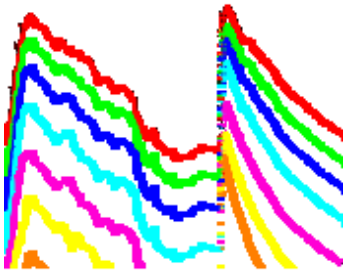

Monitoring solar energetic particles with ESA SREM units

I. Sandberg
Institute for Space Applications and Remote Sensing
National Observatory of Athens, Greece

Collaborators

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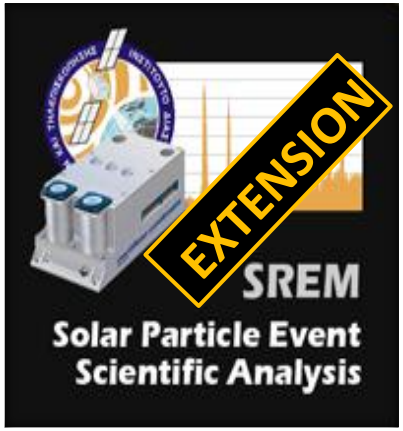
Institute for Space Applications and Remote Sensing, NOA

M. Georgoulis

Research Center of Astronomy and Applied Mathematics, Academy of Athens

P. Nieminen and E. Daly

Space Environments and Effects Section, ESA/ESTEC



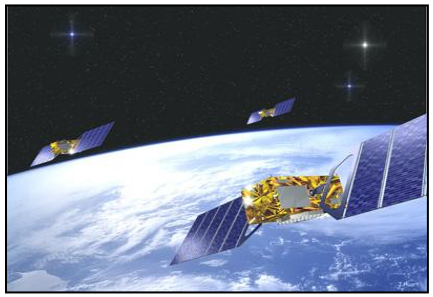
Extension of ESA contract number 21480/08/NL/NR

Outline

- ESA Standard Radiation Monitor
- The ESA SREM missions
- Solar energetic particles and events
- SREM detection principle
- Unfolding SREM data
- Validation of method
- The solar energetic particle flux tool

ESA Standard Radiation Environment Monitor

PROBA-1

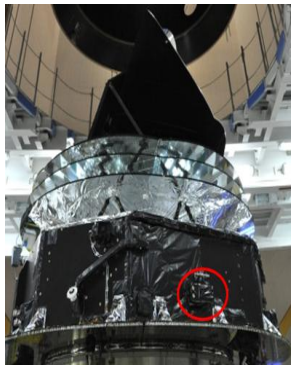


GIOVE-B

INTEGRAL

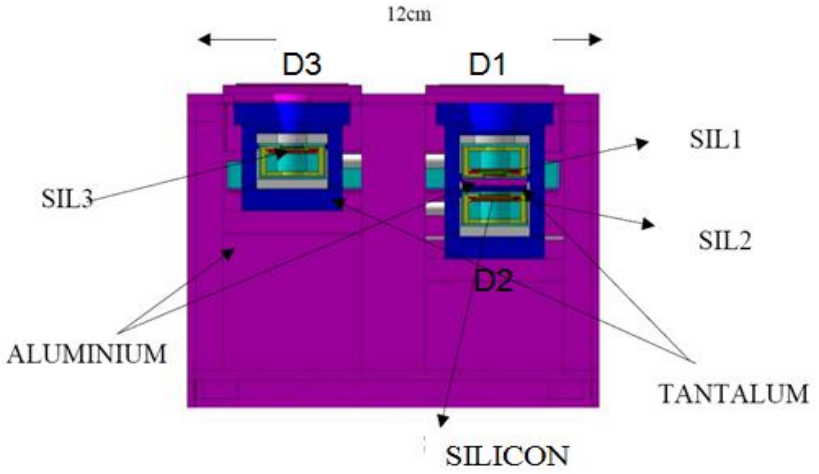
ROSETTA

HERSCHEL



PLANCK

ESA Standard Radiation Monitor

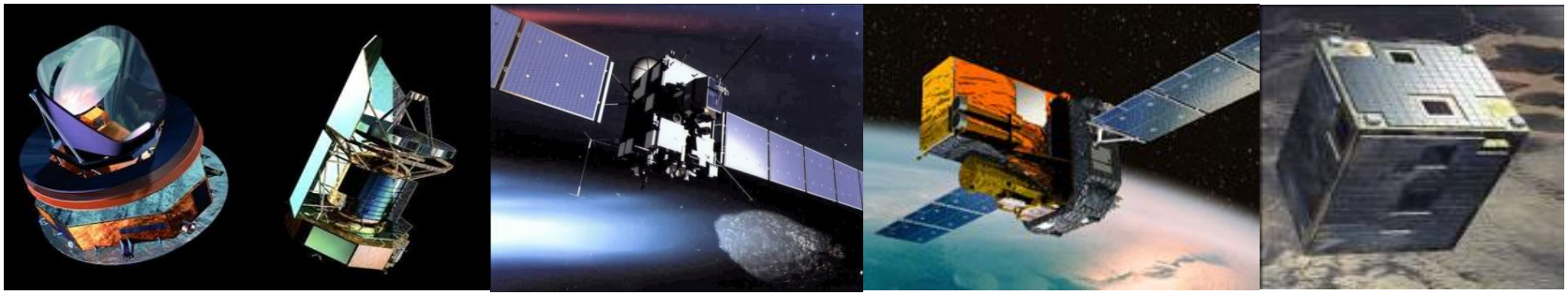


- Charged particle detector based on three solid state *Si* crystals
- Detects high-energy charged particles: e^- E_e>1 MeV, p^+: E_p>10 MeV
- Monitors spacecraft radiation environment
- Provides functions related to space weather hazards for the host spacecraft and its payload
- Provides data associated to various physical processes.

