Empirical SEP modeling: State of the field

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Empirical SEP forecasting models

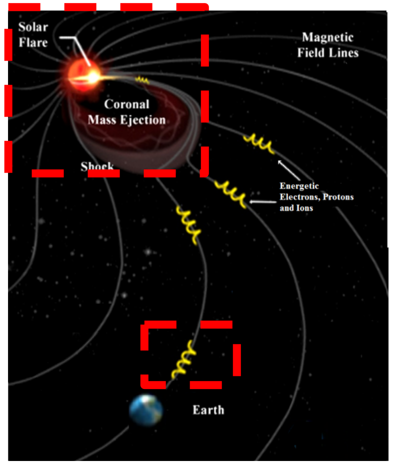
- Empirical models are approaches that use data to discover patterns or relationships among the parameters which in turn point to the underlying physical processes behind SEP generation.
- There are several ways to classify the empirical models. Here we classify these models in function of the *type* of observations:

a) Models that analyze solar data only
  - Remote sensing observations

b) Models that analyze near-Earth data only
  - In-situ particle observations

c) Models analyzing both solar and near-Earth data
  - Solar and in-situ particle data

d) Combination of the above model types



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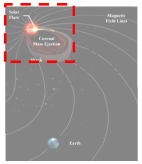
2. Models that use Near-Earth data only
3. Models that correlate Solar and Near-Earth data
4. Combination/Ensemble of model types



Models that analyze solar data only (I)

Empirical relationships: There is a close empirical relationship between flares and CMEs; and between these and SEPs. There is also an empirical relationship between Type II, III, IV radio bursts and SEPs.

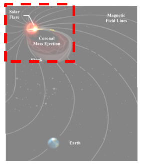
- SEP forecast probabilities from subgroups of flare/CME events

$$Prob_i = N_{i \rightarrow SEP} / N_i$$

where i is a subgroup of flare/CME events (e.g. X1-X3 flares occurred at W40-W70), N_i is the total number of solar events in the subset i, and $N_{i \rightarrow SEP}$ is the number of those events that resulted in an SEP event observation.

Condition to trigger a SEP event occurrence forecast:

- When the SEP event occurrence probability surpasses a threshold.



Models that analyze solar data only (II)

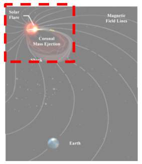
Input data:

- Soft X-ray data (peak and/or fluences)
- Radio data (metric Type II–IV bursts or fluences e.g. 1 MHz)
- Flare features (e.g. location)
- CME data (e.g. plane-of-sky speed and angular width)
- Solar magnetograms and other features→ flare forecast → SEPs

Output forecasts:

- SEP event occurrence probabilities and/or categorical predictions
- Other: SEP peak intensity/time, SEP fluence

Models that analyze solar data only (III)



- ESPERTA (Laurenza et al, 2009)

  Predicts >10 MeV SEP occurrence (S1 and S2 events)

  from ≥M2 flares (location), SXR & 1 MHz radio fluences.

SXR

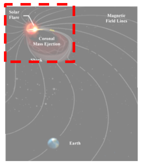
1 MHz radio

- **Technique:** Logistic regression

  $$Prob_i = f\,(\log(SXRfluence_i), \log\,(Radiofluence_i))$$

- **Output:** SEP occurrence if the estimated probability surpasses a threshold

  - if ≥M2 SXR and $Prob_i$ > threshold (e.g. > 28% for West), a S1 event is predicted
  - if an S1 is occurring and Prob surpasses a threshold, a S2 event is predicted



Models that analyze solar data only (III)

- ESPERTA (Laurenza et al, 2009)

  Predicts >10 MeV SEP occurrence (S1 and S2 events)
  from ≥M2 flares (location), SXR & 1 MHz radio fluences.

- PROTONS (Balch, 1999)

  Predicts >10 MeV SEP occurrence & peak
  from ≥C2.4 flares (peak, fluence, location), radio Type II/IV.

- PPS (Smart & Shea, 1989; Kahler et al., 2007)

  Predicts >5, >10, >50 MeV SEP occurrence &peak
  from ≥ M5 flares (peak, location), SXRs.

- COMESEP SEP tool (Dierckxsens et al., 2015)

  Predicts >10, >60 MeV SEP occurrence
  from ≥ M1 flares (peak, location) and/or CME data.

- FORSPEF (Papaioannou el al., 2018, Anastasiadis et al., 2017)

  Predicts >10, >30, >60, >100 MeV SEP occurence & fluence
  from flares (peak, location) or CACtus plane-of-sky CME data.

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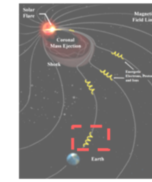


Models that analyze near-Earth data only (I)

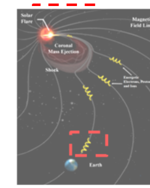
Empirical relationships:

- Prediction of short-term proton/ion intensity from near-relativistic electrons (rise and current fluxes), given the fact that relativistic electrons arrive first than protons in an SEP event;
- Prediction of mid-term integral proton fluxes from empirical formulae on historic proton time series analysis

Condition to trigger an SEP event occurrence forecast:

- When the predicted proton intensity surpasses a threshold

Models that analyze near-Earth data only (II)



Input data:

- Electrons (current flux, flux rise)
- Protons (current/recent flux)

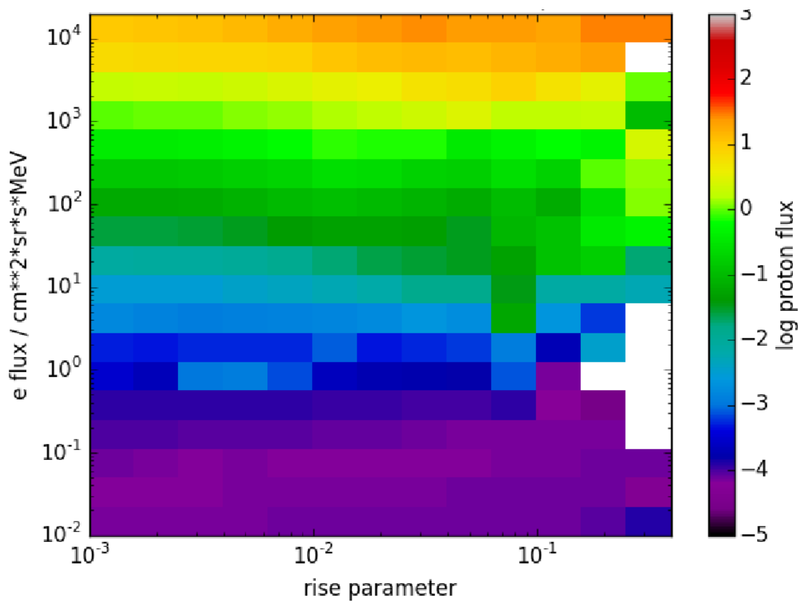
Output:

- Predicted proton flux

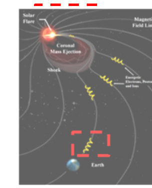
RELeASE (Posner, 2007)

Predicts 30-50 MeV proton flux from near-relativistic electrons: ACE/EPAM or SOHO/EPHIN

RELeASE
1-h forecast matrix



Models that analyze near-Earth data only (II)



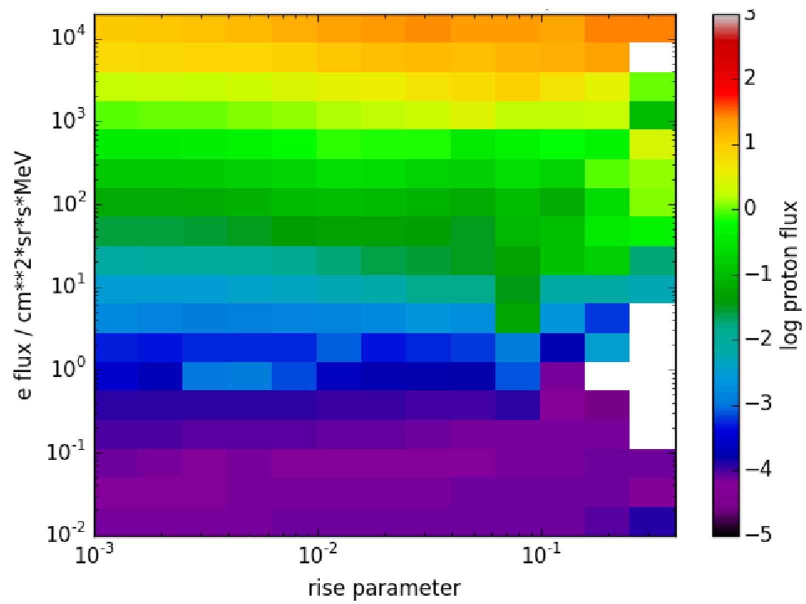
Input data:

- Electrons (current flux, flux rise)
- Protons (current/recent flux)

Output:

- Predicted proton flux

RELeASE
1-h forecast matrix



RELeASE (Posner, 2007)

