IRENE Industry Days – SAPPHIRE2S

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The SAPPHIRE Model - Overview

- The SAPPHIRE SEP model provides for:
  - TID, TNID (incl. solar cell and thin layers)
  - SEEs: Upsets, Latch-up and Burnout
  - Sensor interference
  - Effects on astronauts
- To achieve this SAPPHIRE includes models for:
  - Severe environments (either peak flux or worst week equivalent)
  - Cumulative mission fluence environments
  - Extrapolations from 0.1 MeV/nuc to 1 GeV/nuc
- All outputs are probabilistic in nature with a basis of protons and helium and extensions to Heavy Ions (HIs)

Model Overview: **Jiggens et al. 2017a** **Model Statistics:** **Jiggens et al. 2017b**

Solar Maximum

21 outputs

Prediction periods (0.5 – 35 years)

[5 cycles with 7 active years per cycle]

SEP species

p+, alphas, ext. to U

Particle Energies

Core Model: 5-300 MeV (11 logarithmically-spaced channels)

Extrapolation/Interpolation: 0.1 MeV – 1 GeV (81 Energies)

Confidence Levels

53 outputs from 50 – 99.9%

Ch.	Energy (MeV/nuc)		
	Lower	Upper	Mean
1	5.00	7.23	6.01
2	7.23	10.46	8.70
3	10.46	15.12	12.58
4	15.12	21.87	18.18
5	21.87	31.62	26.30
6	31.62	45.73	38.02
7	45.73	66.13	54.99
8	66.13	95.64	79.53
9	95.64	138.3	115.0
10	138.3	200.0	166.3
11	200.0	289.2	240.5

Solar Minimum

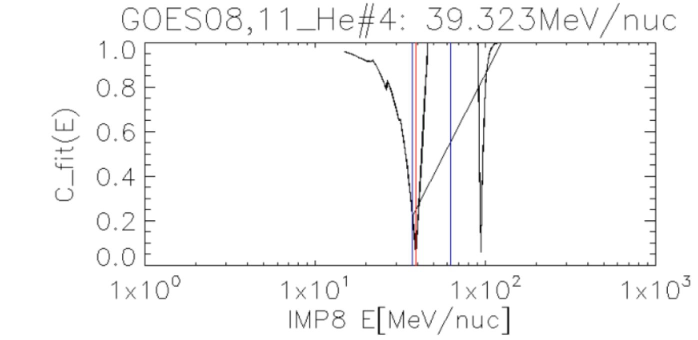
25 outputs

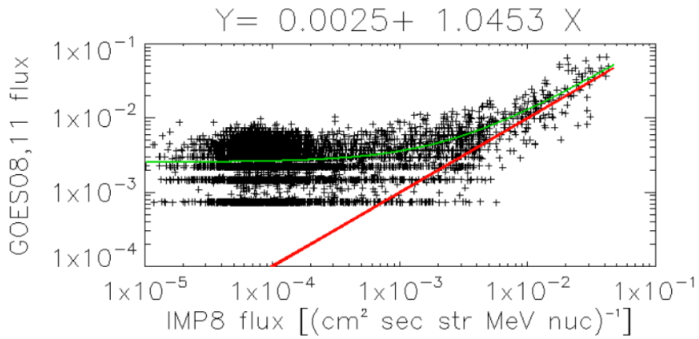
Prediction periods (0.5 – 55 years)

[5 full cycles for statistically sensible implementation]

Current SAPPHIRE Model - Data

- Model uses RDS v2.1: background-subtracted & including solar helium for timespan 1974-2015

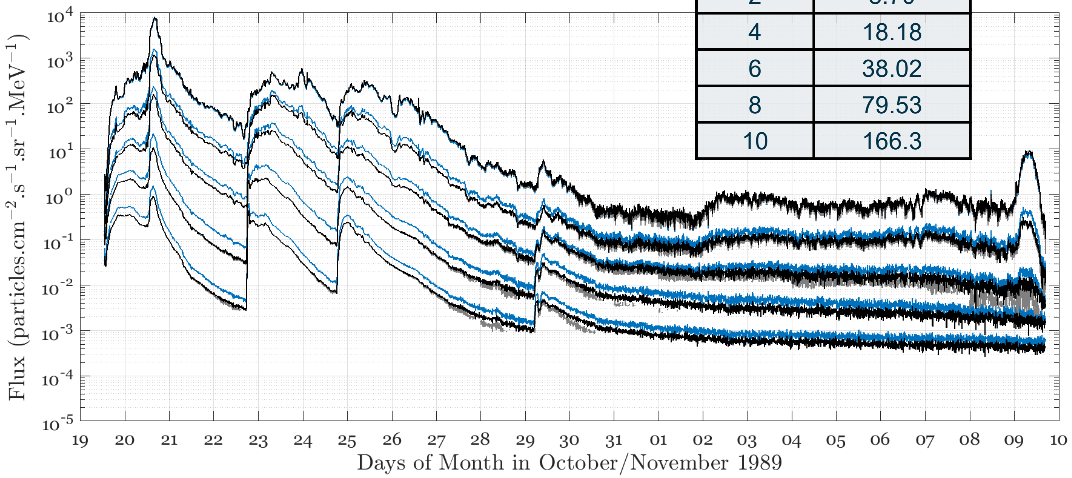




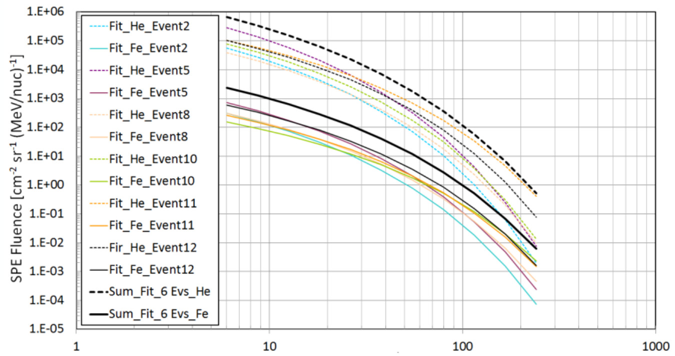
- Based on GOES(SMS)/SEM/EPS/EPEAD data corrected in energy using IMP8/GME [above from Sandberg et al. 2014]
- Proton fluxes show high-energy impact (Blue: CREME96; Red: PSYCHIC) [right]

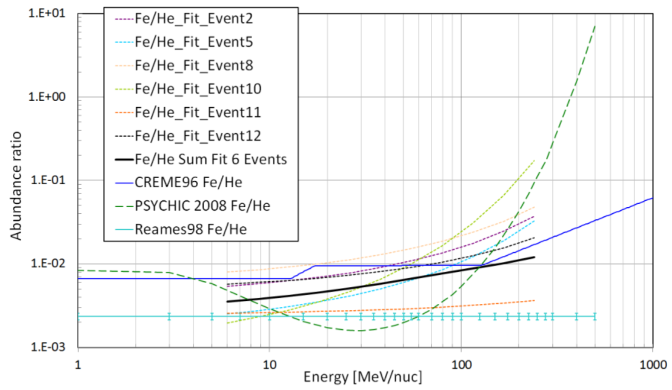
- Underlying Data is available at: http://sepem.eu/help/SEPEM_RDS_v2-01.zip
- ACE/SIS Heavy Ion data processed per SEP event to derive average abundance ratios to helium as function of energy
- Abundances are later applied uniformly on all SAPPHIRE model outputs

Ch.	Energy (MeV/nuc)
2	8.70
4	18.18
6	38.02
8	79.53
10	166.3

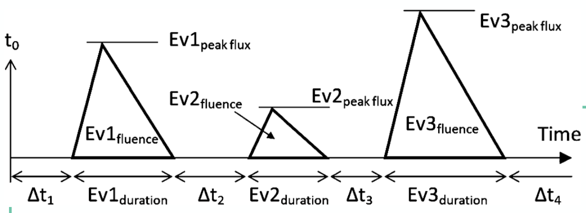


- ACE/SIS Analysis for Fe to derive final abundance ratios (black lines) [below from A. Varotsou]

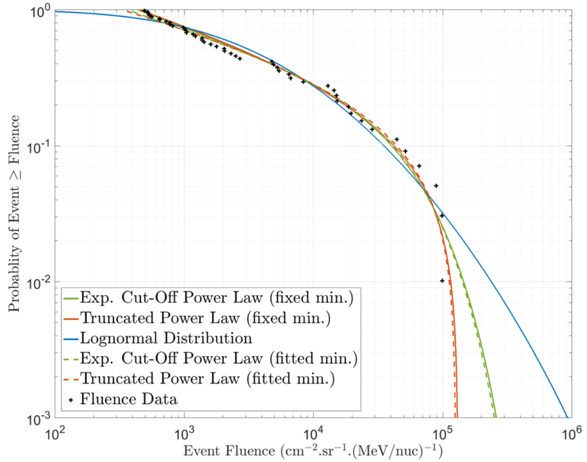




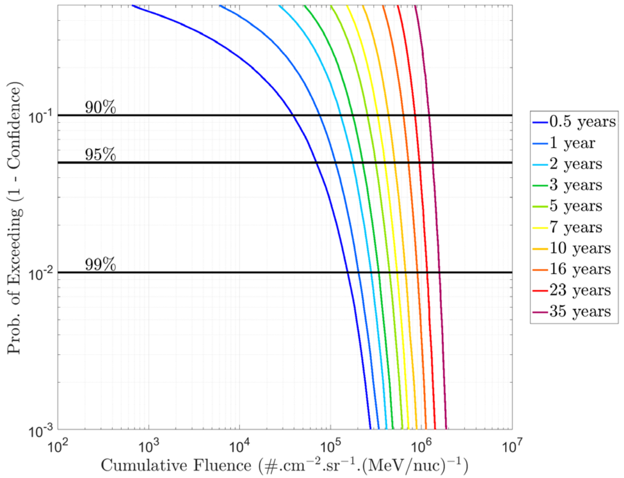
Current SAPPHIRE Model – Distributions & Results



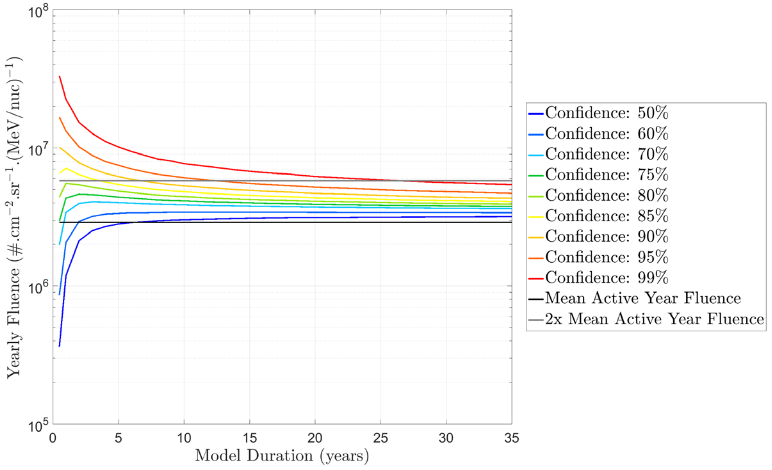
- SAPPHIRE follows the *virtual timelines* method with interspersed SEP events and waiting times

