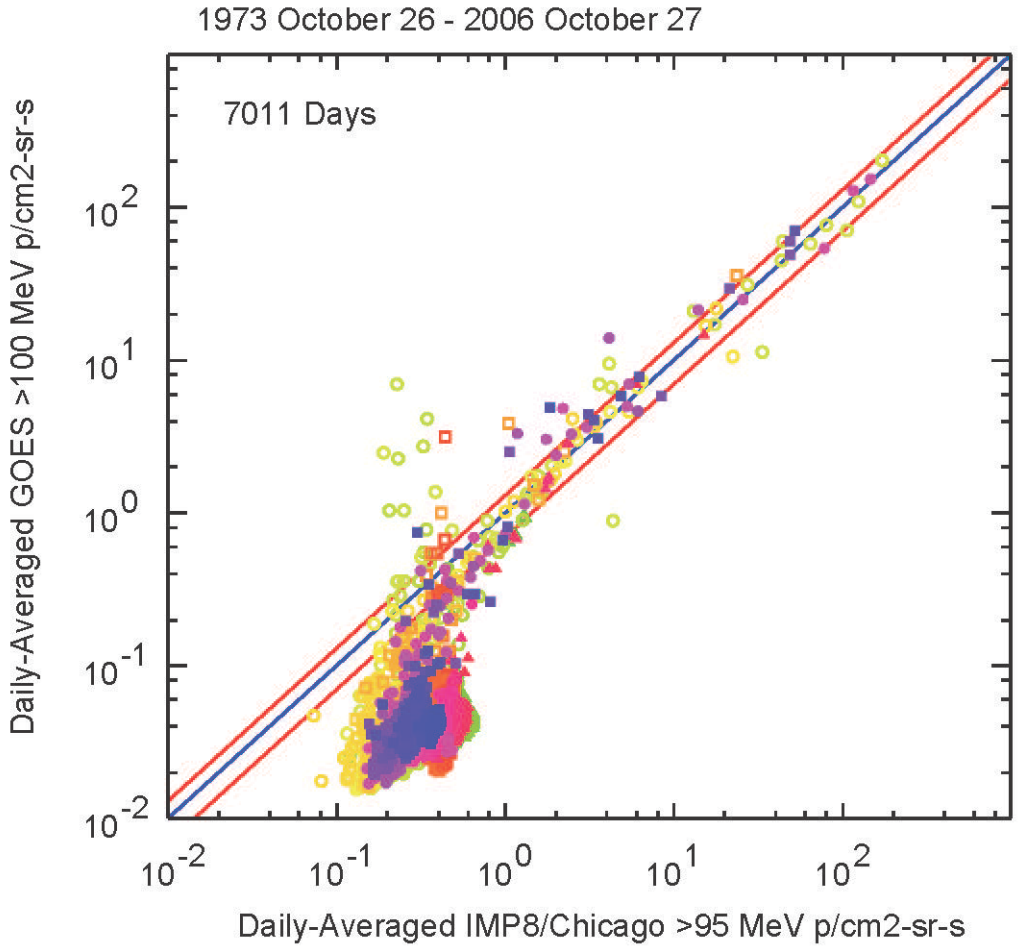
*An event starts with three consecutive 5-minute intervals with flux of $\geq$10 MeV protons exceeding 10 p/cm^2-sr-s and ends when with this flux is $\leq$ 10 p/cm^2-sr-s. Some GOES "events" therefore comprise multiple events.