Predicts 30-50 MeV proton flux from near-relativistic electrons: ACE/EPAM or SOHO/EPHIN

Poorly-Connected Prediction (PCP) Model (Núñez, 2011)

Predicts very gradual >10 MeV proton flux in the UMASEP-10 tool from GOES proton fluxes (only)

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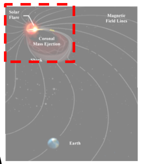


Empirical relationships:

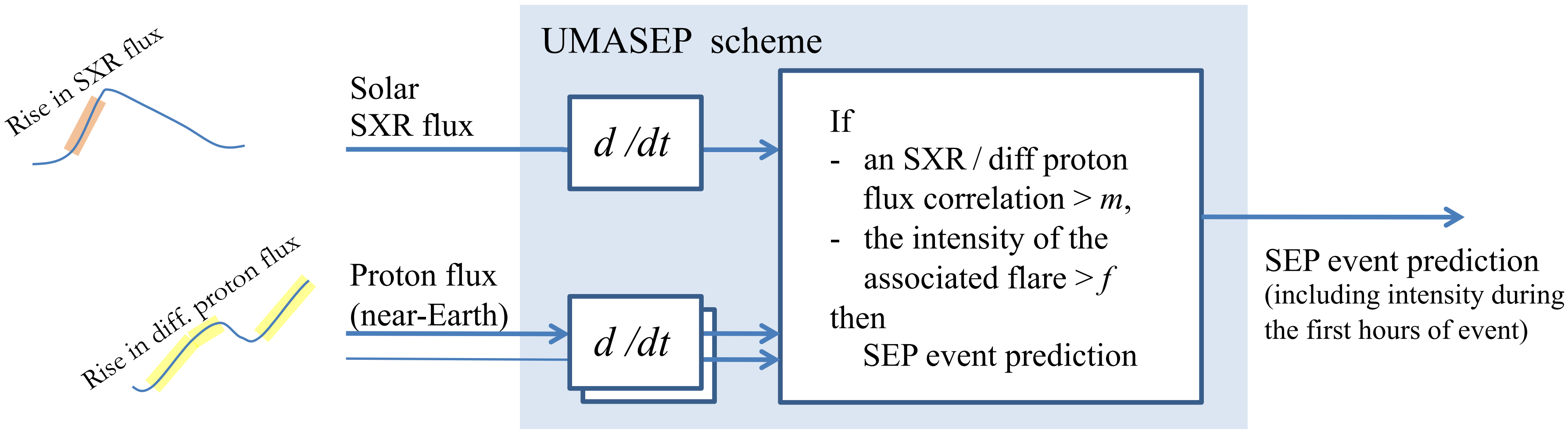
- The correlated occurrence of a rise in SXRs and a rise in a differential proton flux is an evidence that the region of the solar energy release and the S/C are magnetically connected.
  - If a magnetic connection is inferred, and the associated flare is large enough, the tool predicts the proton flux of the next few hours.

- Machine learning from time series of proton and SXR fluxes, and the subsequent SEP occurrence/nonoccurrences

Models that analyze solar and near-Earth data (III)

- Well-Connected Pred (WCP) (Núñez, 2011, 2015; Núñez et al., 2017)

  Real-time prediction of SEP occurrence & intensity from SXRs and protons



Models that analyze solar and near-Earth data (III)

- Well-Connected Pred (WCP) (Núñez, 2011, 2015; Núñez et al., 2017)

  Real-time prediction of SEP occurrence & intensity from SXRs and protons

Real-time Tool	Integral Proton Flux Forecasted	Flare Class to Trigger Forecasts	Cadence of Forecast Outputs	Intensity Forecasts
WCP_{10} in UMASEP-10	>10 MeV	>C4 flares	5 min (since 2010, iSWA)	First 7 hours
WCP_{100} (UMASEP-100)	>100 MeV	>M3.5 flares	5 min (since 2012)	First 3 hours
WCP_{500} (HESPERIA UMASEP-500)	>500 MeV GLE events	>M4.7 flares	1 min (since 2017)	First hour

- Machine-Learning-based model (Boubrahimi et al., 2017)

  Predicts >100 MeV SEP occurrence from SXRs and protons

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Combination/ensemble of model types

The previous models/tools make predictions using the same model *type* (*e.g.* solar- or particle-data-based). The use of several model types is also possible:

- SPRINTS tool (Ergell et al., 2017) integrates:
  - Pre-eruptive data and forecasts from the MAG4 system
  - Post-eruptive data to produce forecasts for: Flares, SEPs, CMEs, HSSs
  - Uses GOES X-ray and particle data (ACE and DSCOVR)
  - Uses machine-learning techniques to make predictions
- UMASEP-10 tool (Núñez, 2011) integrates:
  - Proton data only to predict poorly-connected >10 MeV events (PCP model)
  - Correlates solar and proton data to predict well-connected >10 MeV events

And the future? We could combine empirical and physics-based models:

E.g. SEP occurrence & short-term <u>proton fluxes</u> could be predicted by empirical models, and the time profile (e.g. peak/end <u>times</u>) by physics-based models.

Thank you!

Real-time UMASEP predictions during July and September 2017

The UMASEP scheme

- UMASEP is a scheme that is used in several tools. All these tools share the same Well-Connected Prediction (WCP) model:
  - The UMASEP/WCP model assumes that the correlated occurrence of a rise in SXRs and a rise in a differential proton flux is an evidence that the region of the solar energy release and the S/C are magnetically connected.
  - If a magnetic connection is inferred, and the associated flare is large enough, the tool predicts the proton flux of the next few hours.
- Main characteristics of the UMASEP-based tools:

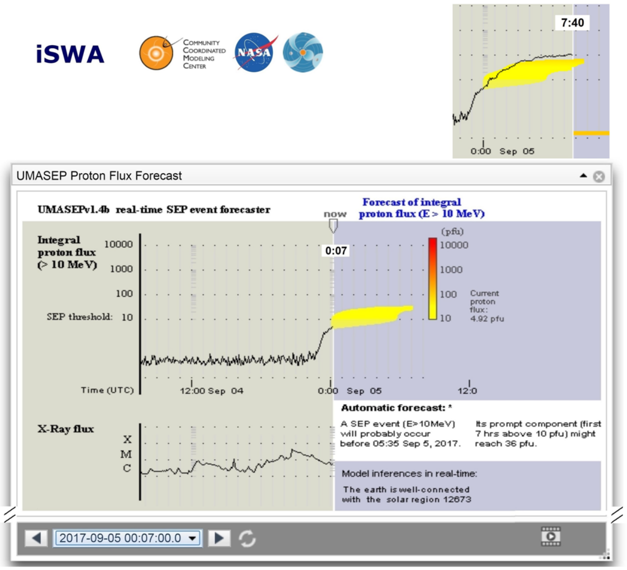
Real-time Tool	Integral Proton Flux Forecasted	Flare Class to Trigger Forecasts	Cadence of Forecast Outputs	Intensity Forecasts
UMASEP-10	>10 MeV	>C4 flares	5 min	First 7 hours
UMASEP-100	>100 MeV	>M3.5 flares	5 min	First 3 hours
HESPERIA UMASEP-500	>500 MeV GLE events	>M4.7 flares	1 min	First hour

- During July-September, 2017, these tools were functioning in real-time. UMASEP-10 predictions were recorded in NASA/iSWA.

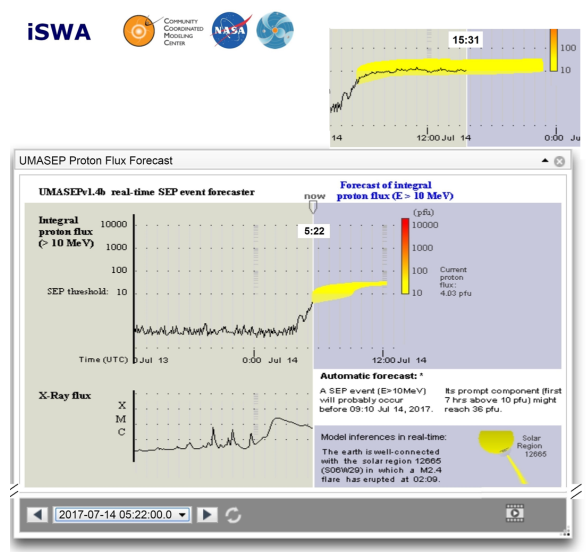
Real-time forecasts of the UMASEP-based tools for the events on July 14 and September 5, 2017

UMASEP-10 predictions recorded by NASA/iSWA:

July 14



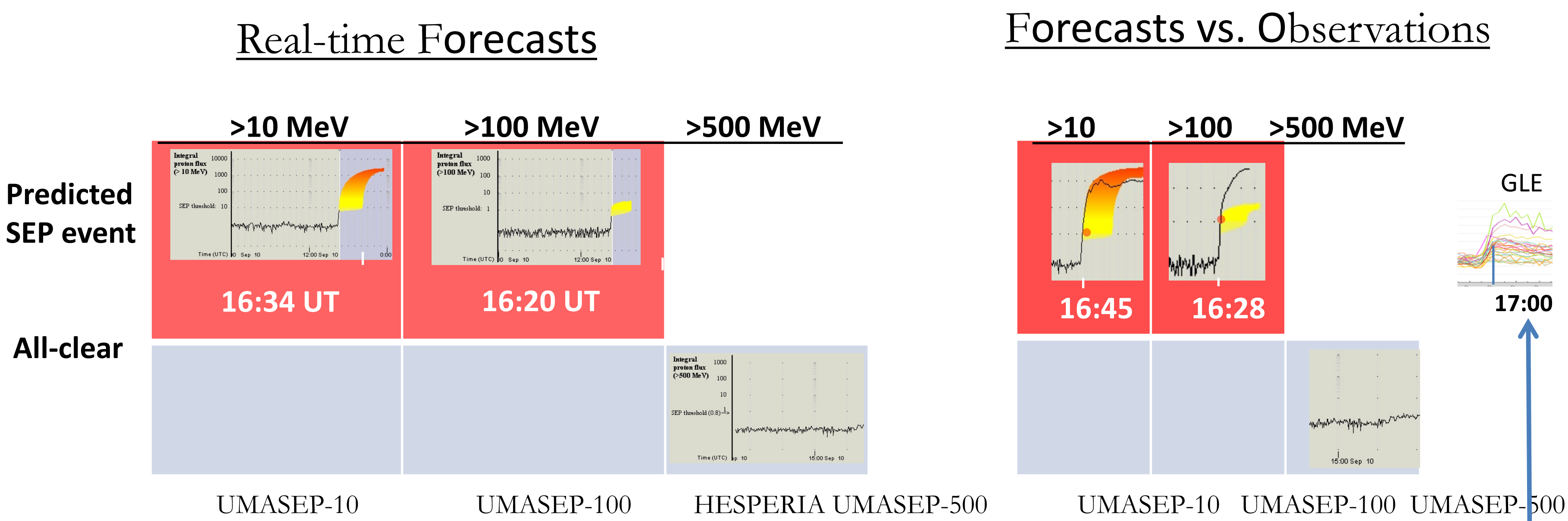
September 5



UMASEP-100 and HESPERIA UMASEP-500:

During July 14 and September 5, no >100 MeV / >500 MeV events took place; UMASEP-100 and HESPERIA UMASEP-500 successfully issued "all-clear" forecasts.

Real-time forecasts of UMASEP-based tools for the event on September 10, 2017



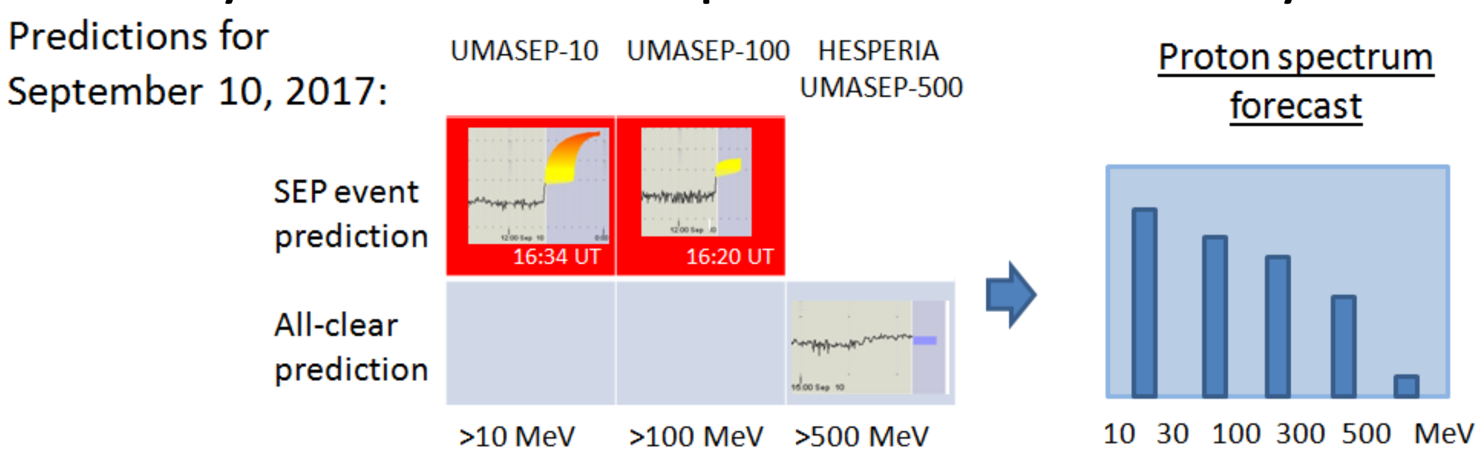
- On September 10, no >500 MeV SEP event took place (the proton flux did not surpass 0.8 pfu, established in the H2020 European HESPERIA project using GOES HEPAD data of 1986-2016); however, a faint GLE took place.
- HESPERIA UMASEP-500 successfully predicted "all-clear" >500 MeV fluxes; however, it missed the GLE event.

Summary of the real-time forecasting performance

Date	Event	Tool	Prediction Result	Warning Time	Error of the Forecasted Intensities (log-10 scale of pfu)
14 July 2017	>10 MeV	UMASEP-10	Hit	3 h 38 min	0.53
5 September 2017	>10 MeV	UMASEP-10	Hit	33 min	-0.44
10 September 2017	>10 MeV	UMASEP-10	Hit	11 min	0.48
	>100 MeV	UMASEP-100	Hit	8 min	1.3
	GLE	HESPERIA UMASEP-500	Miss	-	-

Discussion questions

- How did your optimized run results differ from the initial run?
  - The predictions were issued in real-time; therefore, there was no optimization for the July-September events.
- What aspects of the event does your model capture well, and what aspects were more difficult to capture?
  - This system does not predict the intensity-time
- W



Back-up slides

PROTONS (Balch, 1999)

- The events such that flare >C2.4 and integratedSXR>0.01 were classified into groups according to:
  - 5 possible ranges of integrated flux,
  - 5 possible ranges of maximum flux, and
  - 4 possible values for the radio sweep observations.
- 100 combinations into which proton events and non-sep events were subdivided. Then the probability is estimated accordingly. That is:

For example for Solar events:

SXR peak = X1-X3

integratedSXR= 0.1-0.2 joules m^{-2}

Type II took palce & no Type IV took place

At Earth → 15 SEPs took place and 5 no-SEPs

The forecast approach is: If a future solar event meets this condition, then:

Probability that an SEP takes place will be 15/ (15+5) = 75%

And SEPpeakTime = *flarePeakTime* + empirical$f$ (*flareLongitude*)

Calibration parameter: a probability thhreshold

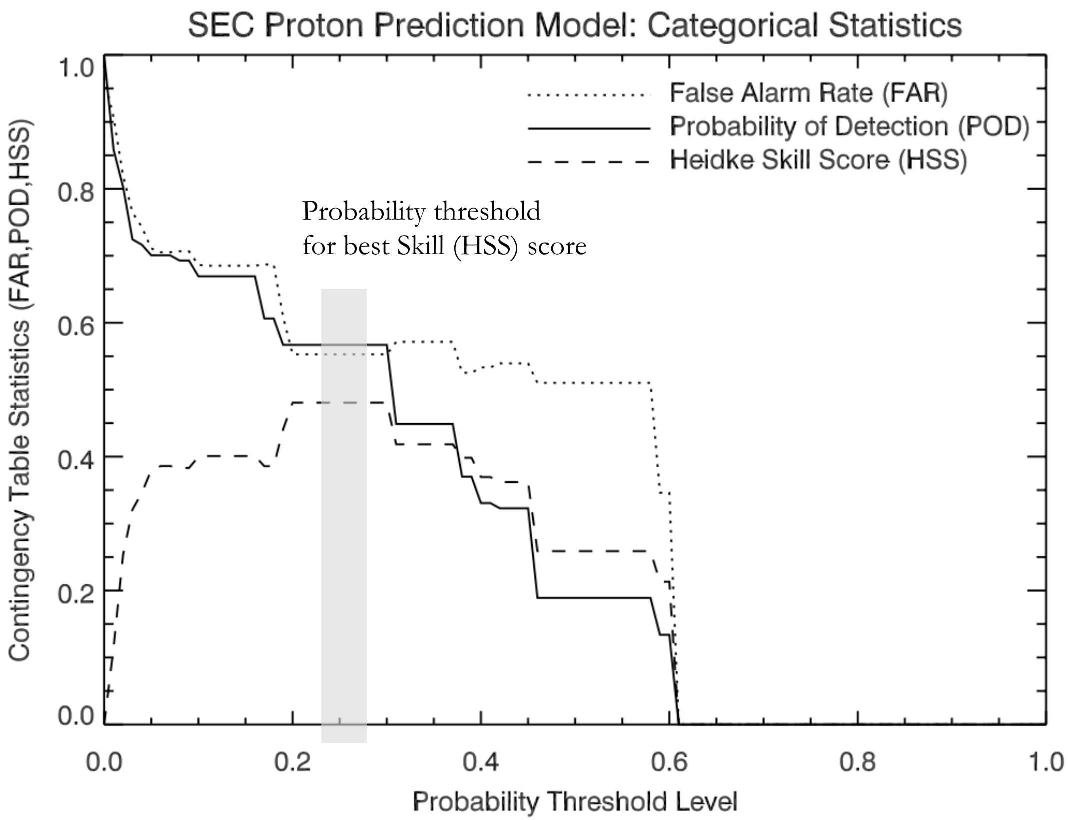


Figure 2. Categorical performance statistics for the proton prediction model as a function of probability thresholds.