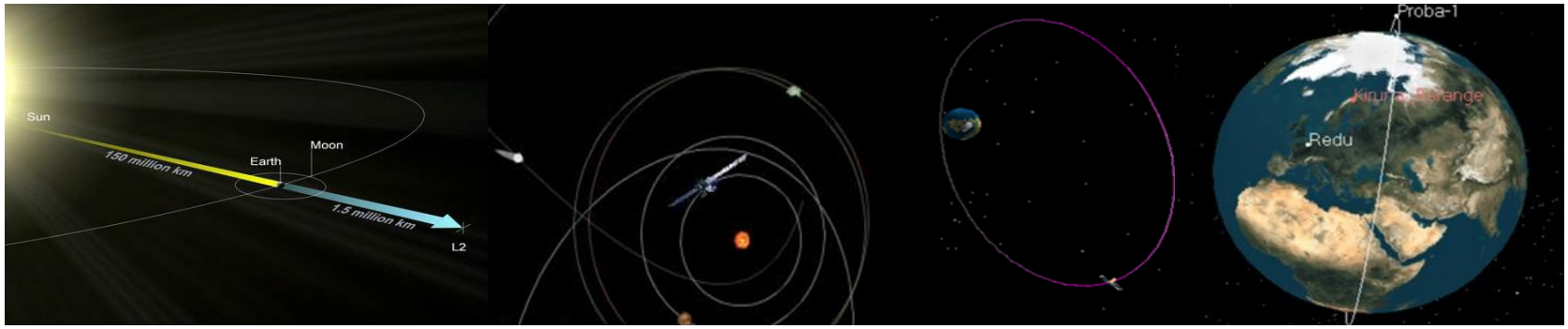
SREM multipoint measurements

Sources

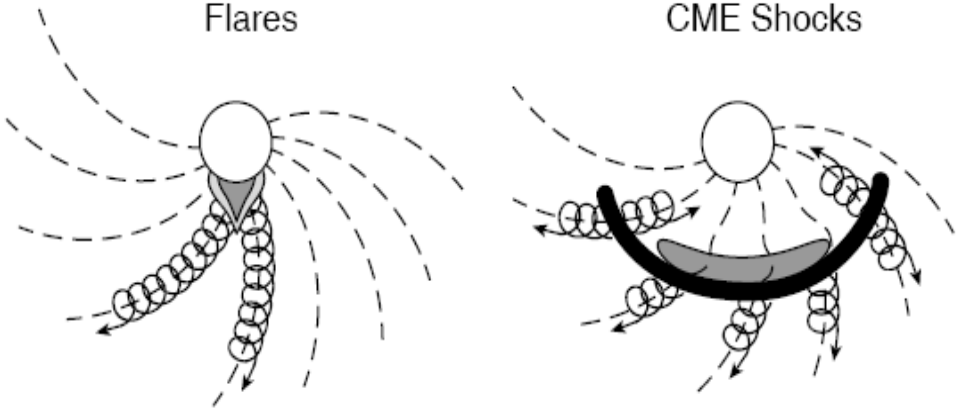
Missions

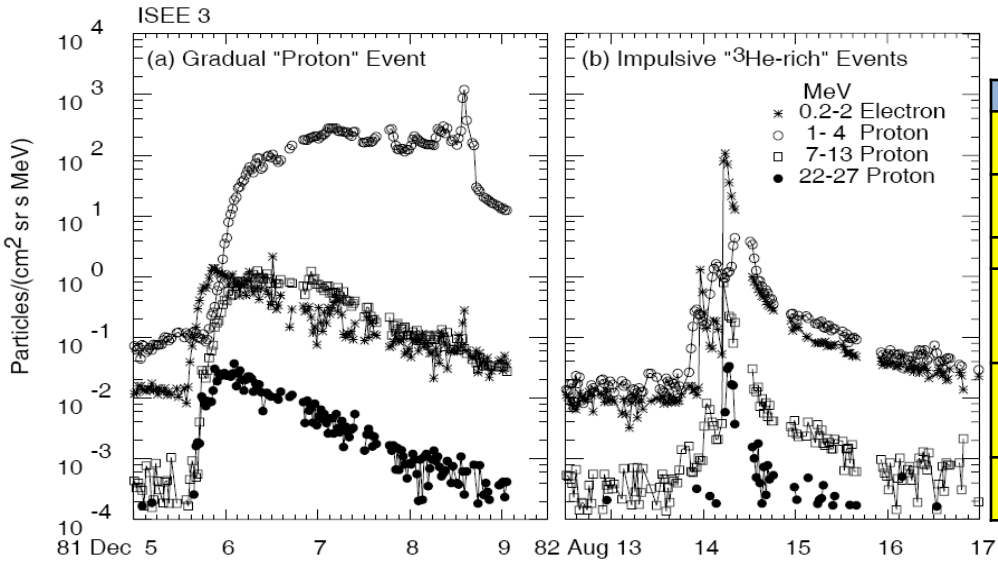


Orbits



Sources of solar energetic particles

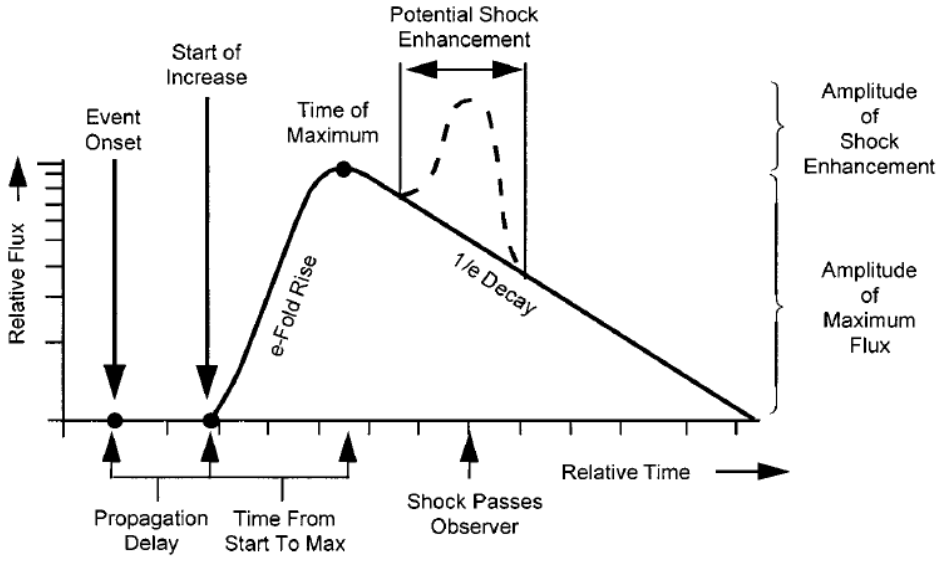




	Impulsive events	Gradual events
Associated Source	Solar flares	CMEs
Particles	electrons, --^{3}He, heavy ions	Proton rich
Occurrence frequency	~10^{3}/y during solar maximum	~10/y during solar maximum
Duration	~ hrs	~ days
Heavy isotope abundances	Enhanced compared to coronal populations	Similar to coronal populations
Ionization state	Enhanced compared to coronal populations	Similar to coronal populations
Net fluence	<10^{7}-10--^{8} particles/cm^{2}	~ 10--^{9} particles/cm^{2}

Solar particle event

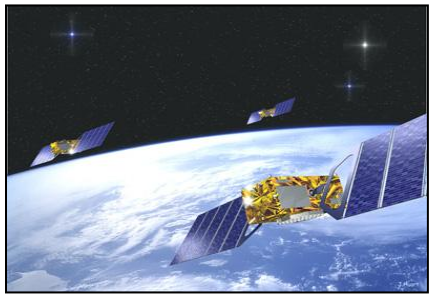
NOAA definition: the period of time when the integral flux of protons with energy greater than 10 MeV exceeds 10 particles/sec/cm^2/sr.