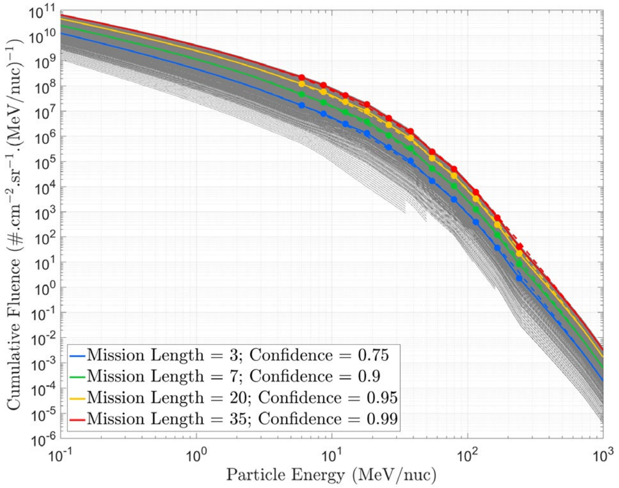


- Each event is randomly sampled from the exponential cut-off power law distribution

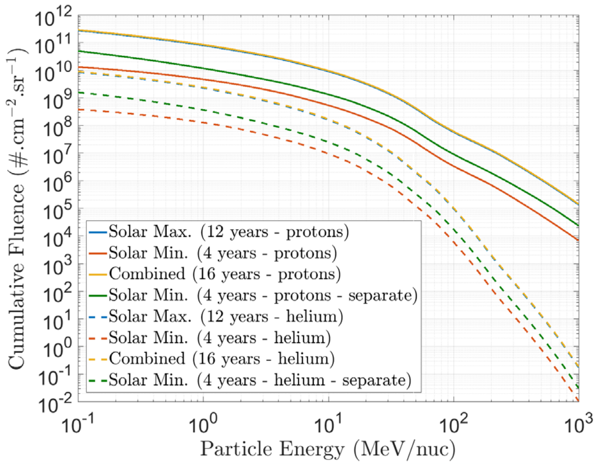


- Channel outputs are given as functions of confidence and duration





- Spectral outputs are derived for all outputs with careful min/max combination

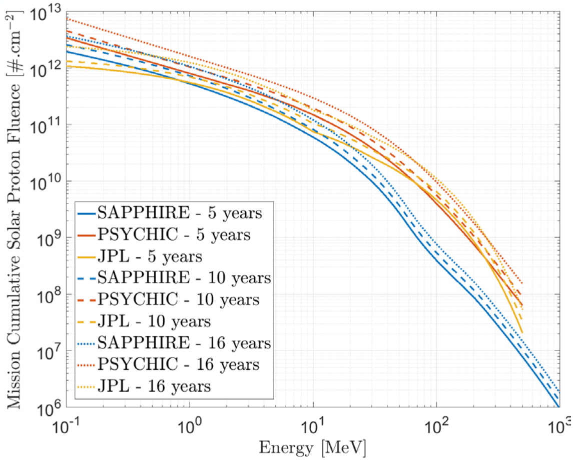


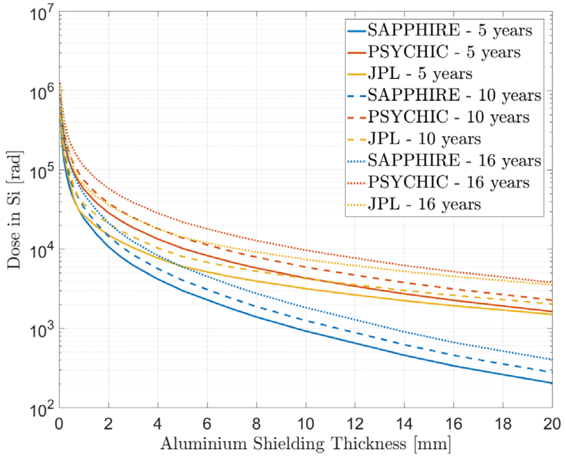
Comparisons to other Models/Standards

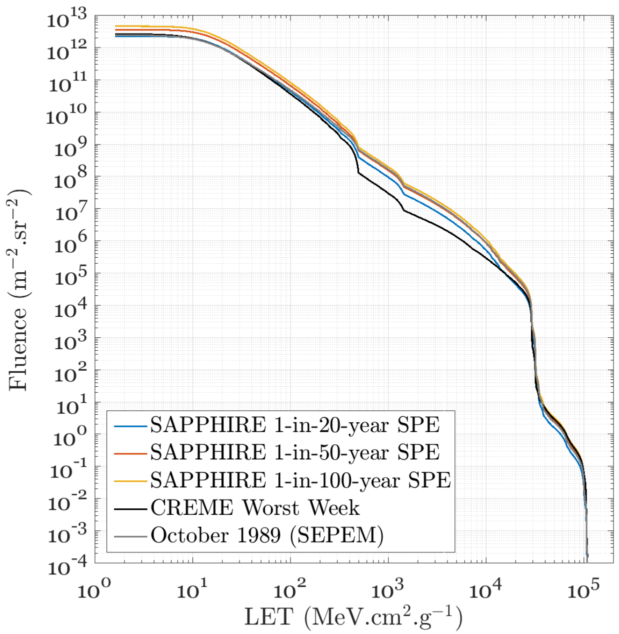
- SAPPHIRE outputs agree reasonably with JPL (and ESP-PSYCHIC) at low energies for short durations and moderate confidence (interpolation regime)
  - Less severe for longer durations/higher confidence (extrapolation regime)
  - High energy differences due to data treatment (see Sandberg et al. 2014)
- Method to transform results into 1-in-n-year SPEs (severe environments)
- New helium-to-heavy ion abundances allows derivation of flux/fluence spectra as function of particle Linear Energy Transfer (LET)

[right] Shielded LET fluence comparison to CREME96 (1 g.cm^{-2})

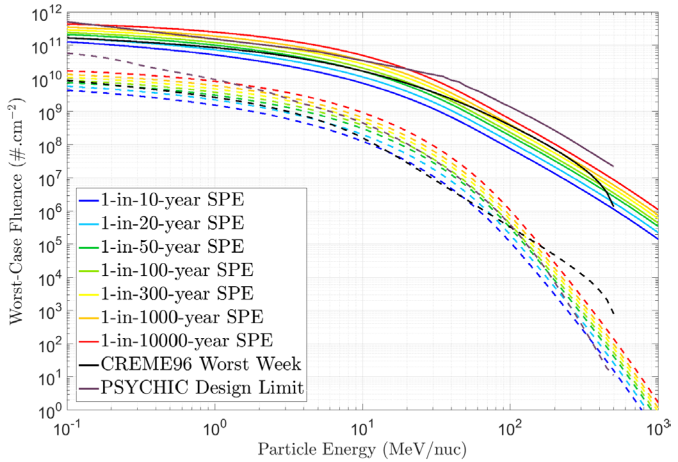
[below] 95% Fluence and dose comparisons to PSYCHIC and JPL

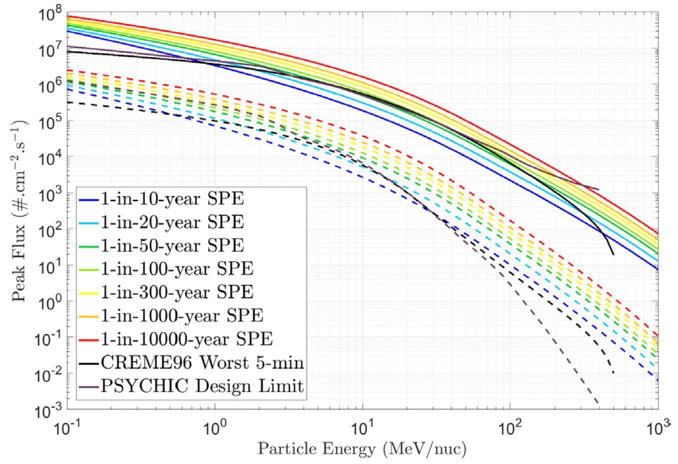






1-in-n-year SAPPHIRE Protons (solid lines) and alphas (dashed) for event fluence [top] and peak flux [below]





Work on Error Propagation – NSREC 2018

Methods for and the Influence of Uncertainty Propagation in the Solar Energetic Particle Environment Modelling (SEPEM) System

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Abstract

The SEPEM system is a web-based environment within which a user is able to perform all the functions needed to generate new statistical models for solar energetic particle (SEP) events and their effects. Recent enhancements to the SEPEM include the propagation of uncertainties in the model generation process. The method of this treatment is described and the relative importance of the contributions discussed.

(1) Introduction

Solar energetic particle (SEP) events present an important threat to the operation of spacecraft, human spaceflight, and also an increasing concern to aviation safety from the perspective of flight control and radiobiological effects. The Solar Energetic Particle Environment Modelling (SEPEM) system [http://sepem.eu] has been developed by ESA to allow users to build SEP event models using reference datasets, execute these models to predict particle environments, and analyse the effects of shielding on energy/LET spectra and single event effects (SEE) rates in microelectronics [1]. SEPEM had previously focussed on the proton SEP environment for interplanetary space. Also mission cumulative and worst-case event or peak flux predictions are generated as a function of confidence level (CL), but *the CL statistics reflect the potential variability of the environment due to the statistical nature of the SEPs and not the uncertainties in the modelling calculation.*

Under the ESA Energetic Solar Heavy Ion Environment Model (ESHIEM) Project, the data and models have been extended significantly to treat SEP heavy ions (HI) both outside of the magnetosphere and also for Earth-orbiting spacecraft environments. In addition, for the first time for such SEP statistical models, a comprehensive analysis is being provided of uncertainties associated with each step of the modelling process, and propagation of those uncertainties, addressing:

- Accuracy of the instrument energy and efficiency calibration
- Statistical uncertainties in the event list
- Uncertainties in the (HI) abundance ratios with respect to proton or He statistical models
- For spacecraft operating within Earth's magnetosphere, the errors in the modelling of the geomagnetic shielding for particles in orbital positions
- Uncertainties in the accuracy of the modelling of physical shielding effects.

Four Principal Modes for ESHIEM/SEPEM SEP Model Generation

1. Interplanetary environment → statistical models of fluxes/fluences → magnetospheric shielding [if Earth orbit] → physical shielding & effects (Figure 1a)
2. Interplanetary environment → physical shielding & effects → statistical models of shielded environments & effects (for interplanetary space)
3. Interplanetary environment → magnetospheric shielding [user-defined Kp] → physical shielding & effects → statistical models of shielded environments & effects (Figure 1b)
4. Interplanetary environment → magnetospheric shielding for actual event Kp → physical shielding & effects → statistical models of shielded environments & effects (Figure 1b)

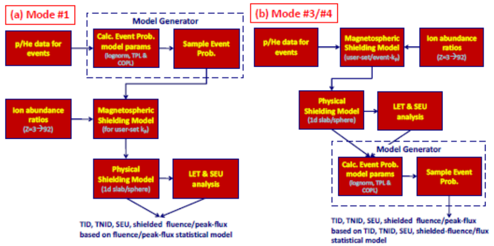

Figure 1: (a) Statistical model created based on event interplanetary fluence/flux for protons and He (Mode #1); (b) Statistical model created based on shielded fluence/flux or other effects associated with events. Geomagnetic shielding based on user-defined Kp (Mode #3) or mean-event Kp for each event (Mode #4).