We see that the optimal skill score (using $\breve{HSS}$) is achieved for the range of probabilities from 20 to 30%. We also note that at the optimal point, the probability of detection is 57% (72/127), the false alarm rate is 55% (89/161)

A calibration parameter: a SXR fluence

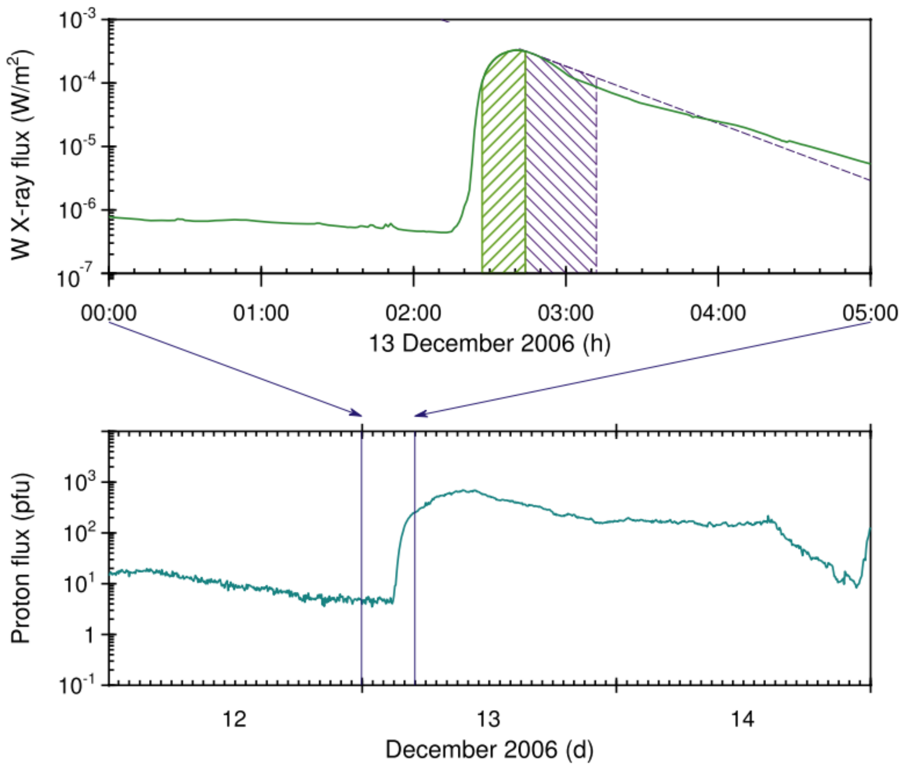


Figure 2. Key parameters for the 2006 December 13 SEP event. From top to bottom: X-ray flux, Radio Waves flux, and Proton flux.

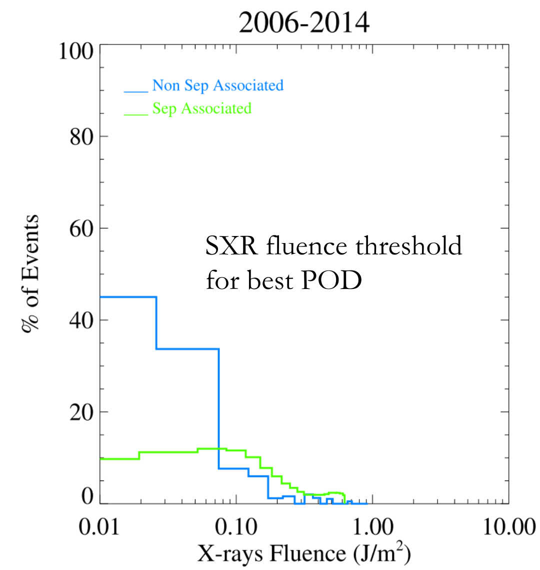
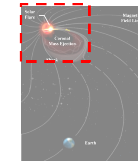


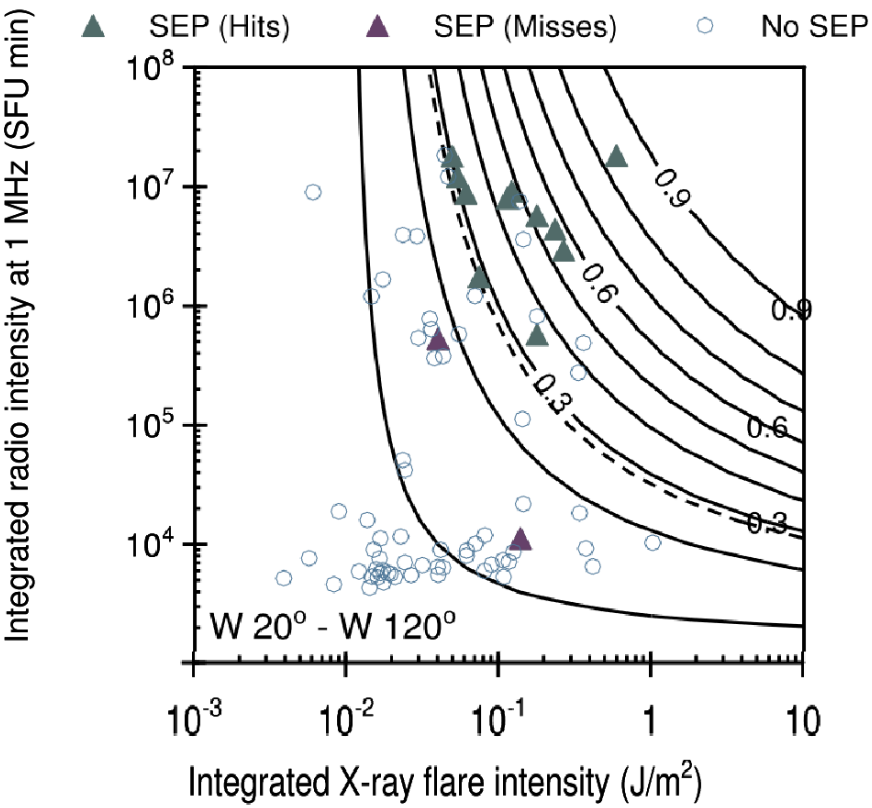
Figure 3. SXR fluence probability density functions: 2006–2014 database

In particular, a critical value for the SXR fluence ($0.1\ \mathrm{J\ m^{-2}}$) can be identified above which the percentage of SEP associated (green line in Figure 3) ⩾M2 SXR bursts increases to 78% (49/63) and 65% (15/23) for periods C and D, respectively). In comparison, the percentage of non-SEP associated (blue line in Figure 3) ⩾M2 SXR bursts having SXR fluence greater than $0.1\ \mathrm{J\ m^{-2}}$ is quite low: 29% (185/641) and 15% (38/253) for period C and D



ESPERTA model
(Laurenza et al, 2009; Alberti et al, 2017)

Based on the SXR and radio fluence values, the probability of a following SEP event can be evaluated:



Probabilities are calculated "*visually*" or by using Logistic Regression:

$$P(\log X, \log R) = \frac{e^{\eta}}{1 + e^{\eta}}$$

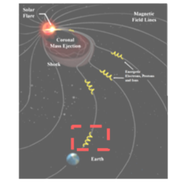
where

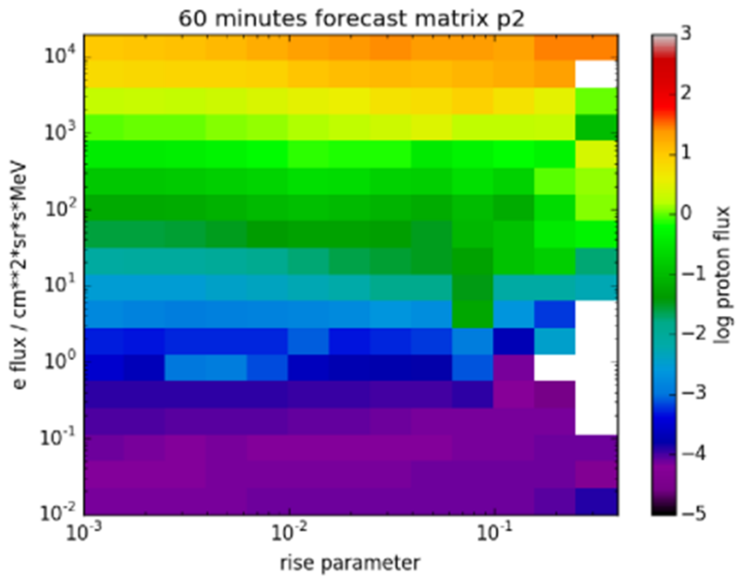
$$\eta = -5 - 1.7 \log(X) + 0.6 \log(R) + 0.4 \log(X) \log(R)$$