SREM/SEP data

PROBA-1

Mission	Data	Orbit
PROBA1	2001-11	LEO (sun synchronous)
INTEGRAL	2002-11	HEO (highly eccentric)
Rosetta	2004-11	Interplanetary
Herschel	2009-06	L2
Planck	2009-06	L2
GIOVE-B	2008-06	MEO (near-circular)

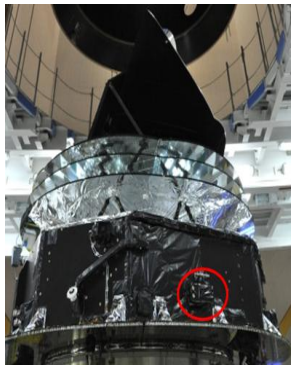


GIOVE-B

INTEGRAL

ROSETTA

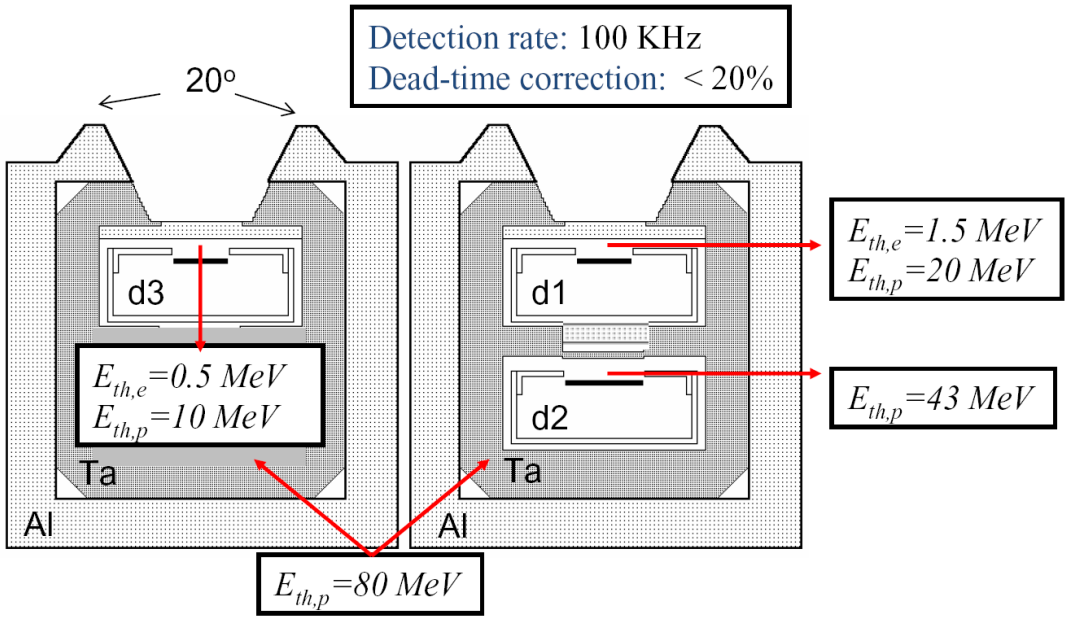
HERSCHEL



PLANCK

SREM: Principle of detection

- SREM consists of three solid-state *Si* detectors (d1 & d2, d3)
- Charged particle interacts with band electrons and creates e^--hole pairs
- Collected charge is proportional to the energy loss of incident particles
- Pre-amplified pulses are scrutinized and registered in 15 counters

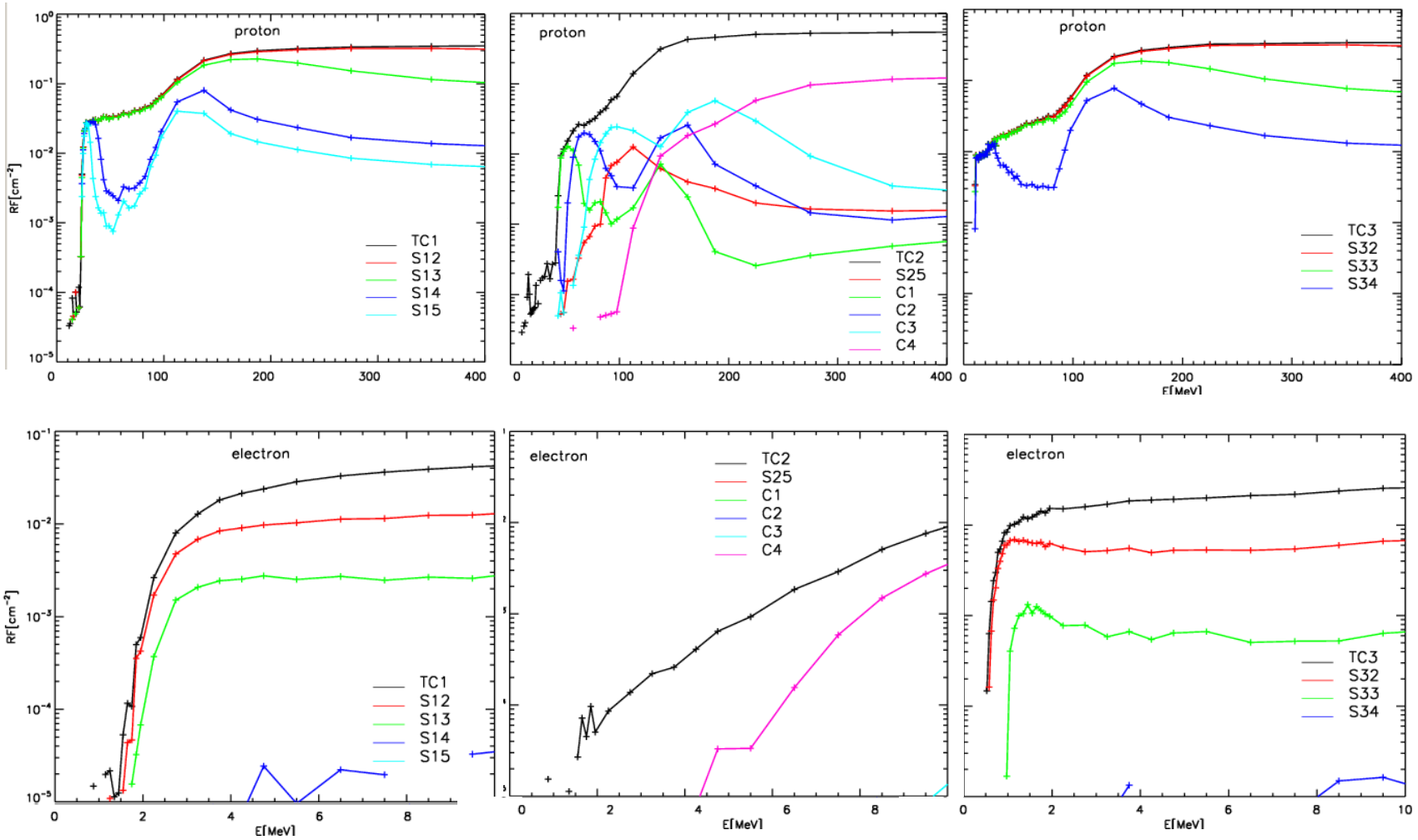


SREM counters

$$C_i = \sum_{q=p,e} C_{i,q} = \sum_{q=p,e} \left[\int_0^{\infty} f_q(E) RF_{i,q}(E) dE \right]$$