(2) The Solar Energetic Particle Environment Model Overview & inclusion of Heavy Ion Modelling

- Original SEPEM System allows users to [1]:
  - Apply data cleaning tools within SEPEM, and browse & plot SEP data which is within SEPEM or from user
  - Proton Reference Data-Set (RDS) from cleaned and GCR background-subtracted GOES 1, 2, 5, 7, 8, 11, 13, and SMS 1 and 2 data – RDS v2.1 covers 1974-07-01 to 2015-12-31, and energy range 5.0 →289.2 MeV over 11 bins [2]
  - Fits performed to event magnitude data (peak flux, event-integrated fluence) assuming lognormal (LN), truncated power-law (TPL) or exponential cut-off power-law (COPL) cumulative distributions
  - Generate a variety of Statistical Models for fluence, peak flux, and effects, usually through Monte Carlo simulation of ≈10^5 mission histories
  - Extrapolation of fluxes away from 1 AU
  - Derivation of effects quantities TID, TNID & SEE and shielded fluxes/fluence based on user 1D geometry
  - (See section "Four Principal Modes for ESHIEM/SEPEM SEP Model Generation")
- New ion data sources implemented in ESHIEM Project:
  - He: Cleaned and background-subtracted GOES 1, 2, 5, 7, 8, 11, 13, and SMS 1 and 2 providing coverage from 1974-07-01 to 2015-12-31 , 5.0→289.2 MeV/nuc (part of RDS v2.1) [2]
  - Both proton and He data subject to cross-calibration (SEPCALIB) providing traceability to IMP8/GME instrument [3]
  - C, N, O, Ne, Mg, Si, Fe, measured by ACE/SIS during SEP events analysed from Nov 1997 to Mar 2013, and abundance ratios determined with respect to GOES & SMS He data (see Figure 2 for C, O and Fe results) [4]
  - Extensive analysis of ACE/SIS data for >100 events applied to select highest-quality (reliable) event data: Ultimately HI abundances at low energies based on 13 to 6 events depending upon ions, and 6 to 4 events at high-E [4]
  - Augmented with relative abundances from data of Reames *et al* (ISEE-3-based) and photospheric abundances from Asplund, Grevesse, *et al* for other non-radioactive elements up to Bi (Z=82), as well as Th and U (Z=90 and 92) [5][6]
  - Updated SEPEM recently used by Jiggens *et al* to develop the Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) model [7]

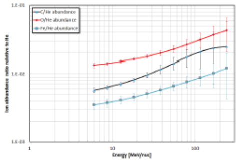

Figure 2: ion abundance ratios and uncertainties for C, O and Fe with respect to He as a function of energy.

- Estimation in uncertainties in p/He fluxes:
  - Typically cross-calibration uncertainties [$\sigma'_{SC:p}$ and $\sigma'_{SC:He}$] are ≈2-3%, and <9% (protons) or <7% (He) for all GOES spacecraft and channels, based on error in mean for cross-calibration fit
  - Provision included to treat absolute calibration of the IMP8/GME instrument responses / geometric factor - Overall calibration term at each energy [$f_{IMP:p}$ and $f_{IMP:He}$]
- Statistical variations in the event ACE/SIS data (event-to-event statistics) leading to uncertainties ΔA_{ion} in the ion abundance ratio A_{ion} relative to He
  - Typically for light nuclei, <10% below 30 MeV/nuc, rising to 60-70% for O, Mg, Si and Fe, but greater still for others (see Figure 3)
  - Note the lower uncertainty for some higher-Z ions may be artefact of reduced numbers of valid SEP events

Therefore the uncertainty in the ion flux or fluence [$\Delta\Psi_{ion}$] is:

$$(\Delta\Psi_{ion})^2 = (A_{ion} f_{IMP:He} \Psi_{He})^2 + (A_{ion}\sigma'_{SC:He})^2 + (\Delta A_{ion}\Psi_{He})^2$$

- Where results and uncertainties are combined for different ions (*e.g.* to determine LET spectra or TID), but which are based on the same ACE/SIS abundances, great care has been taken to ensure the uncertainties are treated as inter-dependent and completely not independent

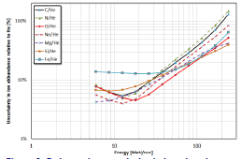

Figure 3: Estimated uncertainties in ion abundances relative to He for ACE/SIS ions .

(3) Statistical Uncertainties from Finite p/He Event Data

- How representative are the statistics of the Reference Event Lists for protons & He (>260 events) of the true parent distribution?
- Error bars in fit parameters for event probability model (LN, TPL and COPL) indicate uncertainty
  - Typical uncertainty for exponential COPL to He, σ_b ≈2-30%, $\sigma_{\psi lim}$ ≈10-30%; uncertainty poorest at bin-centroids 38, 55, and 115 MeV/nuc
  - Uncertainties determined by standard linear regression (LN) or Monte Carlo bootstrap method (TPL and COPL) [*e.g.* see Figure 4]
- Two approaches for dealing with uncertainty in model generation:
  1. Allow user to define fixed number of σs, n_1 & n_2 to apply to fitted model, *e.g.*, for exponential cut-off power-law (COPL):

$$P(\Psi) = \frac{\Psi^{-b'}}{\Psi_{min}^{-b'}} exp\left[-\frac{\Psi}{\Psi'_{lim}}\right]$$

where:

$$b' = \bar{b} + n_1 \times \sigma_b \quad \text{and} \quad \Psi'_{lim} = \overline{\Psi_{lim}} + n_2 \times \sigma_{\Psi_{lim}}$$

  2. In each Monte Carlo history of mission, sample n_1 and n_2 based on Gaussian inverse error functions:

$$n_1 = erf^{-1}(-\xi_1) \quad \text{and} \quad n_2 = erf^{-1}(+\xi_2)$$

where ξ_1 and ξ_2 are random numbers evenly distributed on (0,1). In essence, this combines uncertainties in parameters into the confidence level statistics of the model

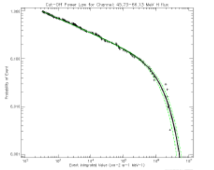

Figure 4: Example SEP event proton fluence for 45.7-66.1 MeV, COPL fit with uncertainties

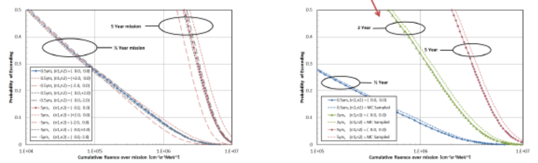

Figure 5: Mission cumulative proton fluence as a function of confidence of not exceeding value based on statistical model for event fluences between 45.7-66.1 MeV (bin centroid 55 MeV) fitted using COPL. Approach 1 (left) using user-defined multiples (n_1 and n_2) of σ_b and $\sigma_{\psi lim}$; Approach 2 (right) using MC sampling of n_1 and n_2 as part of Monte Carlo model generation process.

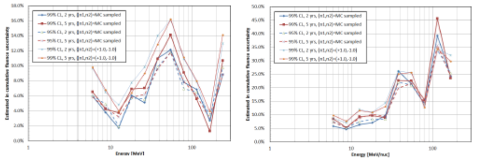

Figure 6: Uncertainties in mission cumulative fluence for 95% and 99% CL; protons (left) and He (right).

Estimated uncertainty in mission-cumulative p and He fluences at 95% and 99% CL indicated in Figure 6:

- ≤16% for protons
- Usually <30% for He
- Similar trends seen for different CL
- Note He uncertainties are comparable to ion abundance uncertainties except above 70-90 MeV

(4) Magnetospheric Shielding (MSM)

- Overview of MSM:
  - Interpolates from extensive new database of Geant4/MAGNETOCOSMICS geomagnetic cut-off maps:
  - 5º x 5º longitude and latitude grid at 450km
  - DGRF/IGRF field models with Tsyganenko 1989 model
  - Epochs for geomagnetic fields 1955 to 2015
  - Cut-off rigidities interpolated and extrapolated, based on the approach of Shea and Smart used in the RCINTUT3 program [8]
- Comparisons of MSM results and Geant4/MAGNETOCOSMICS using maps such as shown in Figure 7 indicate:
  - Typical difference in estimated vertical-cut-off rigidity, ΔR_{VC} ≈1%
  - At other angles, difference in rigidity, $\Delta R_C \approx 5\times \Delta R_{VC}$ = 5%
- Uncertainty in magnetospherically-shielded ion fluence becomes:

$$(\Delta\Psi_{ion,MS})^2 = (T\Delta\Psi_{ion})^2 + \left(\frac{dT}{dR}\Delta R_c \Psi_{ion}\right)^2$$

where *T* is the ion transmission as a function of particle rigidity.

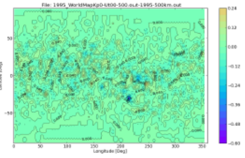

Figure 7: Difference between MSM and Geant4 / MAGNETOCOSMICS vertical cut-off rigidity for 500km.

(5) Implementation in SEPEM

- The ESHIEM-related changes to SEPEM (including error propagation) completed in May 2018, and accessible to registered SEPEM users
- The user can generate model uncertainties if needed, addressing:
  - Uncertainties from SEP p/He event statistics
  - Uncertainties from cross-calibration, abundance ratios, shielding analysis
  - Both of the above
- A number of the changes have included simplifications to the GUI to make data entry more intuitive
- Inclusion of Monte Carlo biasing in the sampling of the event magnitude distribution to improve model generation efficiency
- Some verification testing of these changes is still ongoing

Figure 8: Input web-page for model definition including options to select uncertainty propagation, as well as Monte Carlo biassing.

(6) Conclusions and Recommendations

SEPEM offers a unique and powerful on-line tool to develop new statistical models of SEP events, including treatment of the uncertainties in the calculation process. The analysis indicates the principle uncertainties are arising from:

- Heavy ion abundance ratios The abundance ratio uncertainties range from <10% below 30 MeV/nuc, rising to 60-70% for O, Mg, Si and Fe, but greater still for others (potentially ×2). A key limitation is the lack of sufficient high-quality HI SEP measurements
- Fits to the probability versus event magnitude distribution functions for H and He, e.g. COPL fit, these can be 2-30% for b, and 10-30% for Ψ_{lim}. Resulting uncertainty in He mission-cumulative fluence is typically <30% (same order, but slightly lower than HI abundances)
- Note Ionising dose from SEPs is dominated by protons and therefore the abundance ratios error have less influence compared with the uncertainties in the event magnitude distribution.
- Uncertainty propagation from MSM modelling and physical shielding included in SEPEM calculation (latter detailed in paper) based on comparison to detailed Monte Carlo radiation transport calculations

Future analysis should address:

- There is an important requirement for more high-quality HI SEP data covering a range of event magnitudes
- Consideration should be given to potential artefacts/bias introduced by data-processing for p/He as well as HI data
- Absolute uncertainty in IMP8/GME data - currently remains undetermined