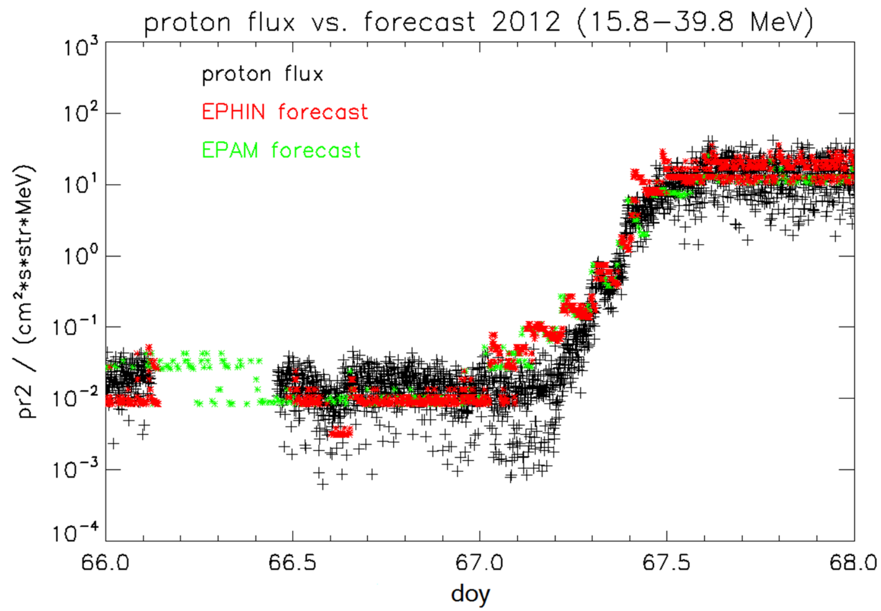
The probability curve level Pt used to evaluate the ESPERTA performance during 2006–2014 (dashed lines in the scatter plot) is 28% for western, events, which maximize the POD and HSS and minimizes the FAR.

For the western $\geqslant$M2 flares, Laurenza et al. (2009) found the optimal point to be $Pt = 28\%$

RELeASE model (Posner 2007)



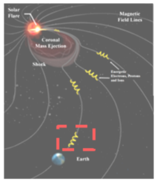




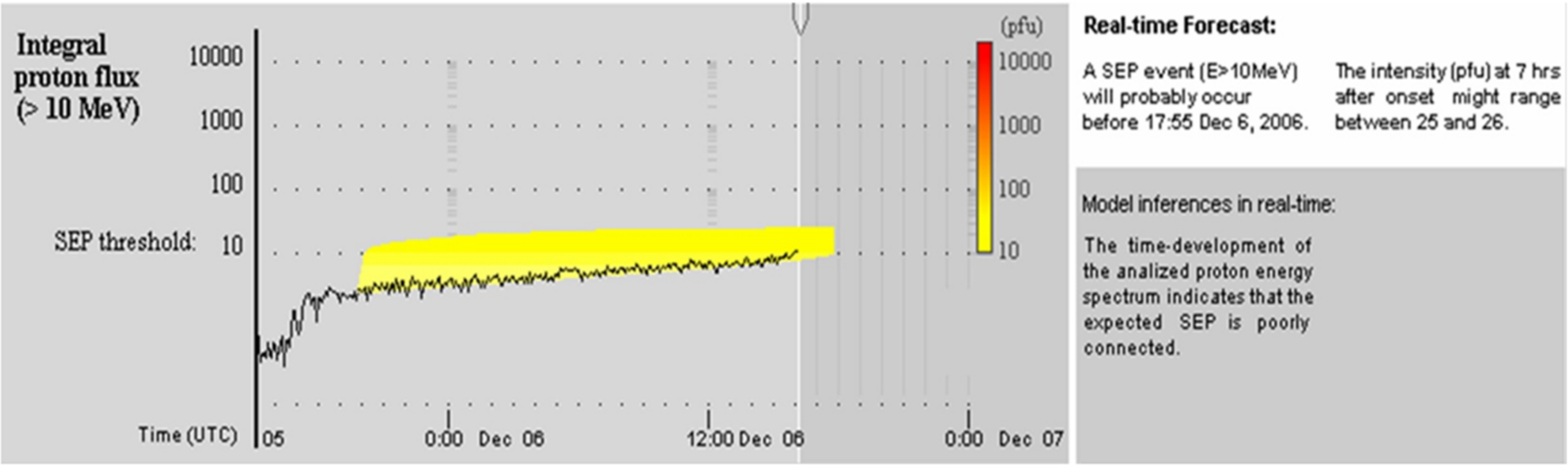
REleASE is based on electron intensity measurements of energies from 0.25 to 1 MeV and their intensity changes. It utilizes an empirical matrix in order to predict the proton intensity 30, 60 or 90 minutes ahead. Figure displays the forecast matrix. This Matrix shows the predicted intensity of protons in one hour as function of the measured absolute electron intensities and the intensity rise parameter.

An example of an SEP event where the EPHIN and EPAM based forecasts predicted the real proton flux accurately

Poorly-connected Prediction (PCP) (Núñez, 2011)



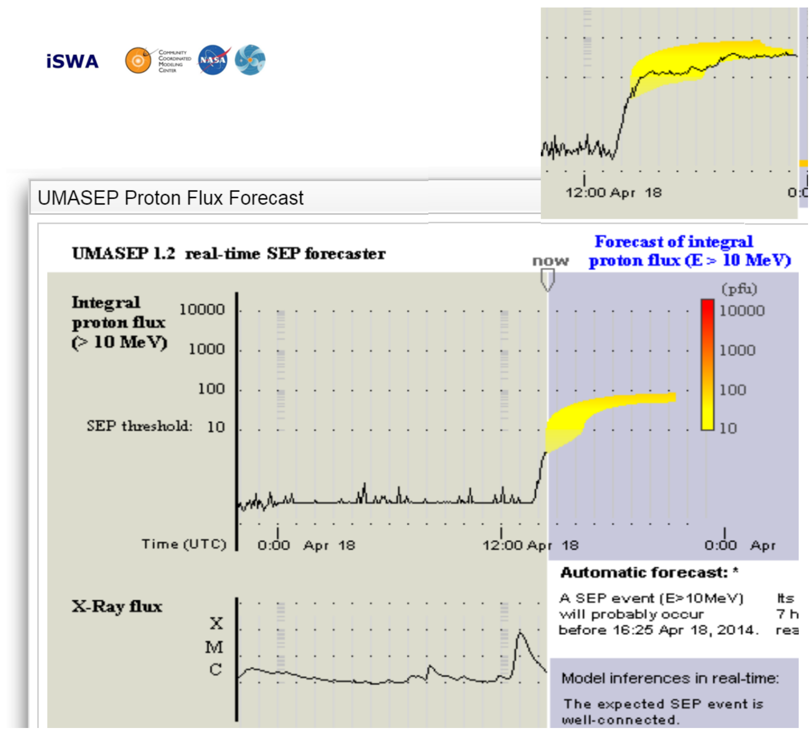
- The PCP model is part of the real-time UMASEP-10 tool



Forecast of SEP event on April 16th, 1990. Warning time was 20 h 05 min

Well-connected Prediction (WCP) (Núñez, 2011)

- The WCP model is part of the real-time UMASEP-10 tool



Forecast of SEP event on April 18th, 2014. Warning time was 40 min.
Error of intensity forecast 7h after SEP start was ~8 pfu

Comparisons of SEP event prediction models

The forecasting performance of two models may be compared if the following evaluation conditions met:

- Same period
- Both models predicting the same target events
  - Using a threshold agreed by space weather users. E.g. *All J* (*E*>10 MeV)>10 pfu)
- Calibration/Validation
  - Both models using calibration data (soft comparison)
    - i.e. Models may ajust parameters for obtaining the best results
  - Both models using out-of-sample data or real-time data (hard comparison)
    - i.e. Make models predict events using data not used during callibration
- Metrics: At least POD, FAR and Average/Median warning time
  - Sugestion: Use combined metrics. E.g. CSI combines POD and FAR in a single metric

Predicting the occurrence of all J (E>10 MeV)>10 pfu) events

Forecast summary for three periods: 1986-2004, 1995-2005 and 2006-2014

Period/Model	POD	FAR	CSI	AWT
1986-2004:				
• PROTONS (SXR ≥C4, radio)	55%	57%	32%	*9 h*
• UMASEP-10 (SXR ≥C4 vs. protons)	74.5%	29%	57%	6:59 h
1995-2005:				
• ESPERTA (SXR ≥M2, radio)	*63%*	*42%*	*43.2%*	*9 h*
• UMASEP-10 (SXR ≥C4 vs. protons)	81.5%	23.5%	65.2%	6:12 h
2006-2014				
• ESPERTA (SXR ≥M2, radio)	52.8%	30%	43%	7h
• UMASEP-10, J (SXR ≥C4 vs. Protons)	83.3%	25%	65.1%	6:32 h