SREM	Proton Energy	[MeV]	Electron Energy	[MeV]
Bin	E_{min}	E_{max}	E_{min}	E_{max}
TC1	27	∞	2.00	∞
S12	26	∞	2.08	∞
S13	27	∞	2.23	∞
S14	24	542	3.20	∞
S15	23	434	8.18	∞
TC2	49	∞	2.80	∞
S25	48	270	–	–
C1	43	86	–	–
C2	52	278	–	–
C3	76	450	–	–
C4	164	∞	8.10	∞
TC3	12	∞	0.80	∞
S32	12	∞	0.75	∞
S33	12	∞	1.05	∞
S34	12	∞	2.08	∞

INTEGRAL/SREM Response functions



Unfold SREM data: Counts to fluxes

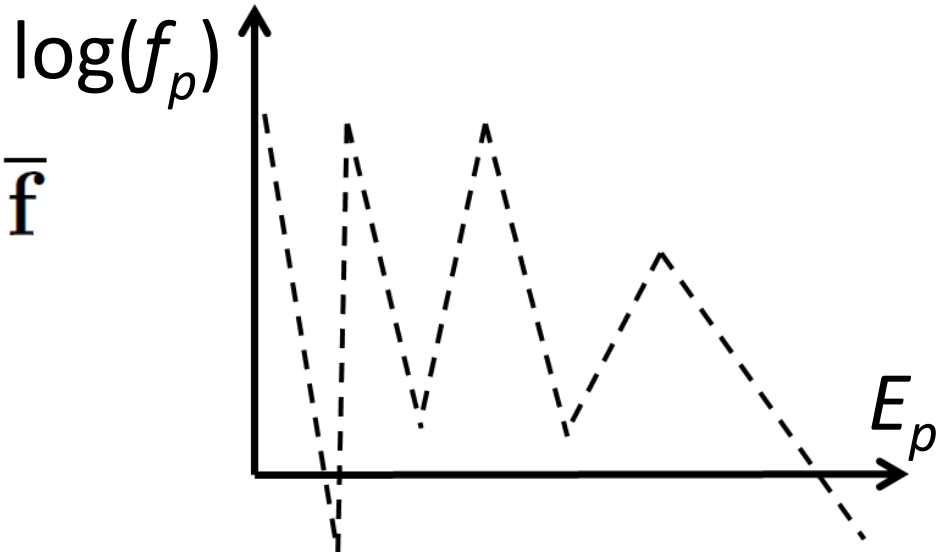
$$C_i = \sum_{q=p,e} C_{i,q} = \sum_{q=p,e} \left[\int_0^\infty f_q(E) RF_{i,q}(E) dE \right]$$

Fredholm integral equation of the first kind -> *Ill-posed problem: non-unique solution, solution is not a continuous function of counts*

The numerical solution of the discrete problem is widely oscillating

- SREM channels have strongly overlapping energy ranges
- Proton/electron contamination effects
- finite spectral resolution/calibration errors
- noise in measurements

$$\mathbf{C} = \mathbf{RF} \cdot \overline{\mathbf{f}}$$



Unfold SREM data: regularization

$$\begin{bmatrix} \mathbf{RF} \\ \sqrt{\tau}\mathbf{R} \end{bmatrix} \cdot \bar{\mathbf{f}} = \begin{bmatrix} \mathbf{C} \\ \mathbf{0} \end{bmatrix}$$

$$\mathbf{R} = \begin{bmatrix}
-1 & 1 & 0 & \cdots & \cdots & 0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\
1 & -2 & 1 & 0 & \cdots & 0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\
0 & 1 & -2 & 1 & 0 & 0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\
\vdots & 0 & \ddots & \ddots & \ddots & \ddots & 0 & \cdots & \cdots & \cdots & \cdots & \vdots \\
0 & 0 & 0 & 1 & -2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & -2 & & 0 & 0 & 0 \\
\vdots & \cdots & \cdots & \cdots & \cdots & 0 & \ddots & \ddots & \ddots & \ddots & 0 & \vdots \\
0 & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 0 & 1 & -2 & 1 & 0 \\
0 & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 0 & 0 & 1 & -2 & 1 \\
0 & \cdots & \cdots & \cdots & \cdots & 0 & 0 & \cdots & \cdots & 0 & 1 & -1
\end{bmatrix}$$

The regularized system of equations can be solved using basic properties of the Singular Value Decomposition (SVD) technique. The decomposition of the product

$$\mathbf{RF} \cdot \mathbf{R}^{-1} = \mathbf{USV}^{\tilde{\mathbf{T}}}$$

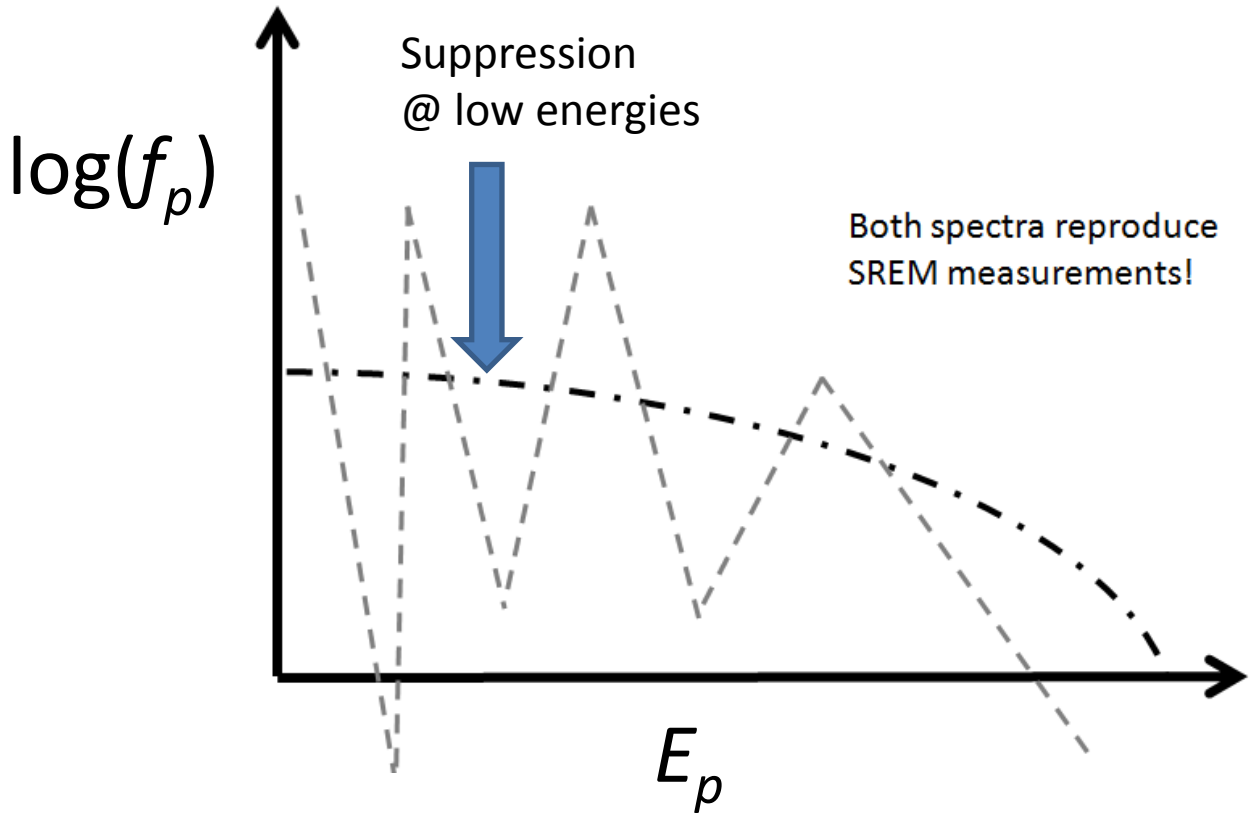
into its left $\tilde{\mathbf{U}} \in \mathcal{R}^{N_b \times N_b}$, right $\mathbf{V} \in \mathcal{R}^{N_x \times N_x}$ singular vectors, and the $\mathbf{S} \in \mathcal{R}^{N_b \times N_x}$ diagonal singular value