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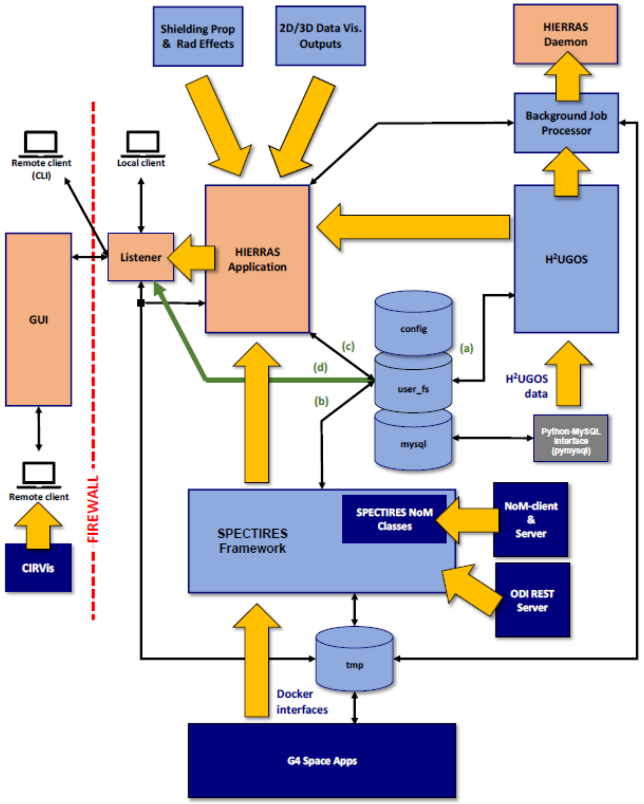
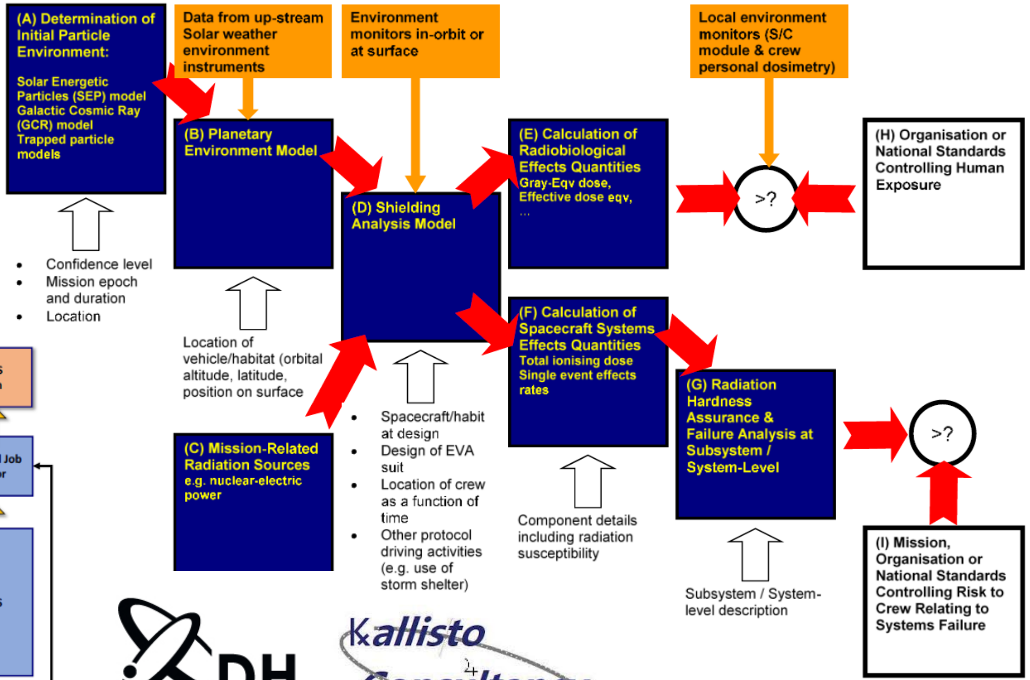
High-Energy eXtension (SAPPHIRE-HEX) - Context

- In the context of human spaceflight end user needs ESA issued a contract to develop a Human Interplanetary Exploration Radiation Risk Assessment System (HIERRAS)

ESA Contract No. 4000127129/19/NL/HK

- HIERRAS is built using docker containers has been designed to be able to communicate with other environment tools via ESA's Network of Models {NoM}





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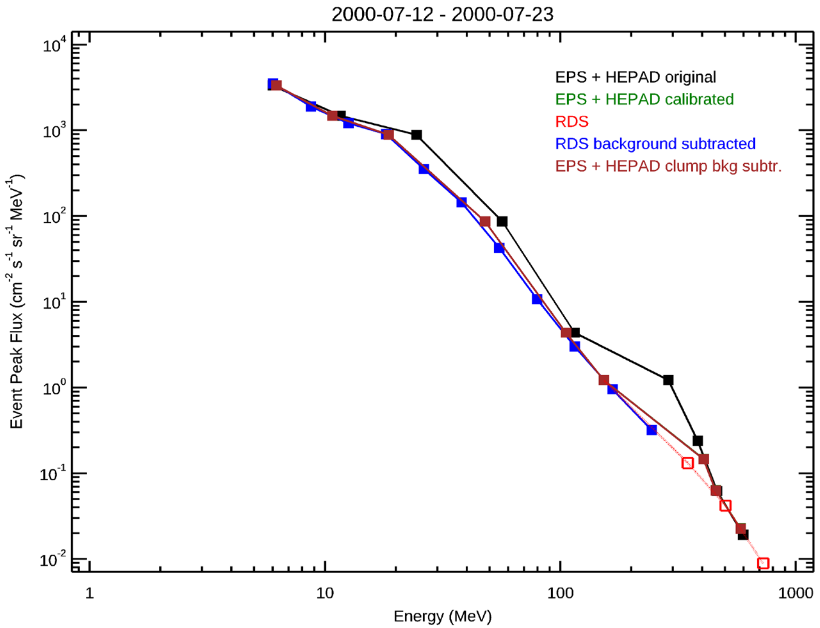
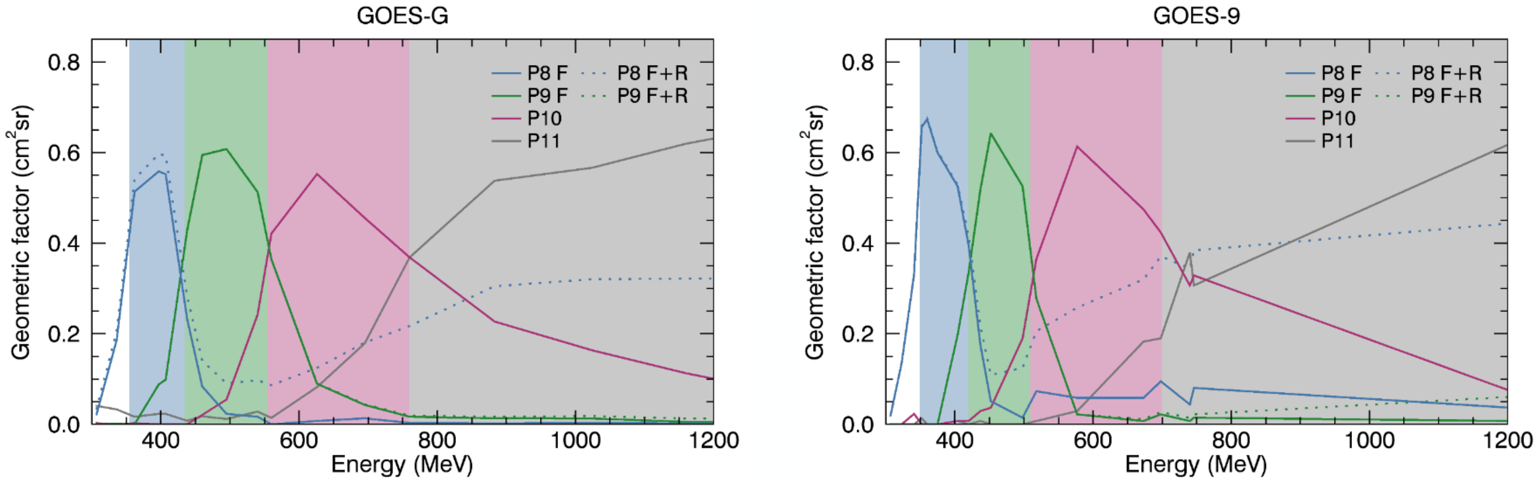
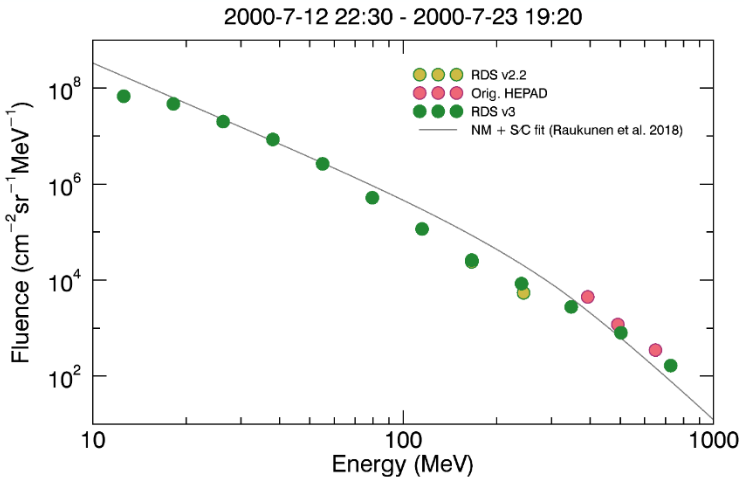
- For such applications, spectral resolutions at high energies are important due to heavily-shielded environments and the impact of induced secondary particles

High-Energy eXtension (SAPPHIRE-HEX) - Data

- Detailed processing of GOES/HEPAD data carried out
- The response functions are energy dependent inside the nominal HEPAD channels (colored areas in the figures)
- Some channels have significant response outside nominal range
- Geometric means and nominal channel ranges are not suitable to describe the channels in SEP measurements
- Bow-tie analysis gives better effective channel energy estimates
- The resulting data is the basis for SEPEM RDSv3







High-Energy eXtension (SAPPHIRE-HEX) - Data

Finalised version of SEPEM RDSv3 will include 3 sub versions:

- **RDSv3.0**

  Caveats removed and stamped with effective energies

- **RDSv3.1**

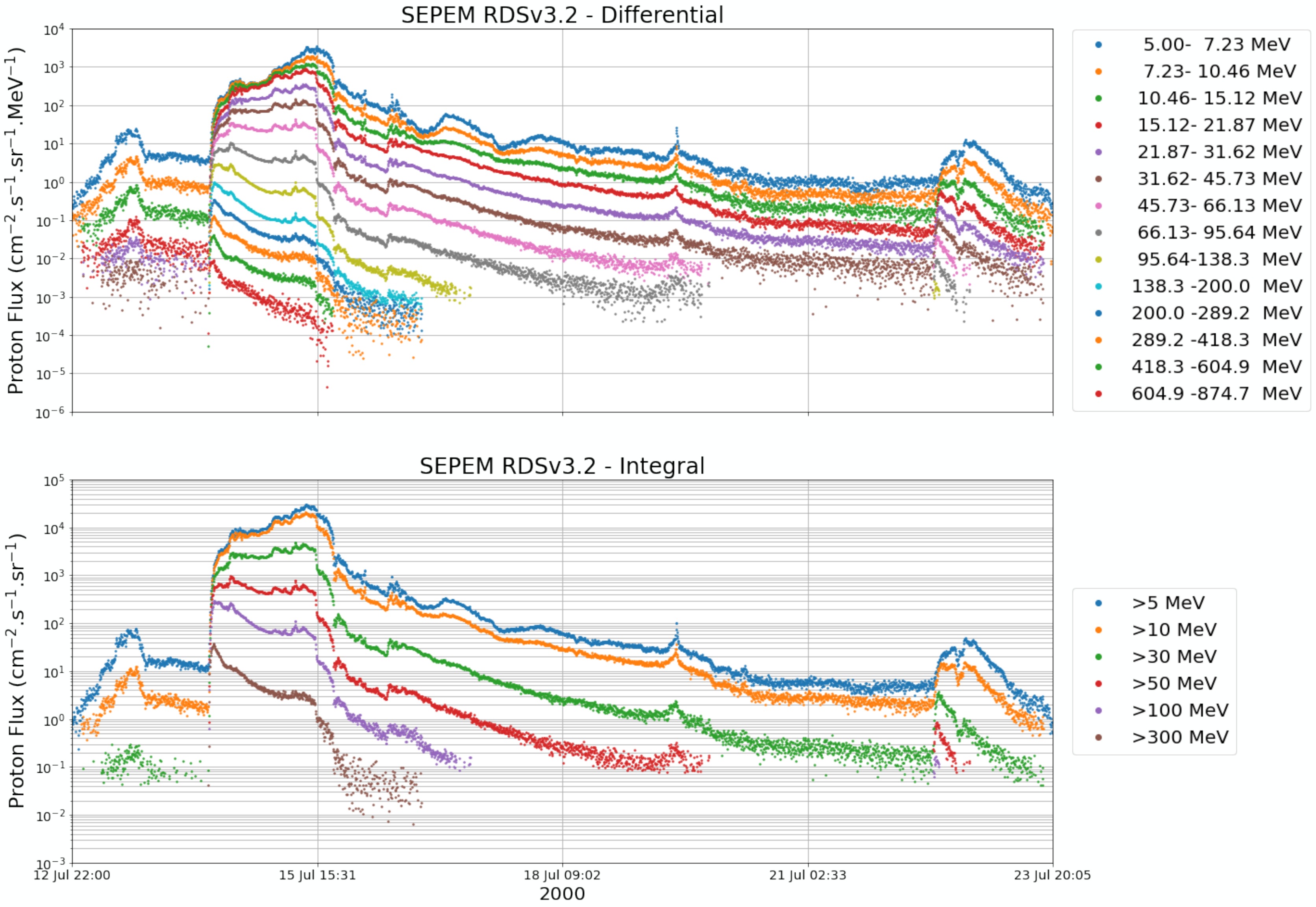
  Signal Extracted/Background subtracted