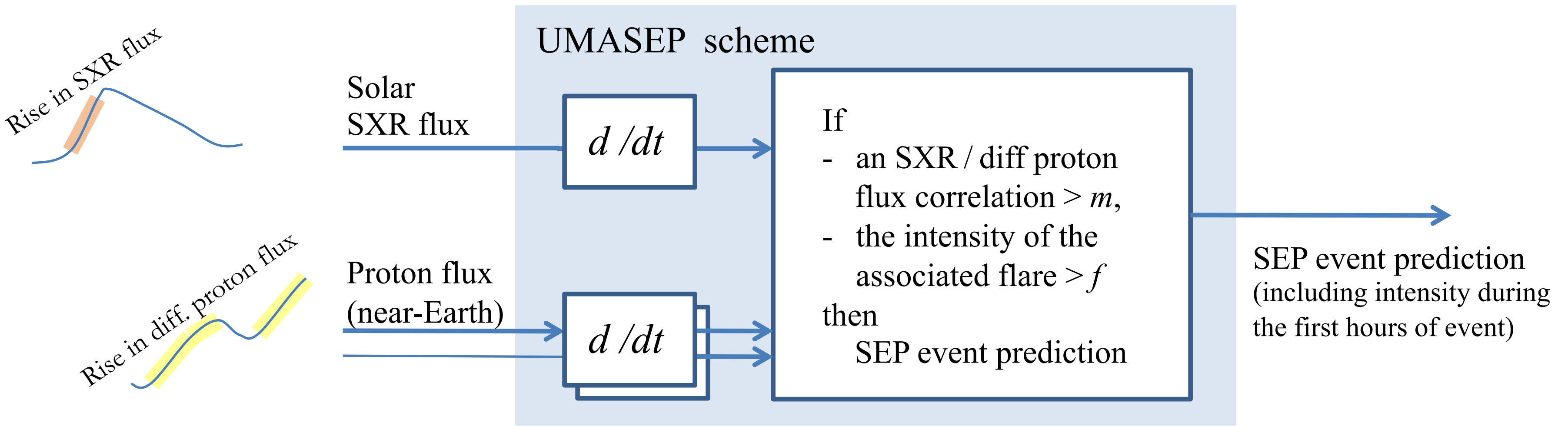
Note: Other models are not listed here because the target events are different:
e.g. RELeASE predicts 30-50 MeV SEP events

ESPERTA (Laurenza et al 2007, Alberti et al 2017)

- It is based on the logistic regression analysis on three solar parameters: the flare location, 1 – 8 Å SXR and ~ 1 MHz Type III fluence (time-integrated intensity), to provide a warning within 10 minutes following the SXR peak for ≥ M2 flares.
- For three longitude ranges, soft X-ray (SXR) fluence and ~ 1 MHz radio fluence for ≥M2 SXR were computed during two periods: 1995 – 2005 and 2006-2014.
- Probability Density Funtion of SXR fluence for SEP and non-SEP event. → the SXR fluence that maximixes SEP minimizes non-SEP

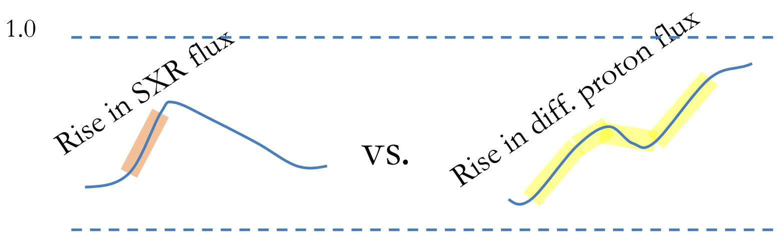
The UMASEP/WCP model (Núñez, 2011, 2015)

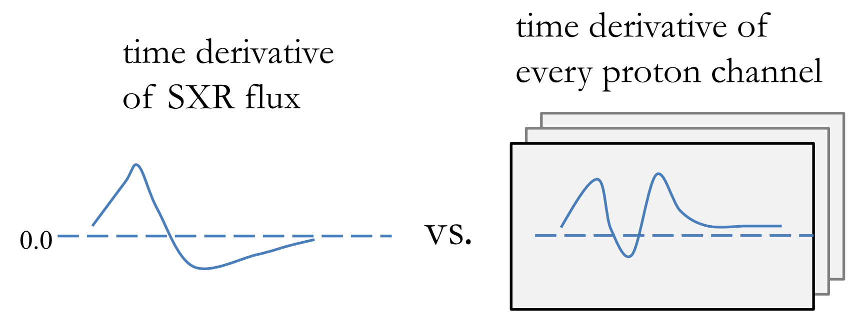
- The UMASEP scheme infers whether an eruptive event occurs at the Sun with a magnetic connection to the Earth, by correlating SXR flux with several differential proton fluxes at near-earth.
- If one of the correlations is high and the associated solar flare is strong, then the UMASEP scheme issues a SEP event prediction.

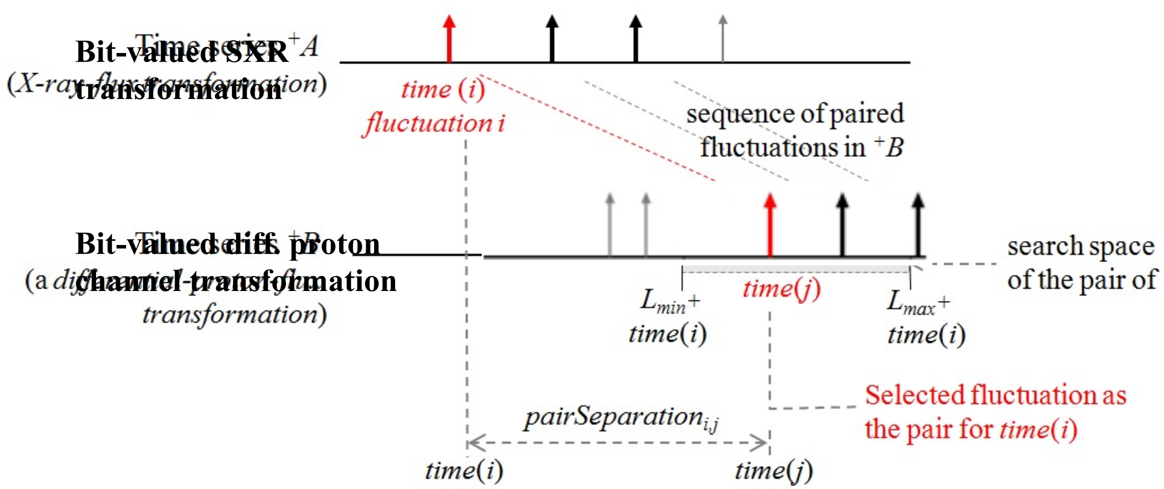


References:
- Núñez (2011/*Space Weather)* explains the correlation function for low-energy SEPs
- Núñez (2015/*Space Weather)* explains the correlation function for high-energy SEPs