GOES/IMP8 Cross-Calibration: Daily-Averaged Proton Intensities, 1973-2006

> 30 MeV

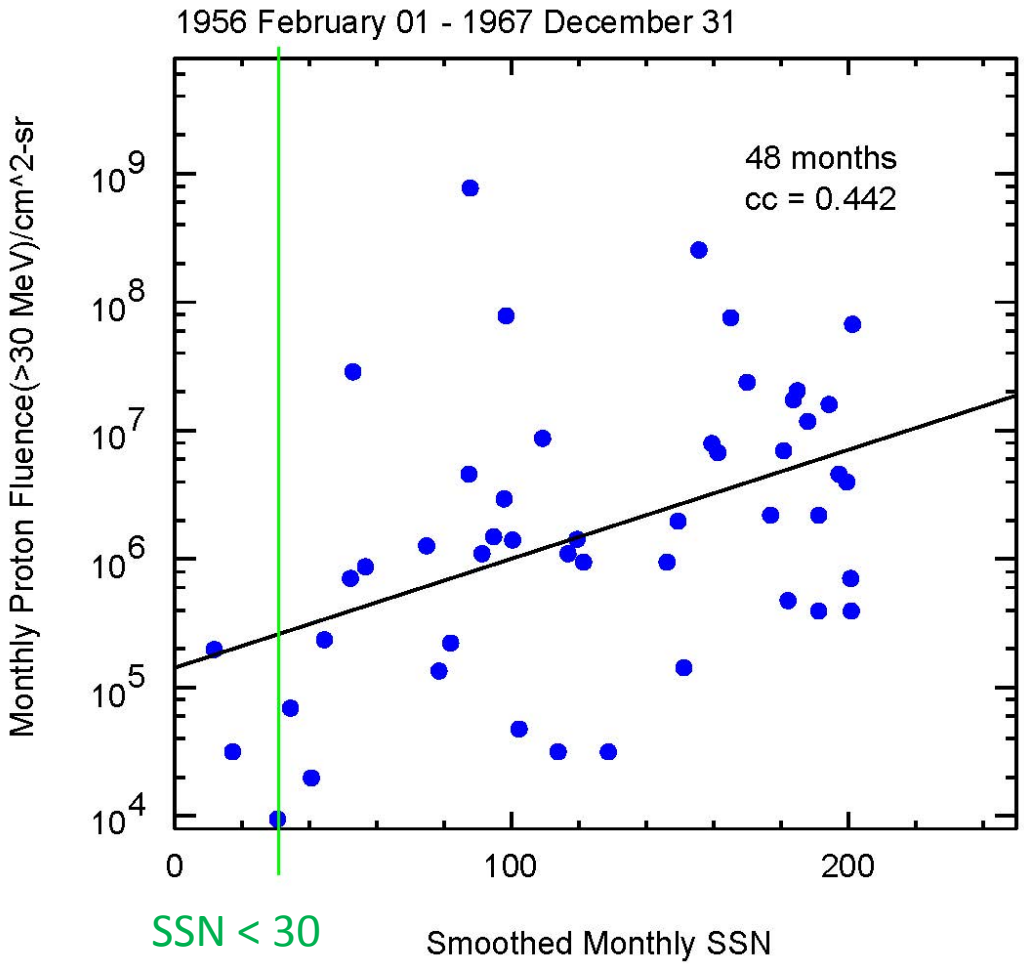


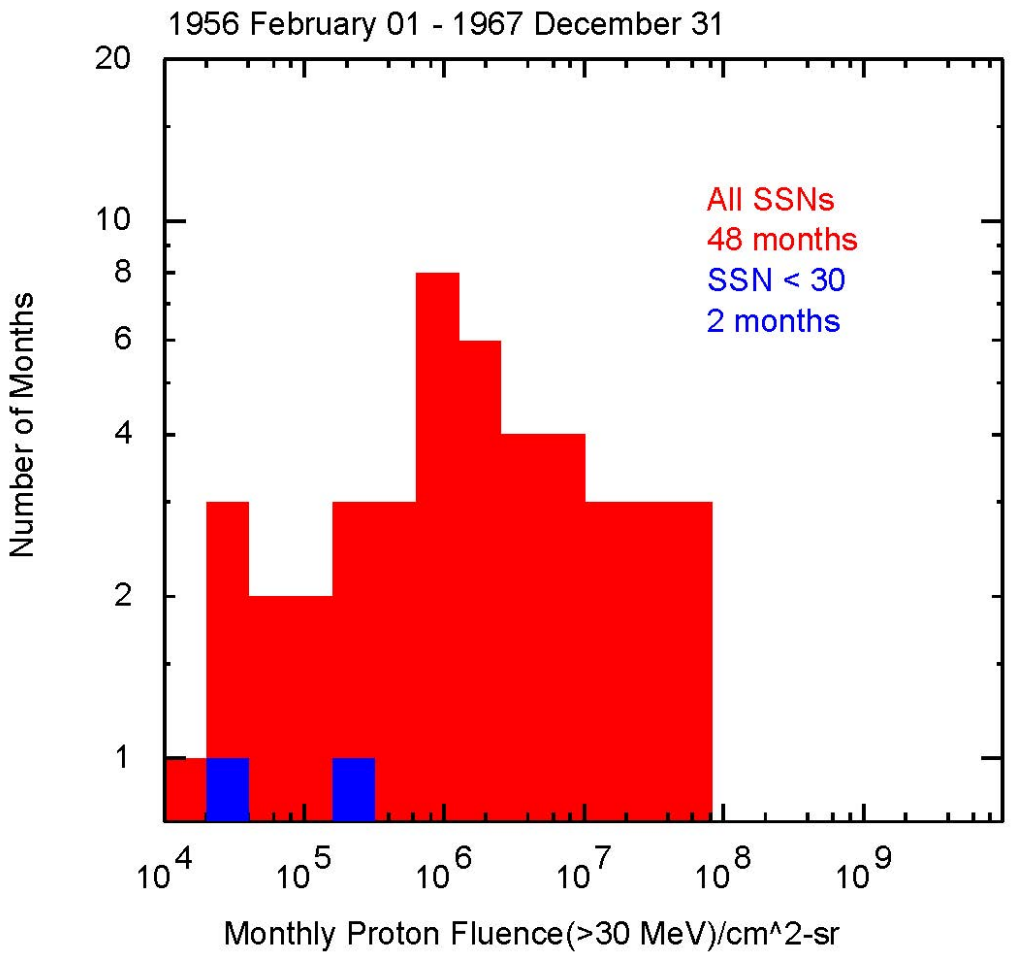
> 100 MeV



Blue diagonal line maps perfect agreement; red diagonal lines mark +/- 30% discrepancy.
Colors correspond to different dates.

From ground-based measurements and early spacecraft, 1956-1967 (from Feynman et al. 1988) :





This era had limited coverage and poor instrumental sensitivity. For that reason, there are no proton fluence measurements for months without a significant solar event. However, it is still relevant that no large monthly proton fluences are associated with SSN < 30.