- **RDSv3.2**

  Re-binned into reference energies with integral (see image) and helium extension

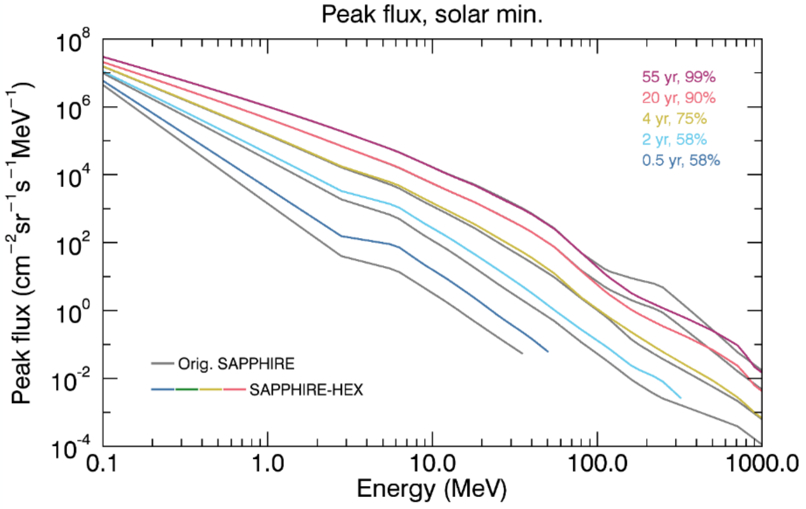
There will be a new accompanying event list

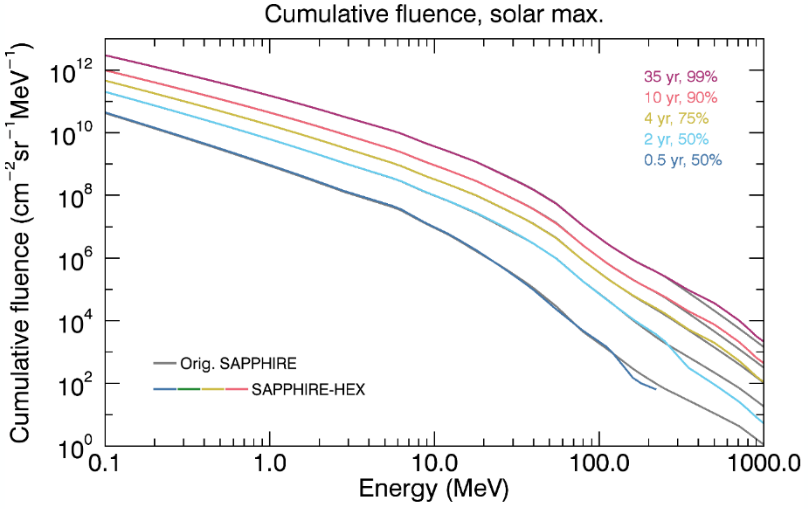
Should be released soon

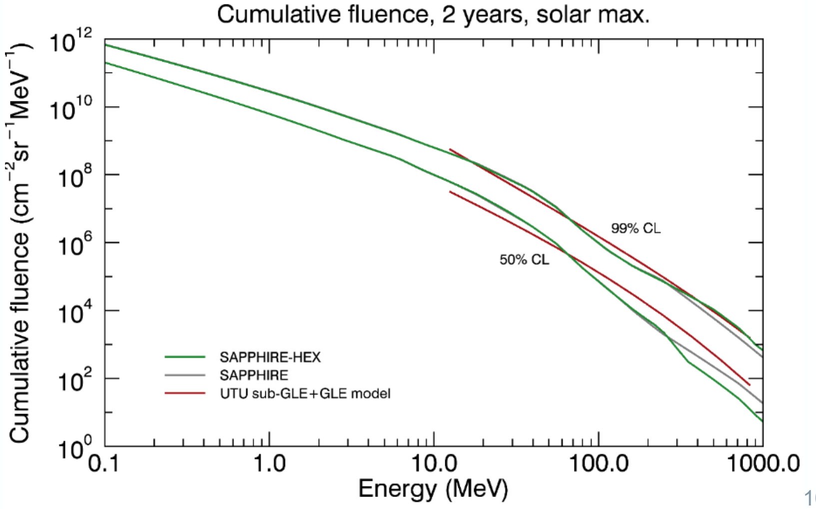


High-Energy eXtension (SAPPHIRE-HEX) - Outputs

- In general the results compare very well to the existing SAPPHIRE model outputs
  - Fluence model agrees very well with the UTU NM + S/C-based GLE + sub-GLE model
- Better confidence of fluence results at high energies
  - Broader spread of model outputs (duration/confidence) at higher energies
  - Very little extrapolation needed to reach 1 GeV (low energy extrapolation validated)
- Peak flux model problem as January 2005 event is an order of magnitude above others at high energy
  - For HEX this event is excluded from the peak flux model because distribution fits are not reasonable
  - Low energy extrapolation is still erroneous but there is no established use case (applies only to peak flux)







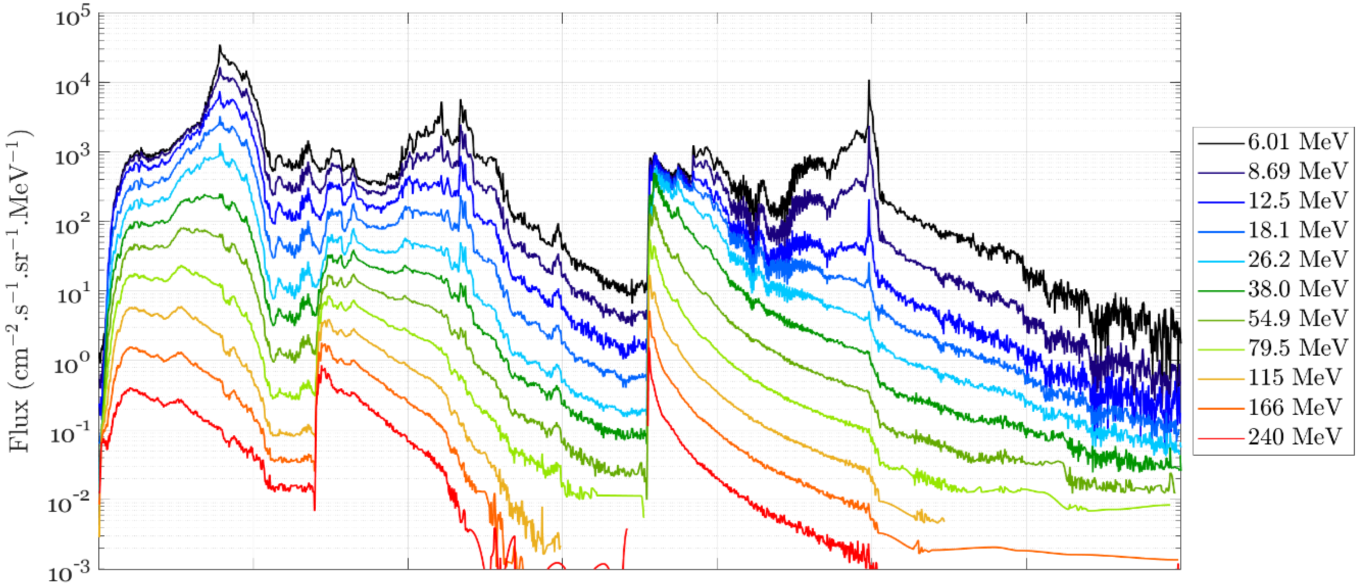
SAPPHIRE-2S – Rational

- Existing SEP specification models give the following outputs at a range of energies:

  Peak Flux - Largest Event Fluence - Mission Cumulative Fluence
- However, proper assessment of Single Event Effects (SEEs) and sensor interference requires time series.
- Presently, coarse data-driven CREME96 (peak 5-min, worst day, worst week) outputs based on October 1989 SPE widely used
  - For future operational missions this is not sufficient
- Such missions include (but are not limited to) Space Weather Missions such as ESA's planned L5 mission Vigil
- In the context of collaboration on the International Radiation Environment Near-Earth (IRENE), ESA issued a contract to develop new radiation models and tools including a new SEP model

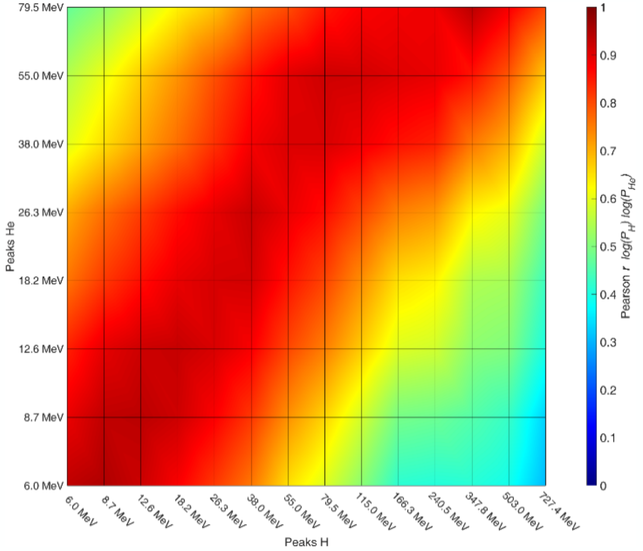
ESA Contract No. 4000127282/19/NL/IB/gg

[below] Composite time series produced for Lagrange based on October 2003 and January 2005 SPEs scaled to match SAPPHIRE statistical outputs