High-energy UMASEP model
for predicting >100 and >500 MeV events





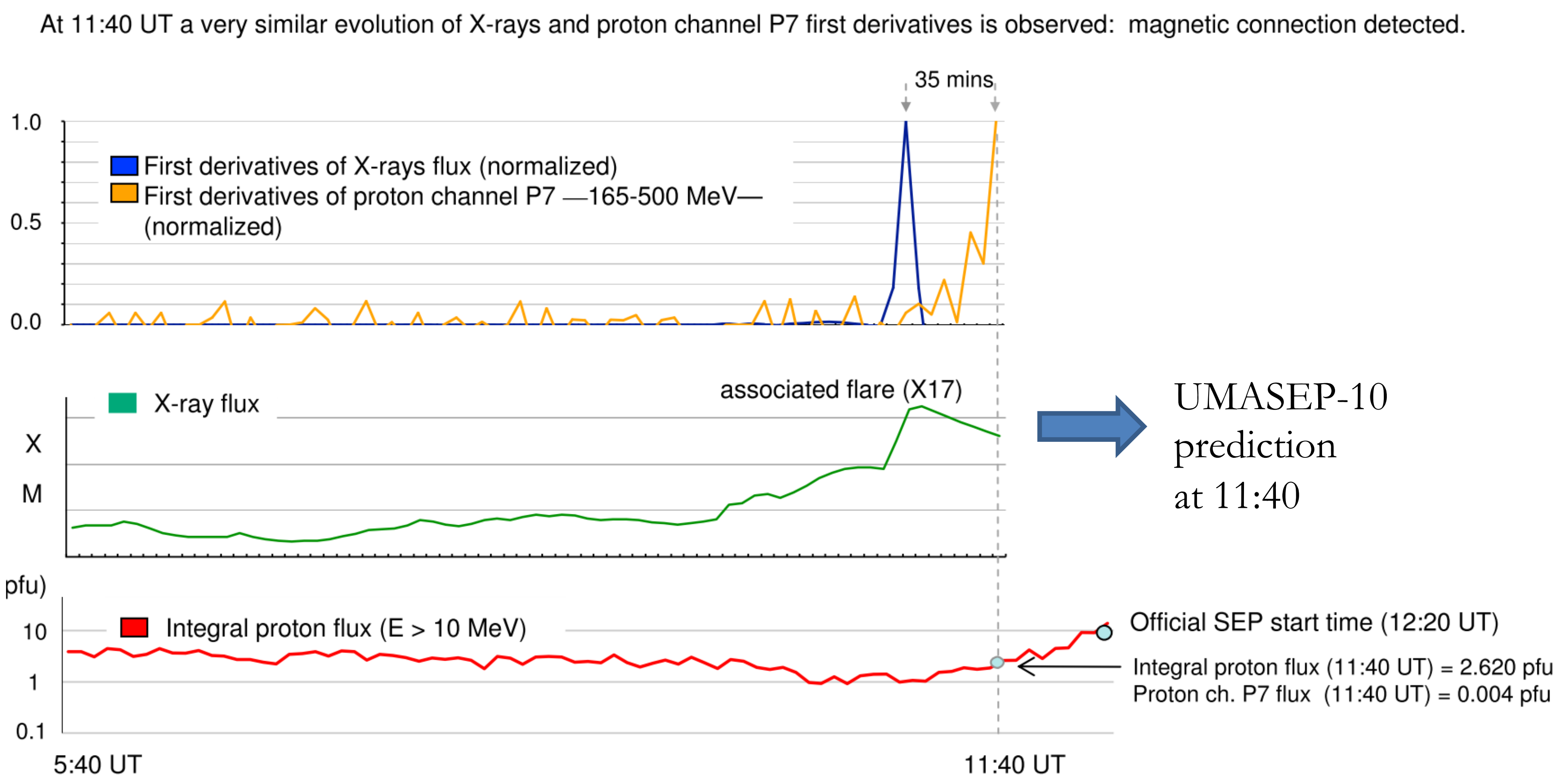


For more information:
Núñez, M. (2015),
Space Weather, 13

A forecast of UMASEP-10/WCP model

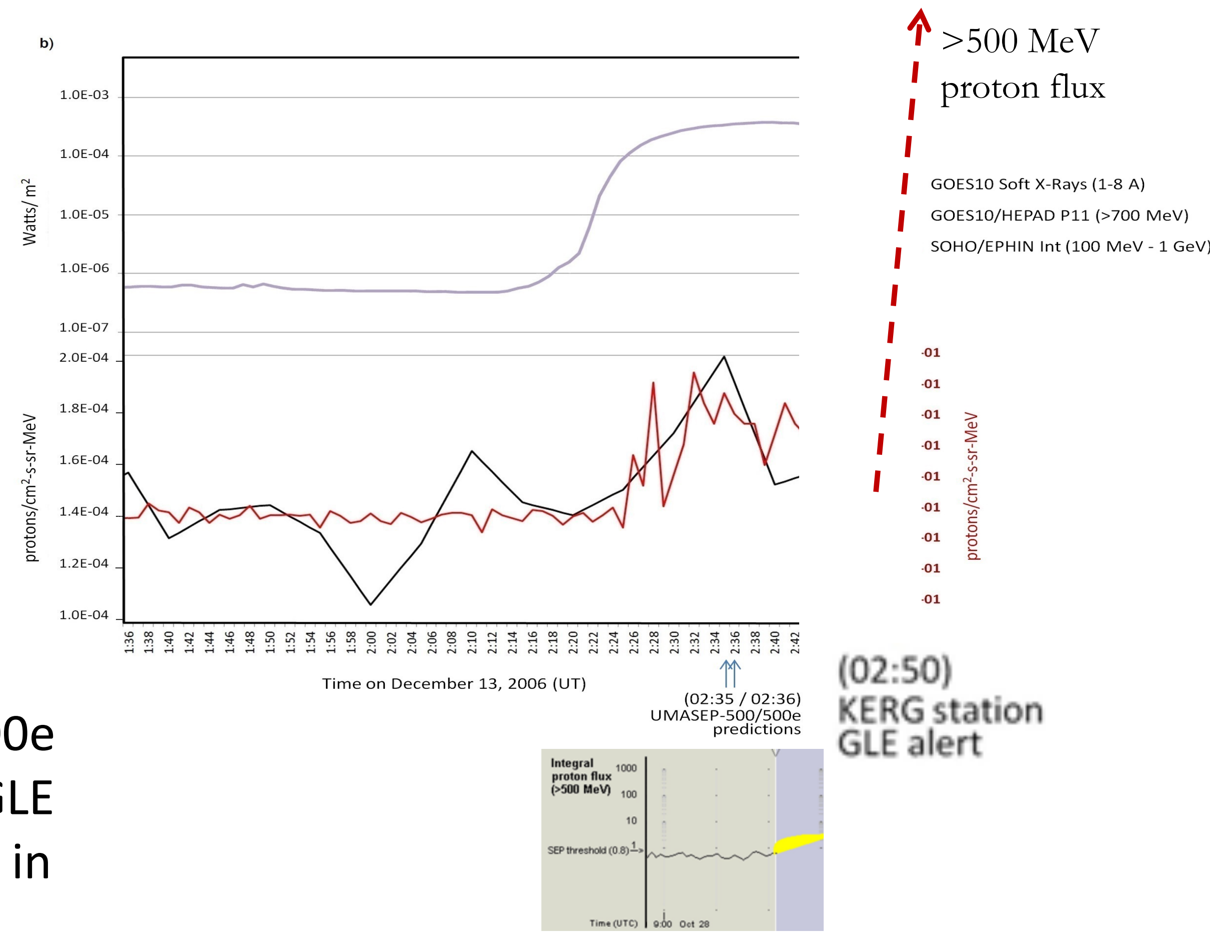
Flux rises are measured by estimating the first time-derivatives.

Event on Oct 28, 2003 (11:40 UT)



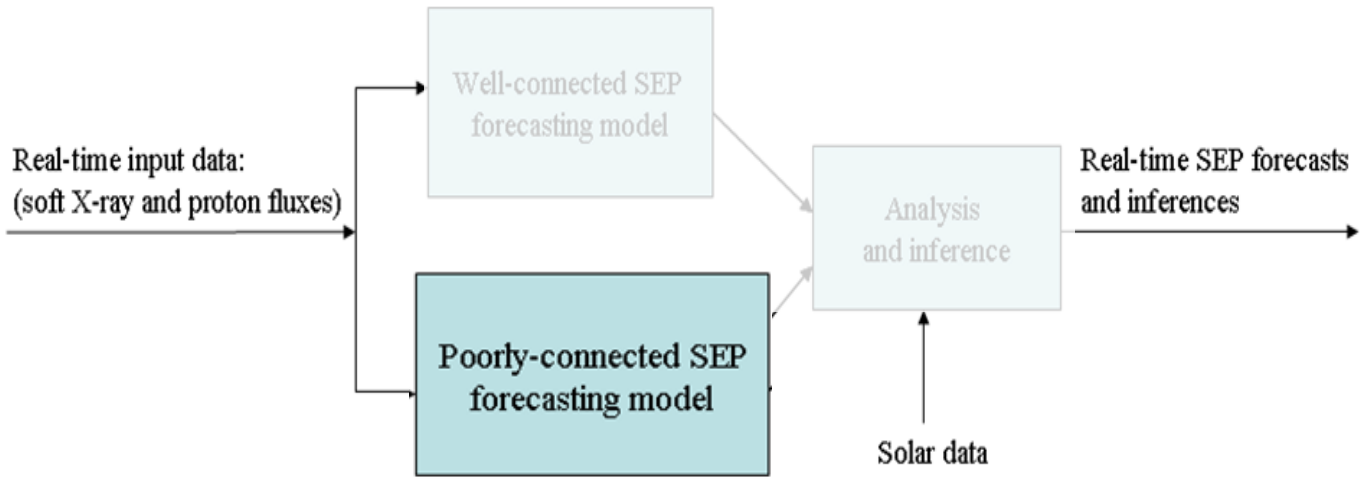
A forecast of the HESPERIA UMASEP-500/WCP model

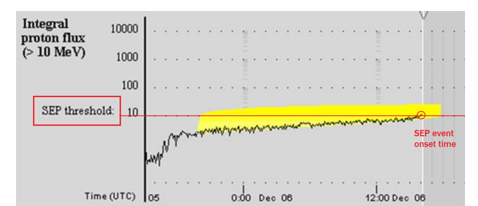
SXR/proton flux scenarios before GLE-70 and the corresponding GOES/HEPAD P11 and SOHO/EPHIN integral proton fluxes



The time of the HESPERIA UMASEP-500 and UMASEP-500e predictions, and the earliest GLE Alert onset time are indicated in the time axis.