*[Höcker A. and Kartvelishvili V., Nucl. Inst. Phys. Res. A **372**, 469-481 (1996)]*

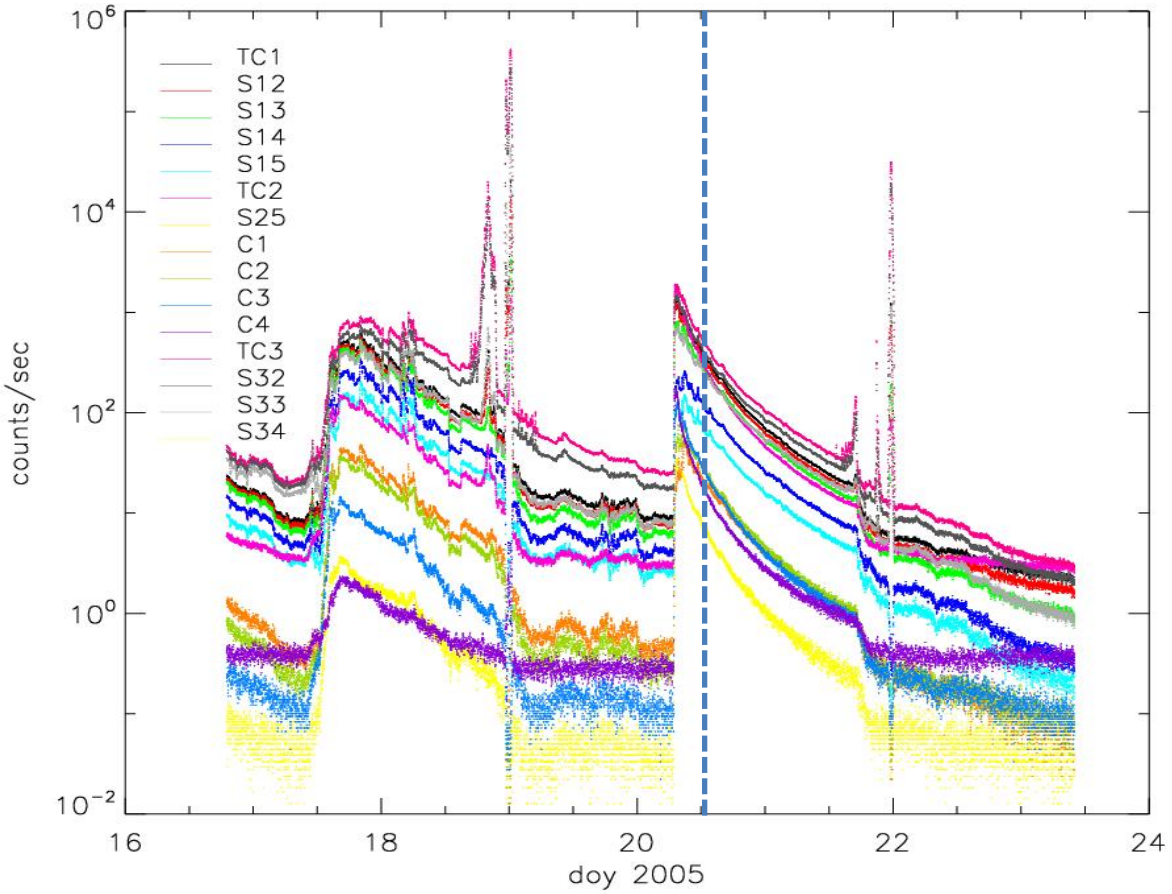
Regularized solution

$$\overline{\mathbf{f}} = \mathbf{R}^{-1}\mathbf{V}\mathbf{z}, \text{ where } z_i = \frac{d_i s_i}{s_i^2 + \tau}$$

The non-zero τ regularizes the singularities - small s_i's - acting as a cut-off low pass Fourier filter.