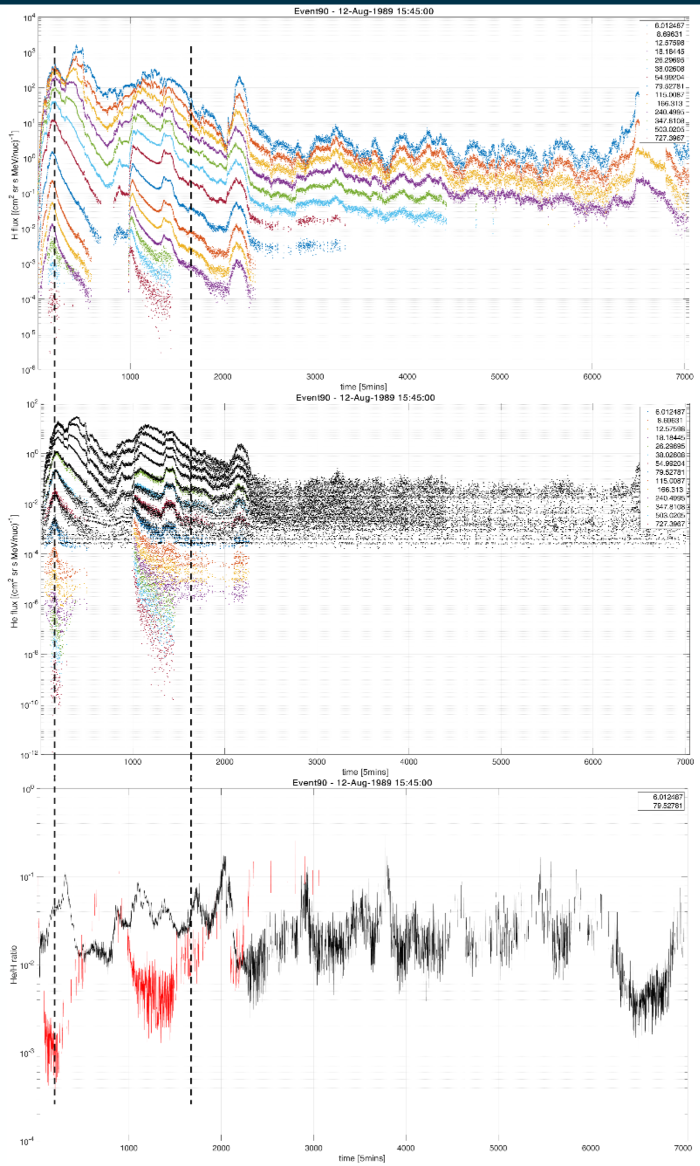
SAPPHIRE-2S – Context and Data

- The next generation of the model or version 2, named SAPPHIRE-2S [S: Space Applications & Research Consultancy (SPARC), Greece]
- SEPEM RDSv3 includes helium extension (see right)
- With complete flux time series SAPPHIRE is extended to derive complete model output time series in addition to synoptic results of peak flux and fluence
- This model is expanded to heavy ions and to helioradial distances other than 1 AU



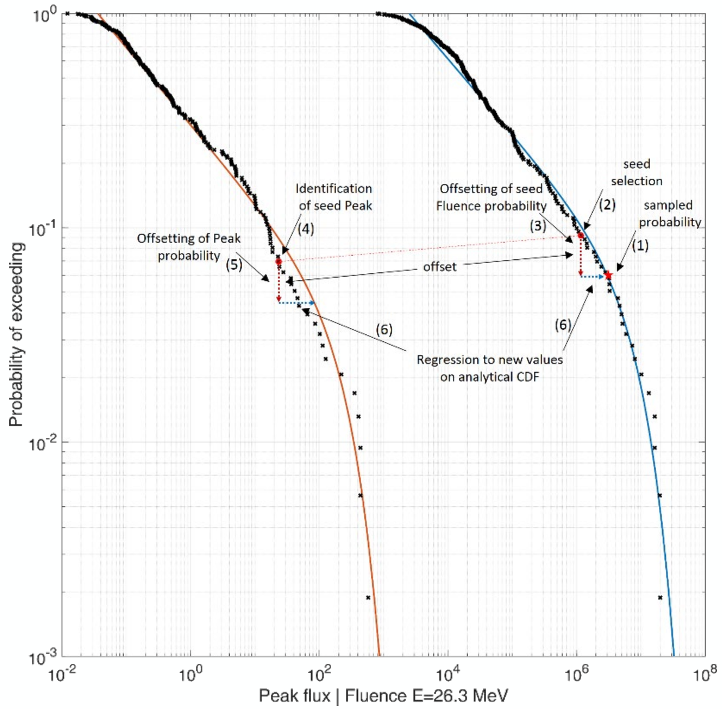
[left] Correlation map of proton peaks vs helium peaks for all available channels indicating trend for higher-energy protons to be related to lower-energy helium.

[right] RDSv3 proton fluxes (top), RDSv3 He fluxes and extrapolated high-energy channels (middle), ratio of helium to proton flux (lower)

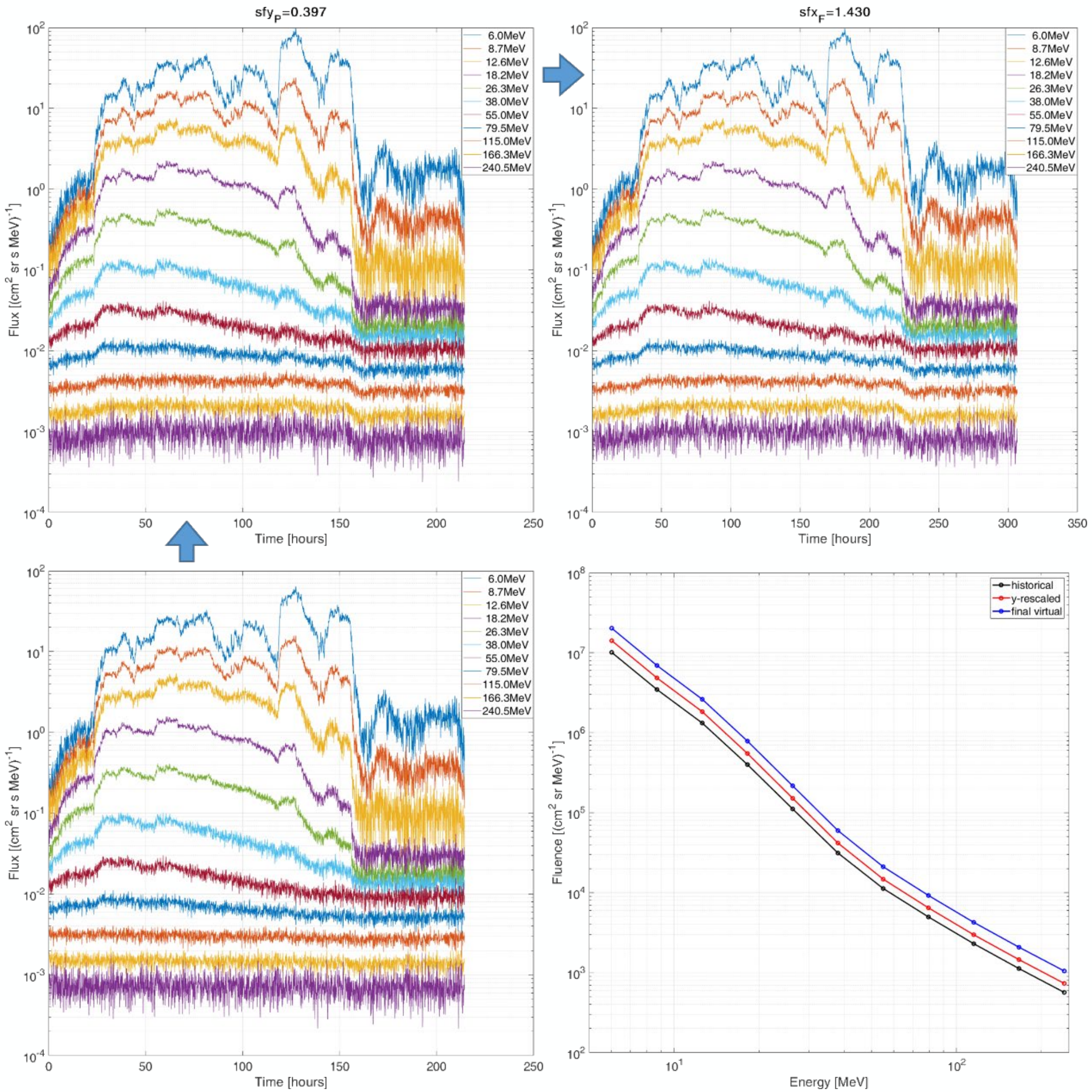


SAPPHIRE-2S - Methodology

- SAPPHIRE-2S continues in following the virtual timelines approach but with notable upgrades:
  - Flux time series are provided as output
  - Outputs are derived for all channels simultaneously
  - Via re-scaling of historical enhancements

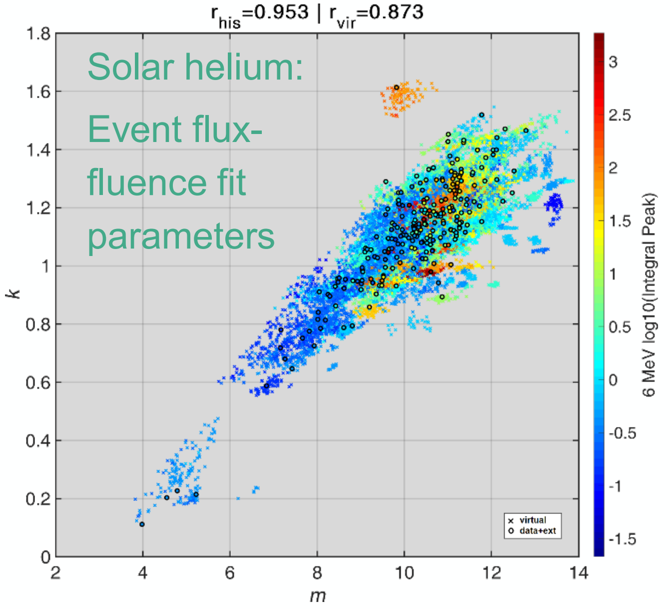


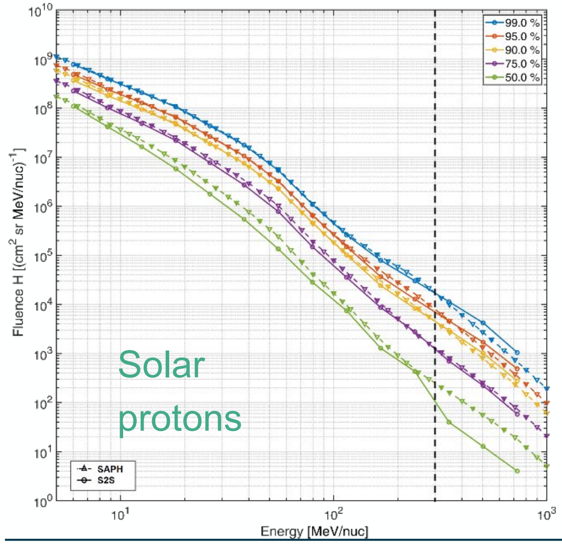
- Reference channel peak and fluence randomly sampled
- Model selects appropriate (historical) seed event based on flux/fluence
- Time series are scaled in flux to match the peak and time to match fluence
- All channels scaled; spectral coherence preserved