Other UMASEP-10 components





- UMASEP-10 also has a model for predicting poorly connected SEP event "PC-model"
- The UMASEP PC-model analyzes proton flux rises (only). This model does not analyze SXR flux

Ref: Núñez, *Space Weather*, 2011

Verification of categorical forecasts

Forecasting Performance

Contingency table:

		observed: yes	observed: no
predictions	yes	***hits***	***false alarms***
	no	***misses***	***correct negatives***

Fraction of the observed SEP events that were correctly predicted:

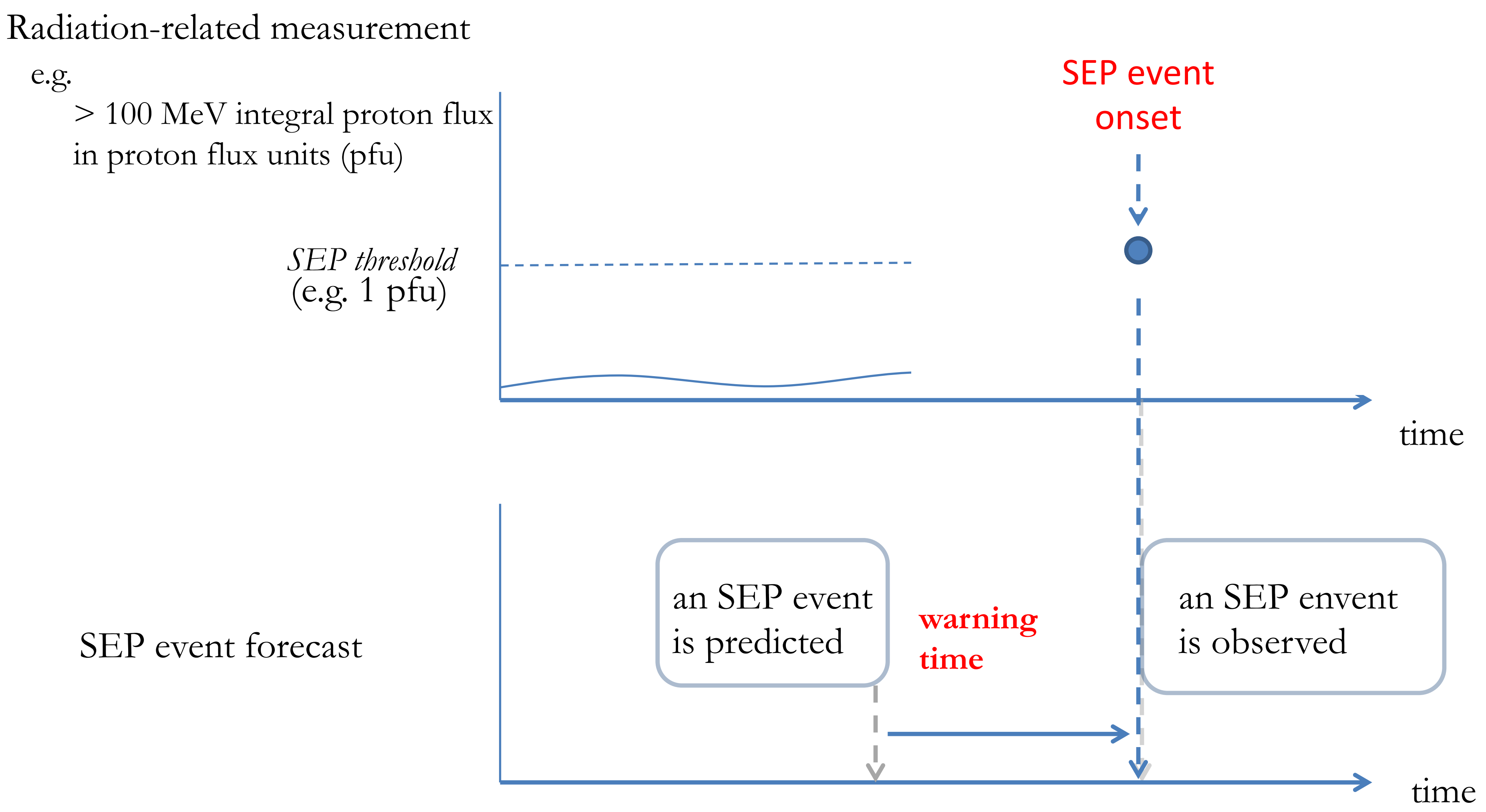
- Probability of Detection (POD) = *hits*/ (*hits* + *misses*)

Fraction of the predictions that actually did not occur:

- False Alarm Ratio (FAR) = *falseAlarms* / (*hits* + *falseAlarms*)

FAR is calculated by simulating real-time operations as much as possible, (e.g. using not-corrected flux data, not ignoring any period)

Average Warning Time

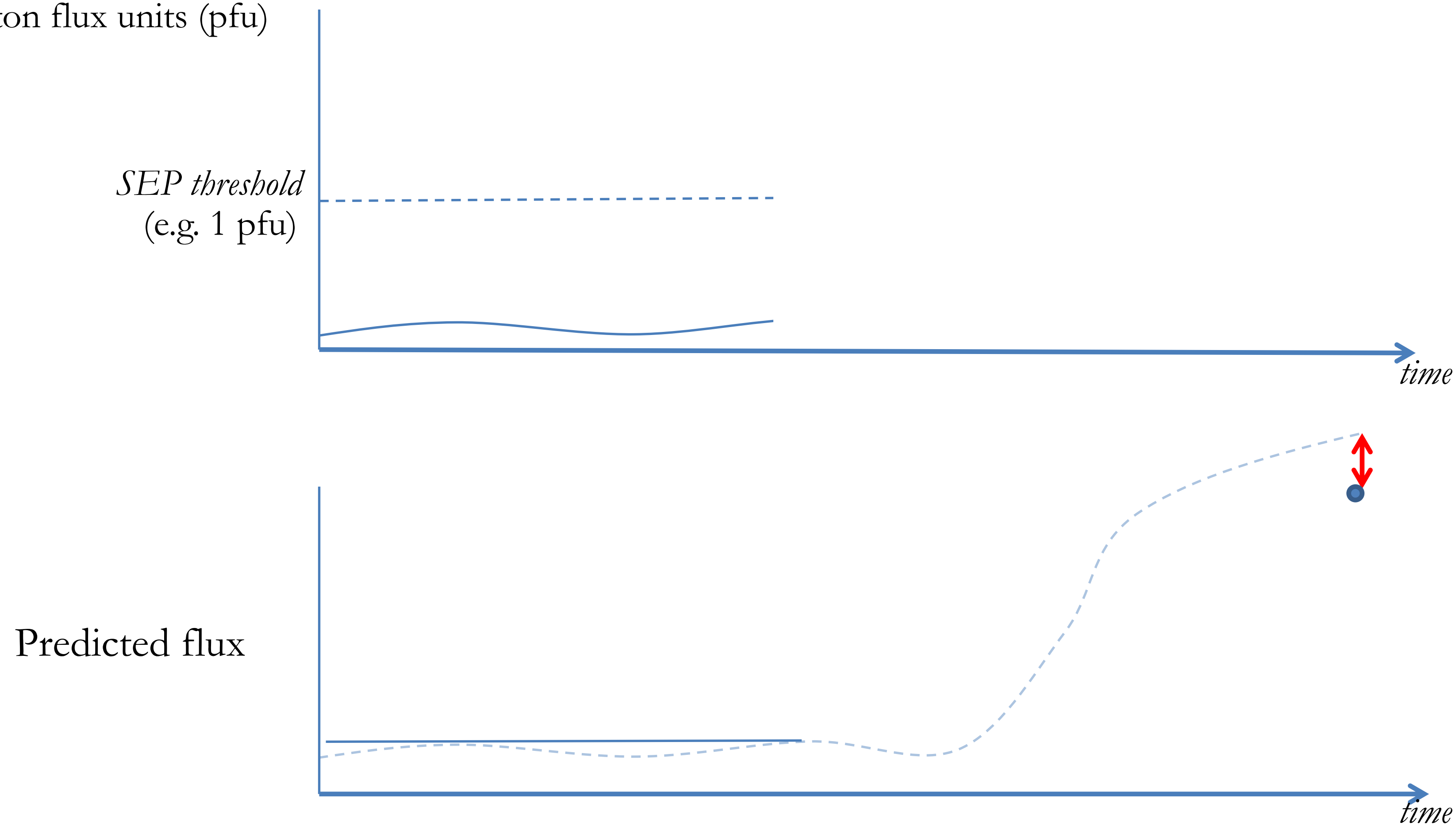


The **average** of all anticipation/warning times is called here as AWT (**Average Warning Time**)

Mean Absolute Error of predicted intensity

Radiation-related measurement

e.g. > 100 MeV integral proton flux
in proton flux units (pfu)



Mean Absolut error (MAE)= abs (real flux - predictd flux) using physical units or $\log_{10}$ of physical units