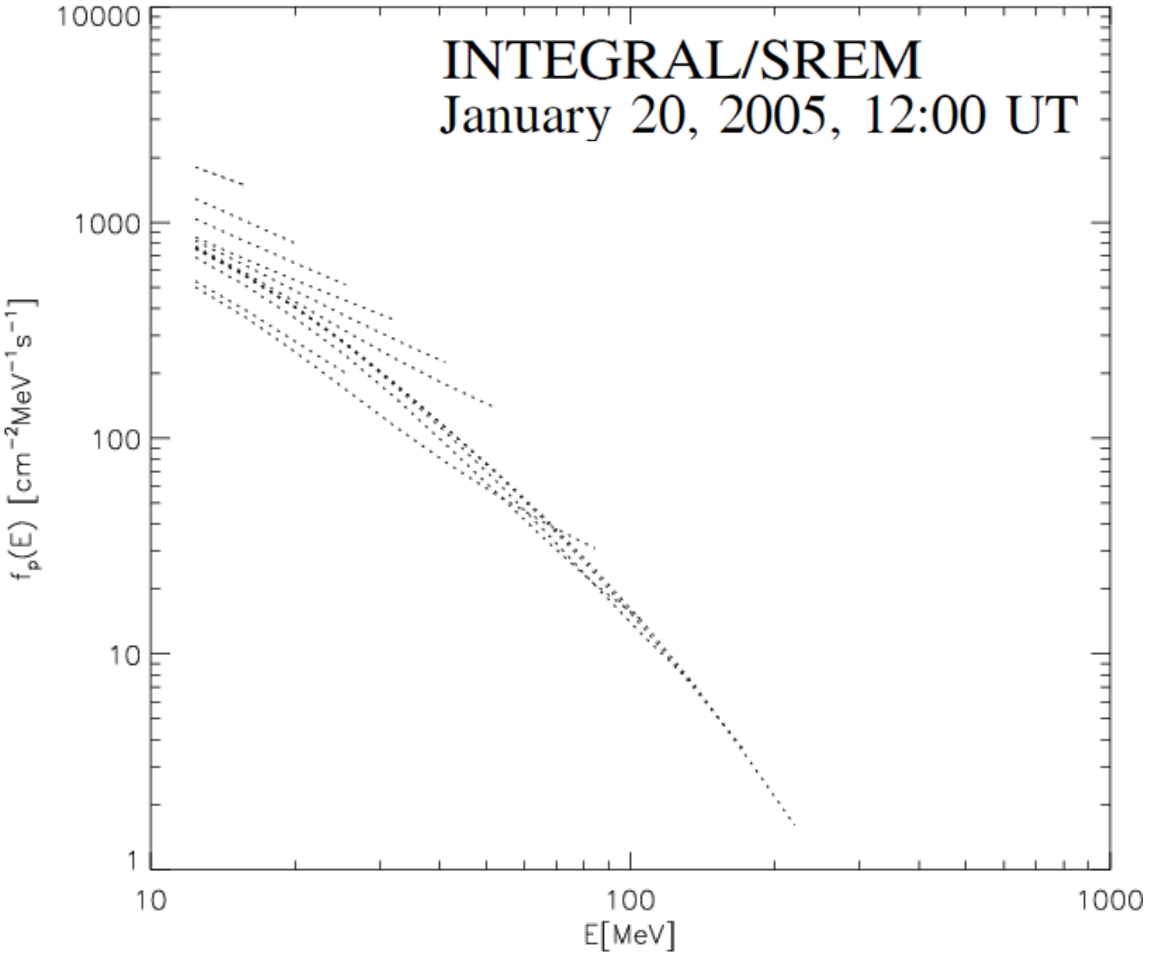


SREM/INTEGRAL data during January 2005



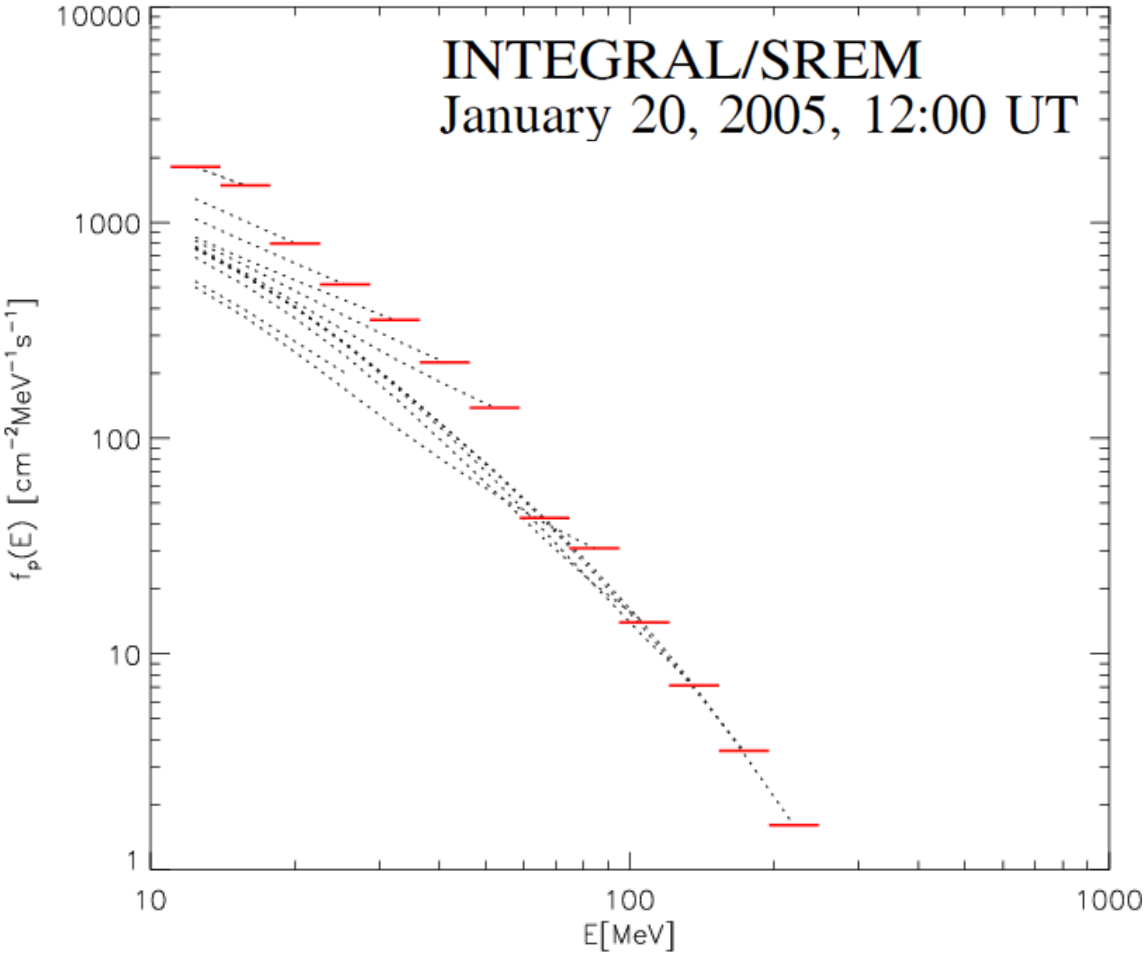
Non-suppressed regularized solutions

1. Unfold SREM data for different energy ranges