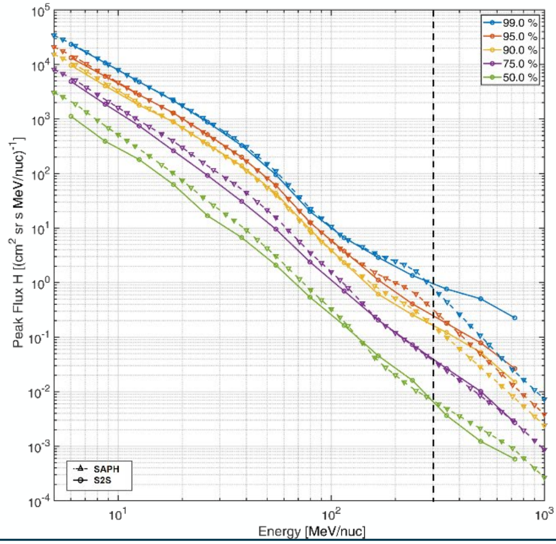


SAPPHIRE-2S – Preliminary Results

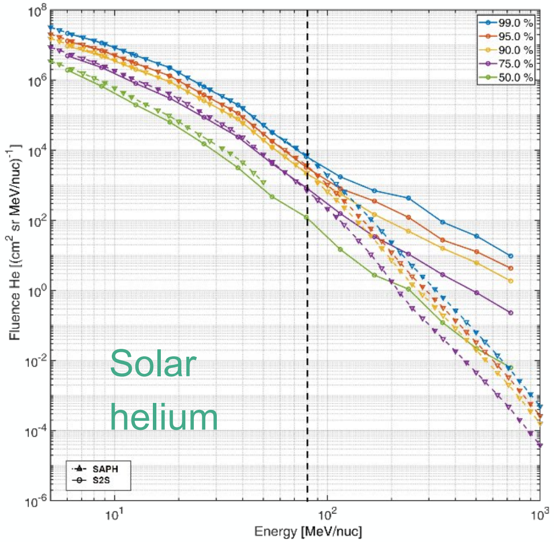
- Model matches event data spectral parameters whilst filling in the grid.
- Synoptic proton outputs for SAPPHIRE-2S agree closely with SAPPHIRE
- Proton model is no longer extrapolating to high-energy protons but using RDSv3
- Note that the Jan 2005 event is captured but high-energy protons channels are not used as references (no distribution fits need to be applied to these channels)
- He model is using extrapolated fluxes (but is not extrapolating results)
- In extrapolation regime there is strong divergence in (especially fluence) results
- We are checking the underlying data and routines before finalisation

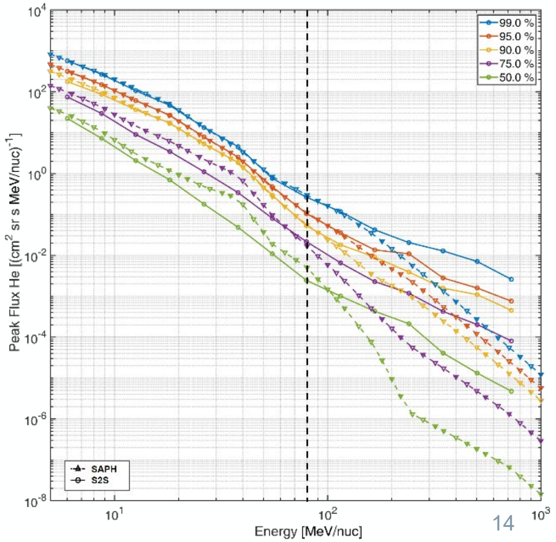






Black dashed lines show SAPPHIRE extrapolation





How will SAPPHIRE-2S run?

The model takes a JSON file as input:

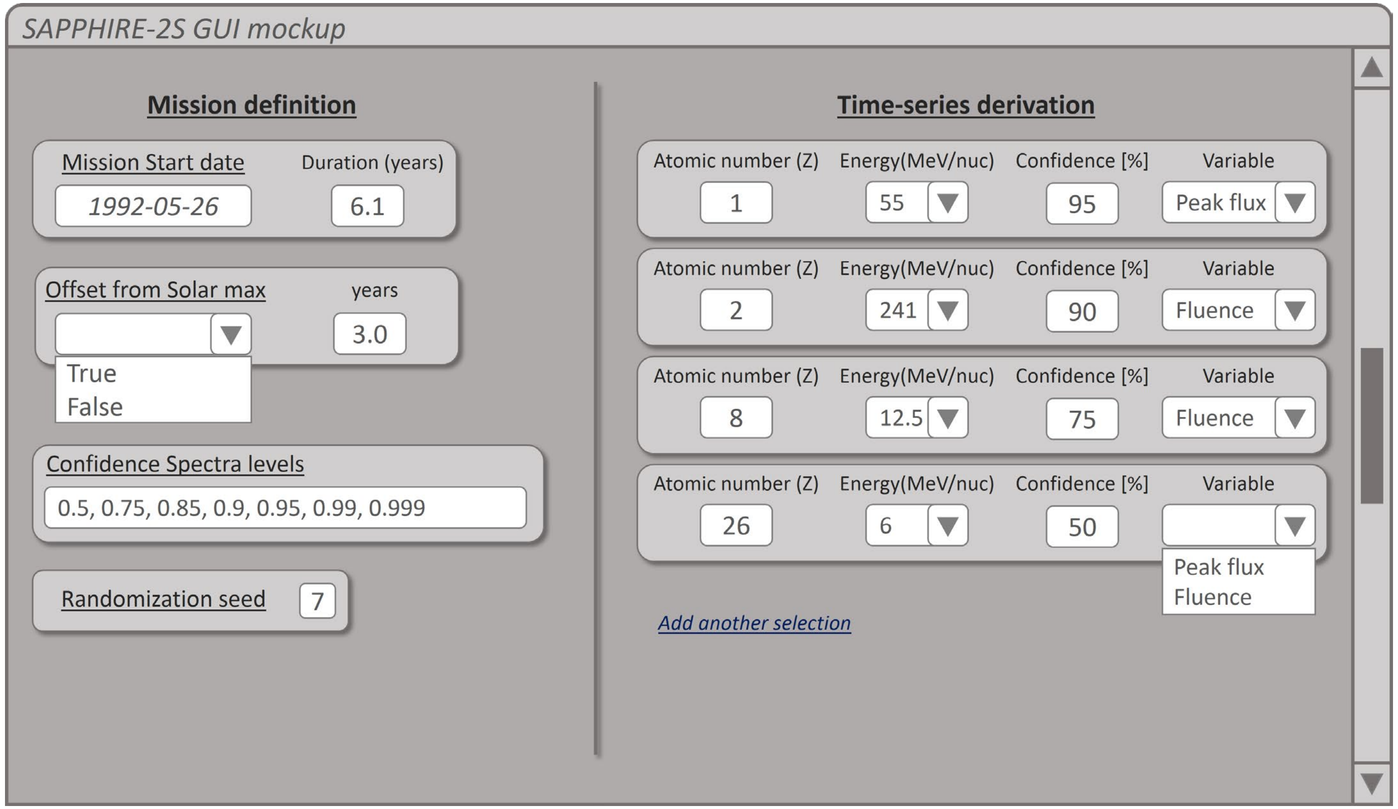
"mission_params": [mission start date, duration (in years), logical flag for offset from solar max., years (of offset)]

“Z_Var_E_Q": A list of desired time series [Z(atomic number) basis, variable (Peak Flux/Fluence), Energy (MeV/nuc), Confidence Level]

"conf_levels": List of confidence levels (applied only to mission for derivation of Fluence and Peak flux confidence spectra)

"scenario": a seed for random variable extraction, if left empty takes fixed seed from hidden_vars file – should be integer but will be rounded if not

"MSM": Logical flag for magnetospheric shielding model MSM (currently only placeholder)

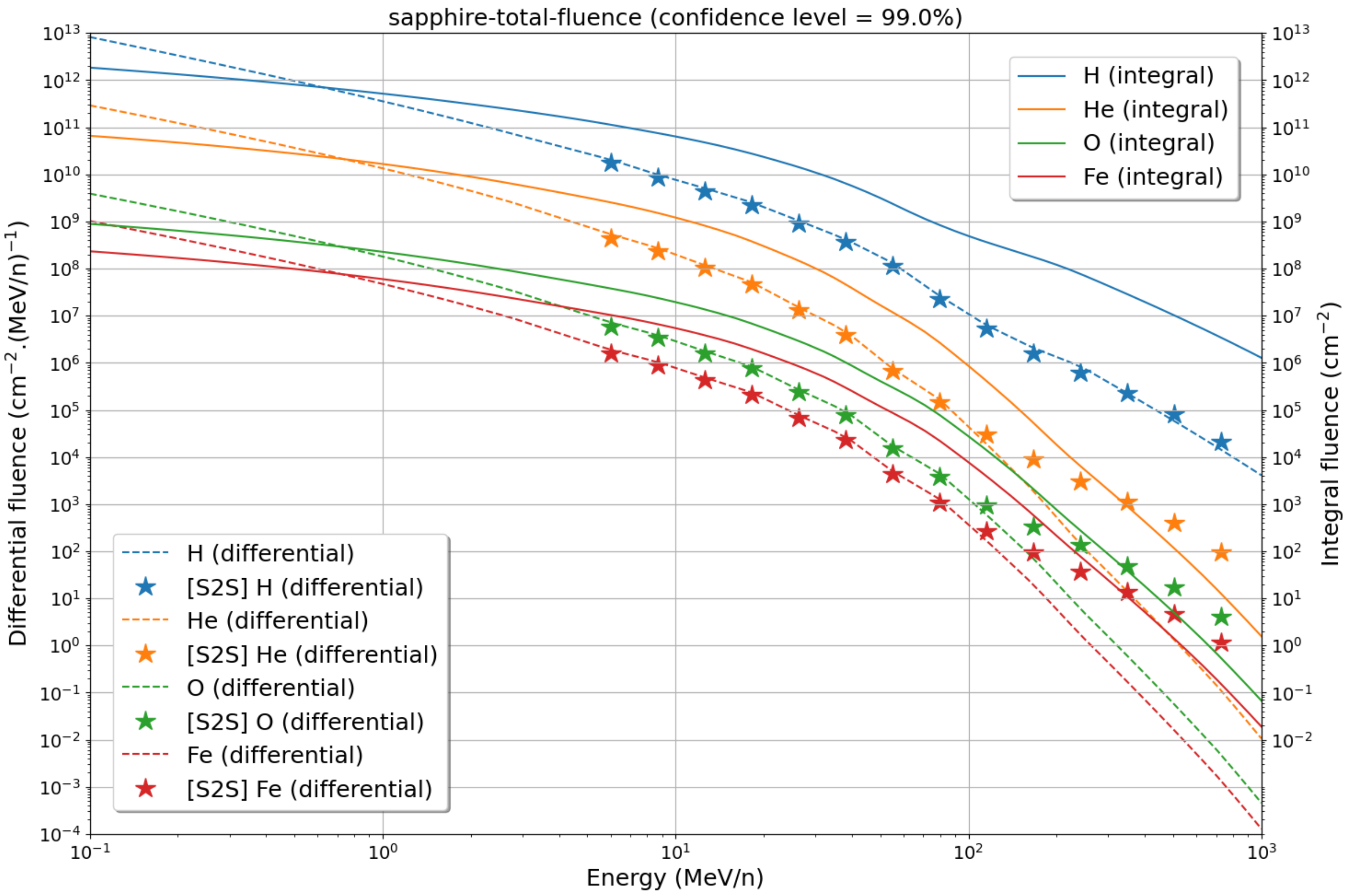


What will SAPPHIRE-2S give the user?

Two types of results.