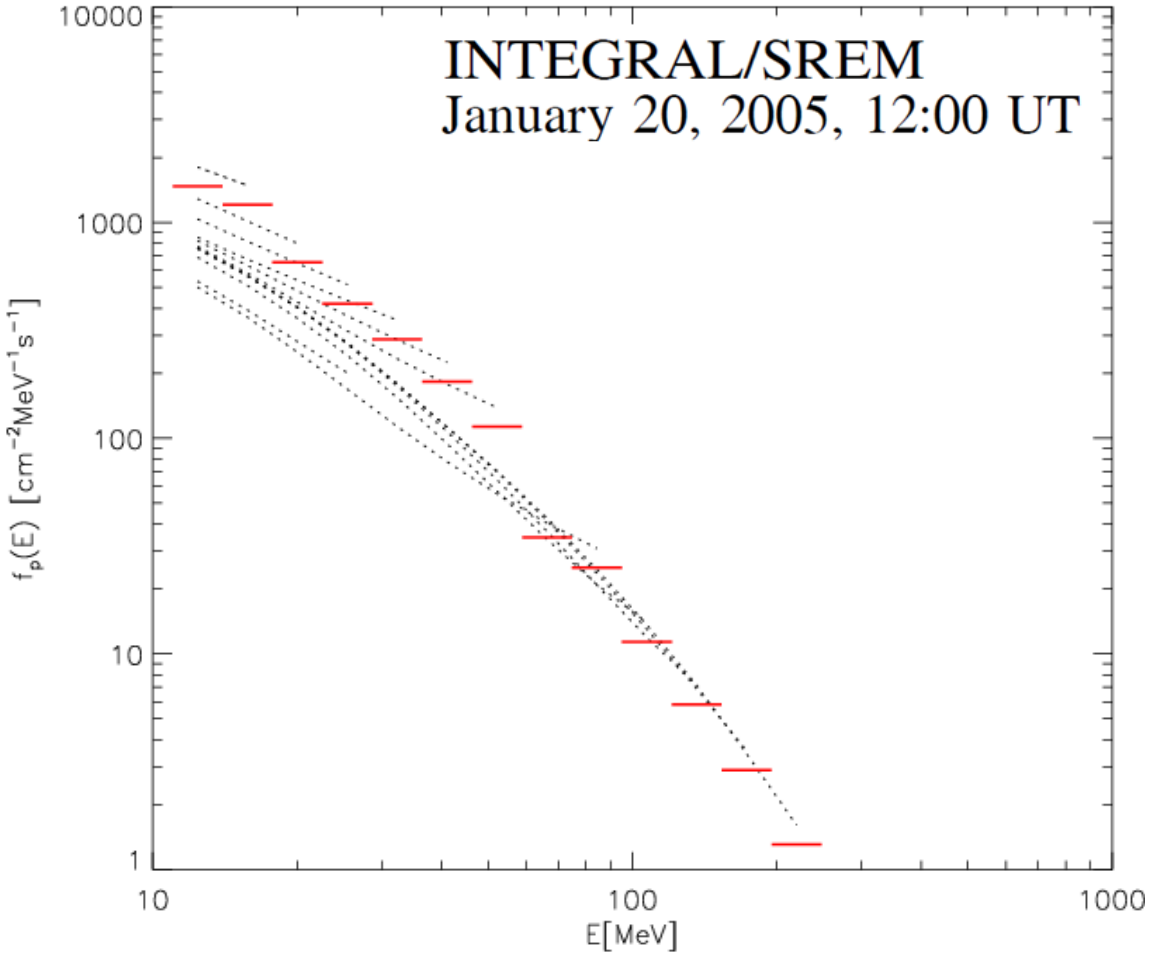
Non-suppressed regularized solutions

2. Select the maximum values for each energy level



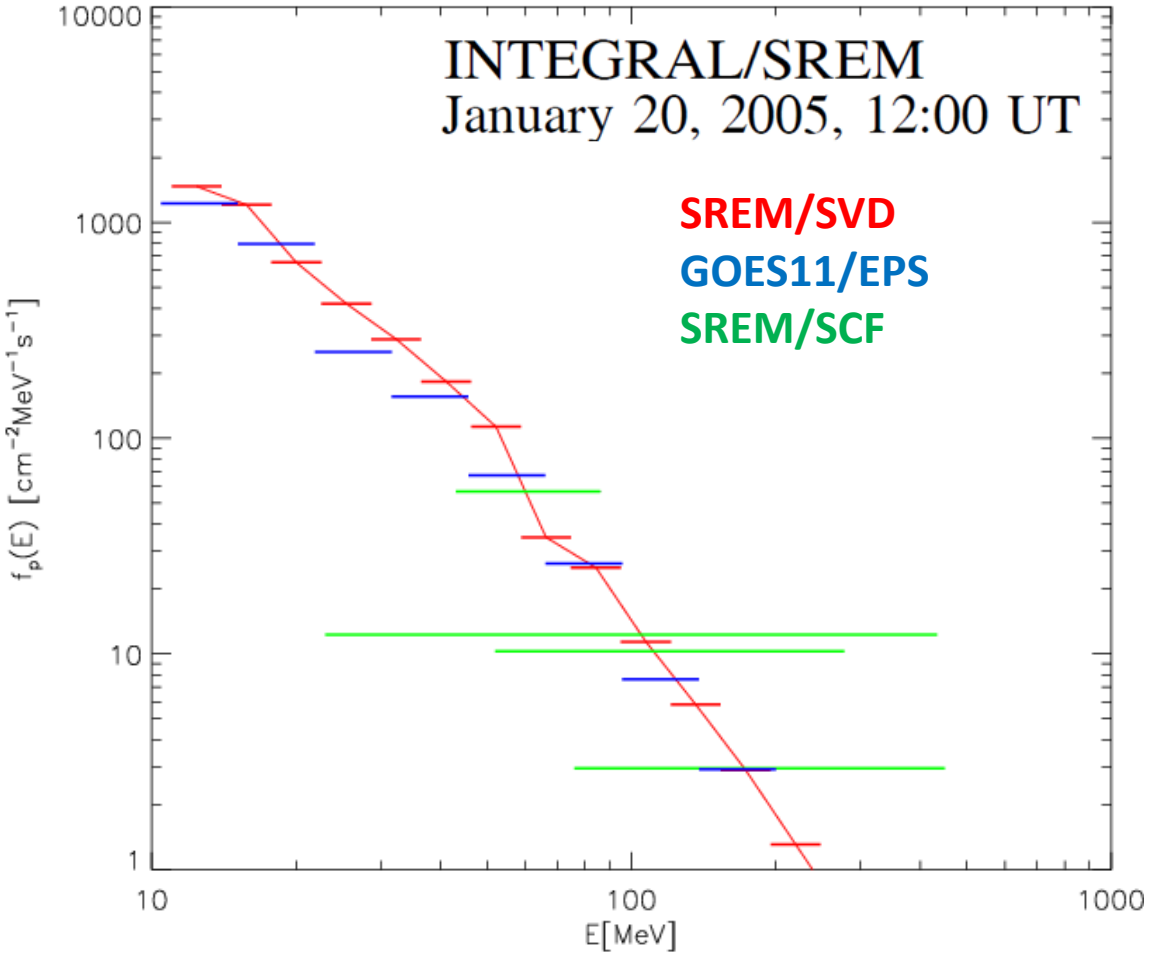
Non-suppressed regularized solutions

3. Apply a small correction factor – if