Type 1 is the synoptic results

- Mission Fluence and Peak Flux at a user specified (set of) confidence level(s)
- 92 Species
- 14 energies from 5 – 900 MeV/nuc

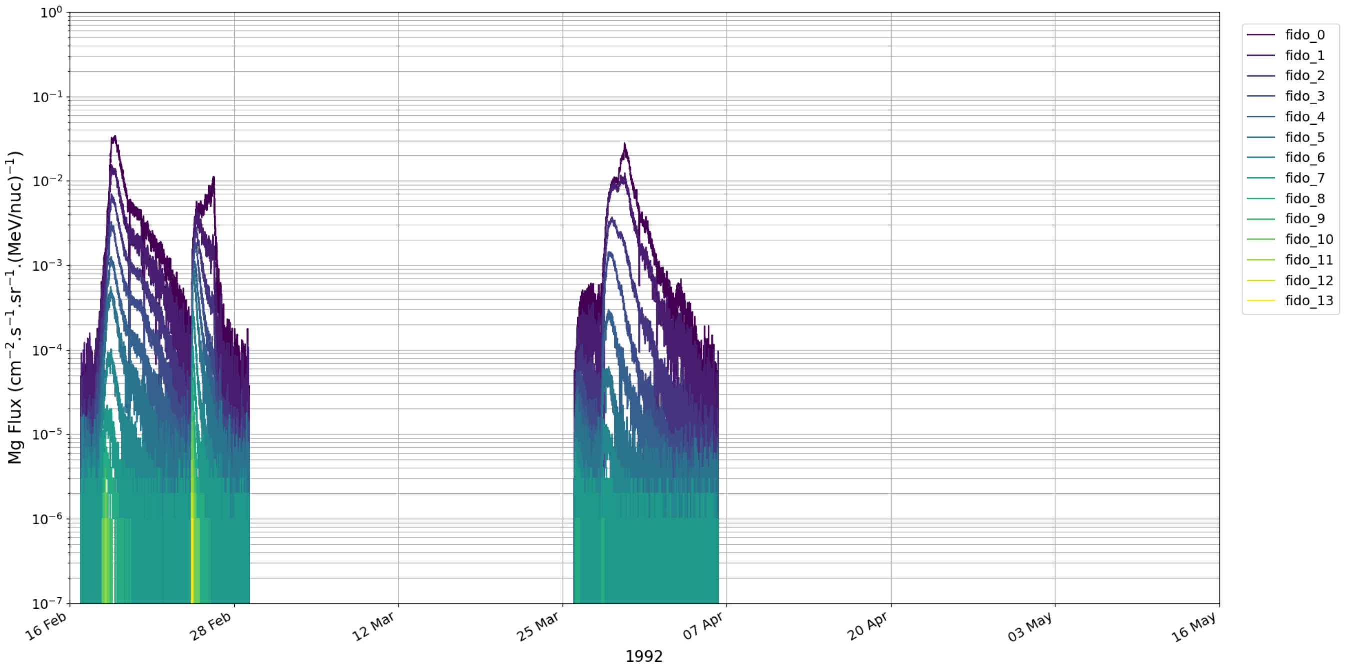


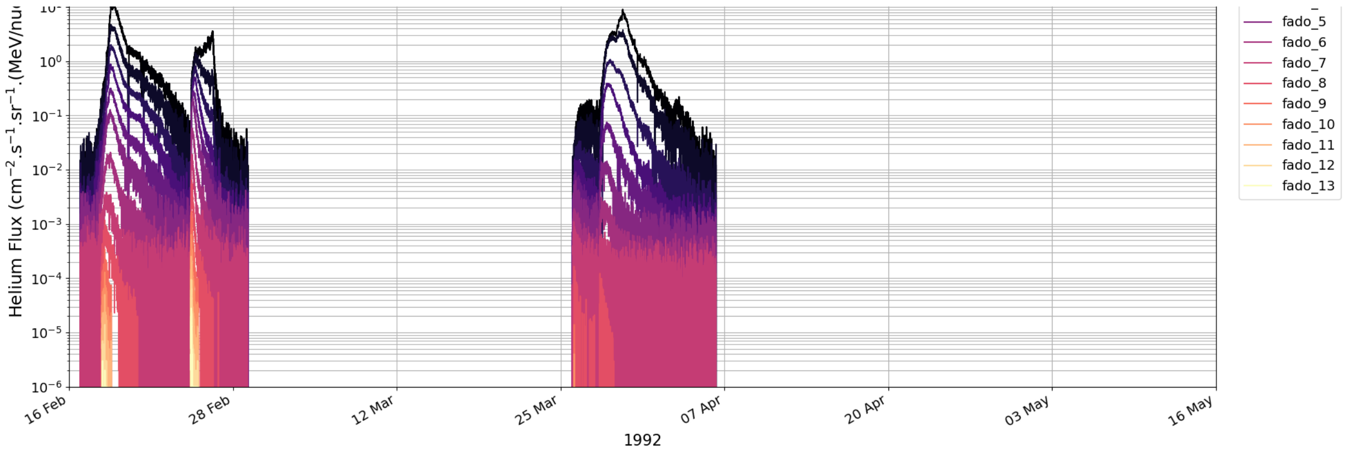
What will SAPPHIRE-2S give the user?

Two types of results.

Type 2 is the time series results

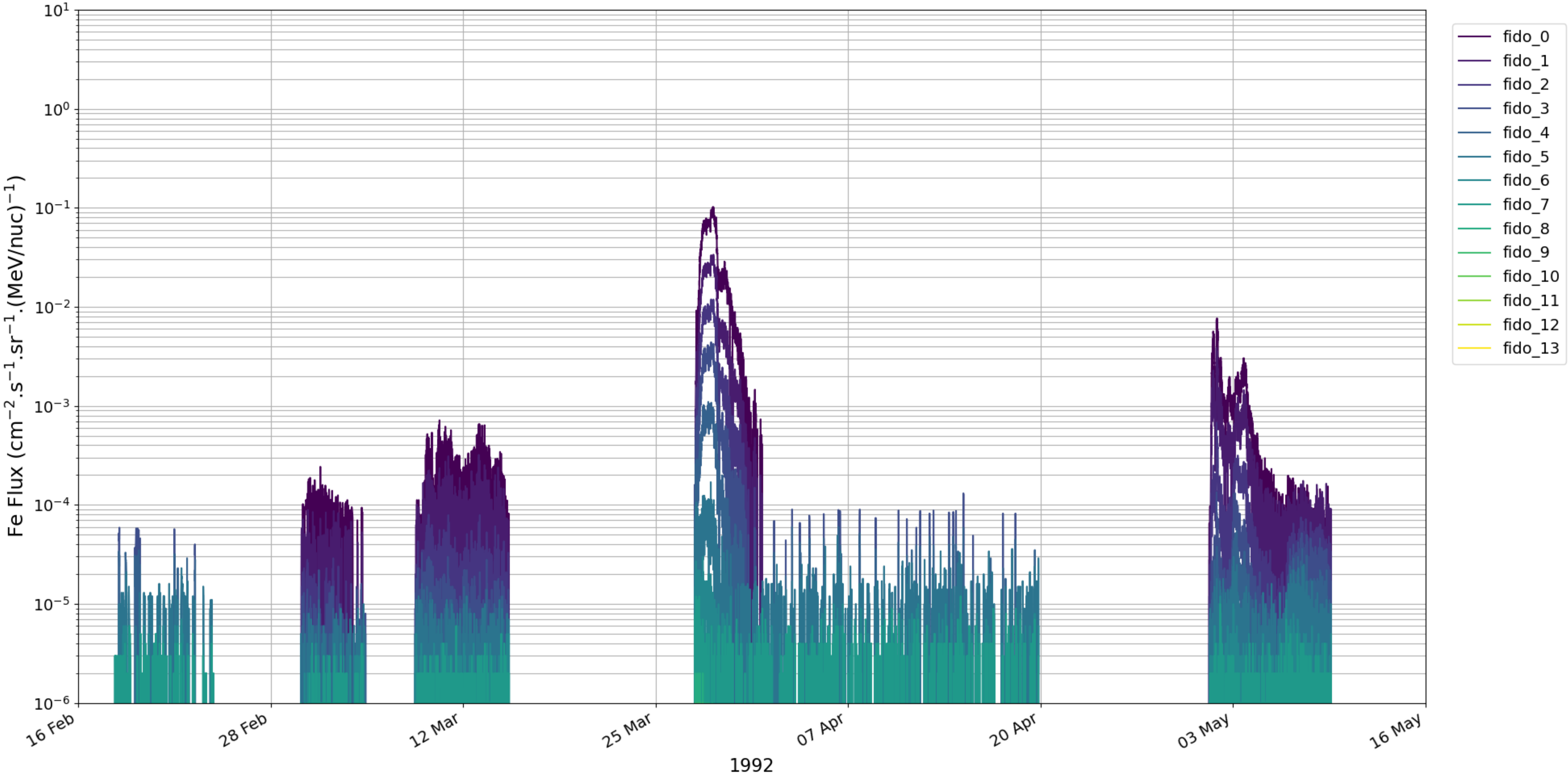
- Time series is defined by confidence level defined
- It is assessed based on the species and energy specified
- Protons and Alpha particles always output
- If specified species is >Z=2 then that output is also given
- 14 energies from 5 – 900 MeV/nuc





Example: Peak Flux Fe @ 50 MeV & 99.9% (6 years)

esa



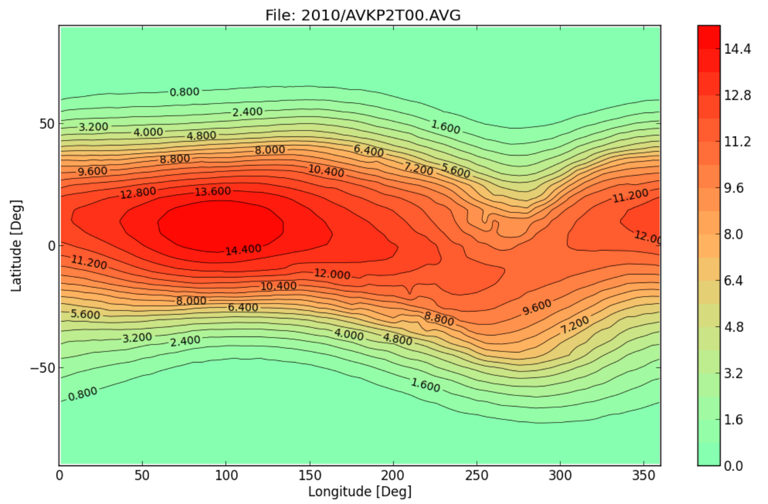
Where Next For SAPPHIRE-2S

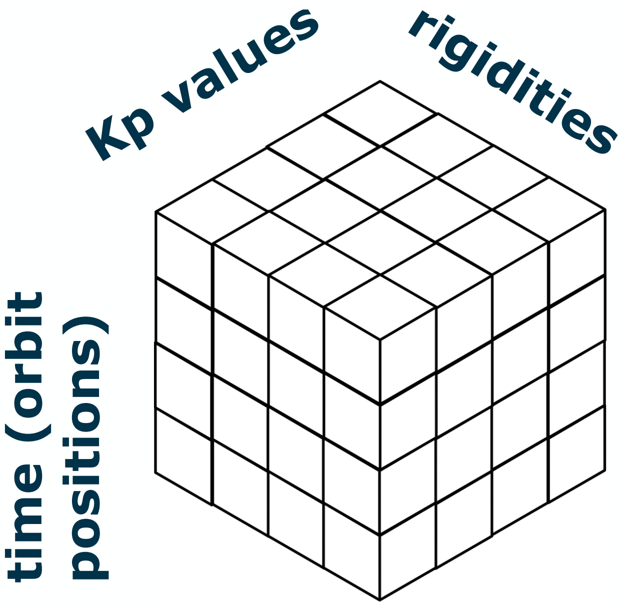
Near Future

- Update the model to the final version of the SEPEM RDSv3.2
- Hopefully update the model to use the newer version of the SEPEM Reference Event List (REL)
- Incorporate the first version of the model dealing with helio-radial variations
- Connect the model with the MSM code to treat geomagnetic shielding

Not-too-distant Future

- Include solar electrons in the model
- Extend the low-energy limit down to plasma energies for material damage/erosion
- Include an updated version of the model dealing with helio-radial variations





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