needed- $\sum_{i=1}^{15} C_i / \sum_{i=1}^{15} C_i^{rec}$

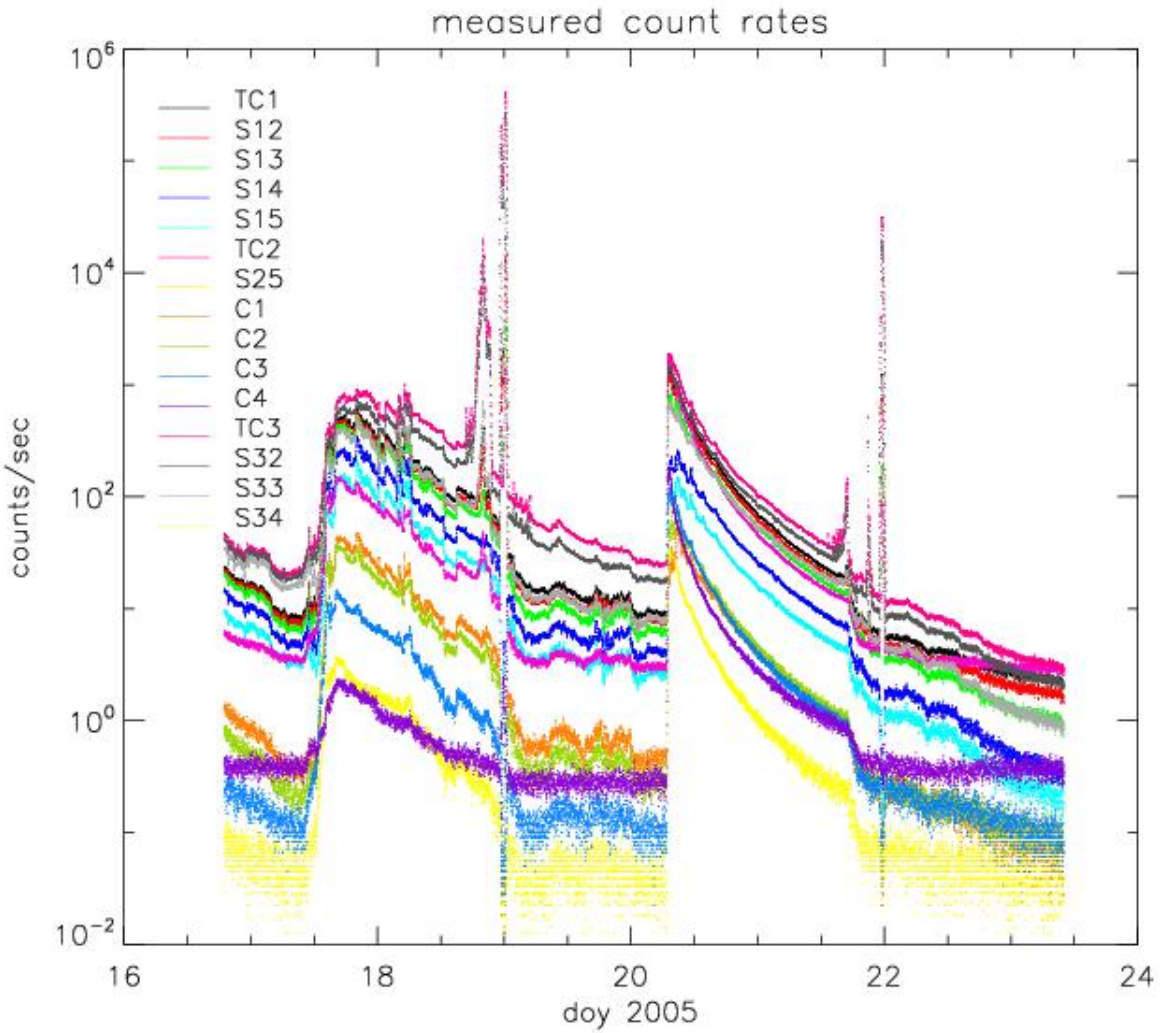


Non-suppressed regularized solutions

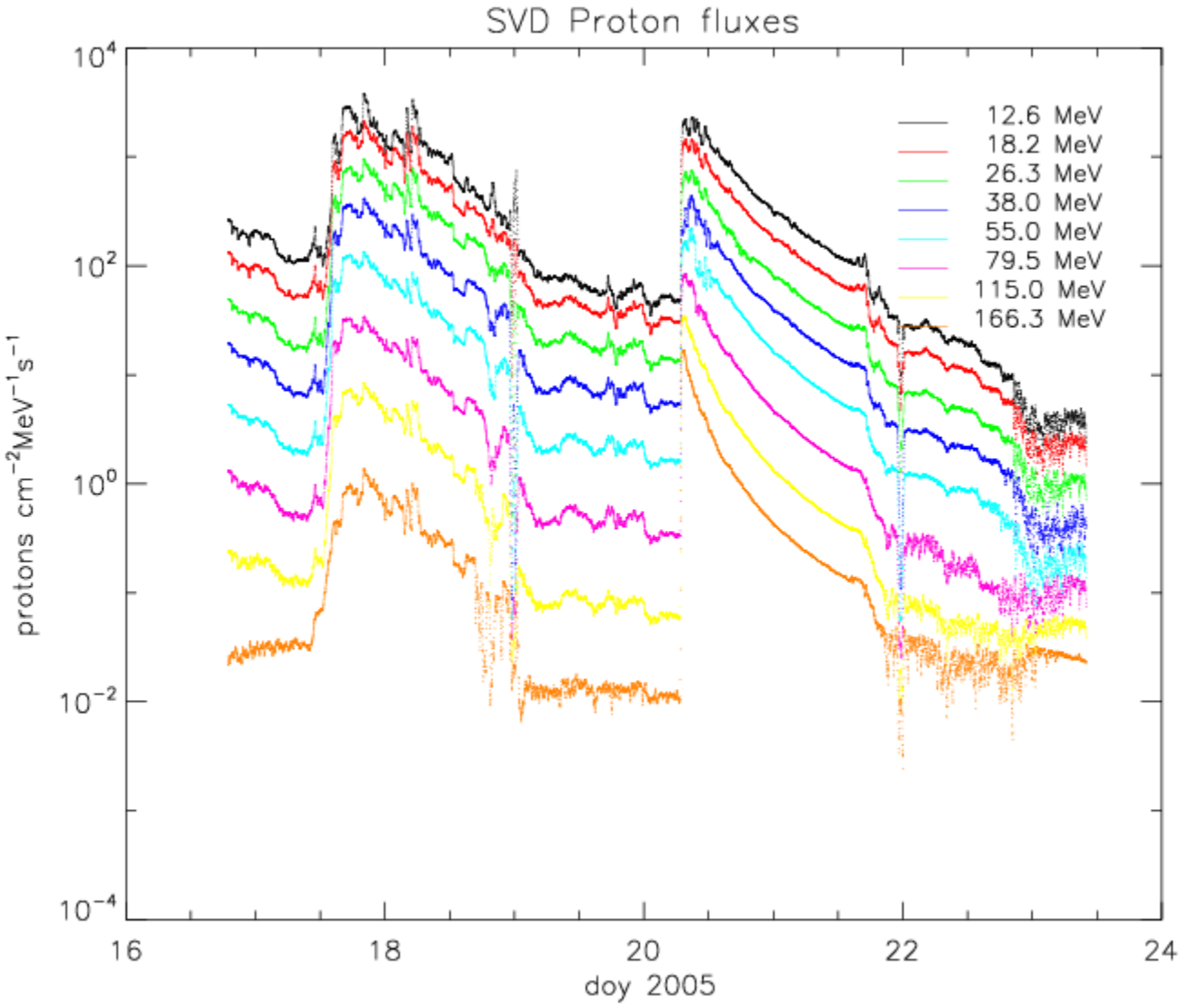
4. Comparisons with independent methods/datasets



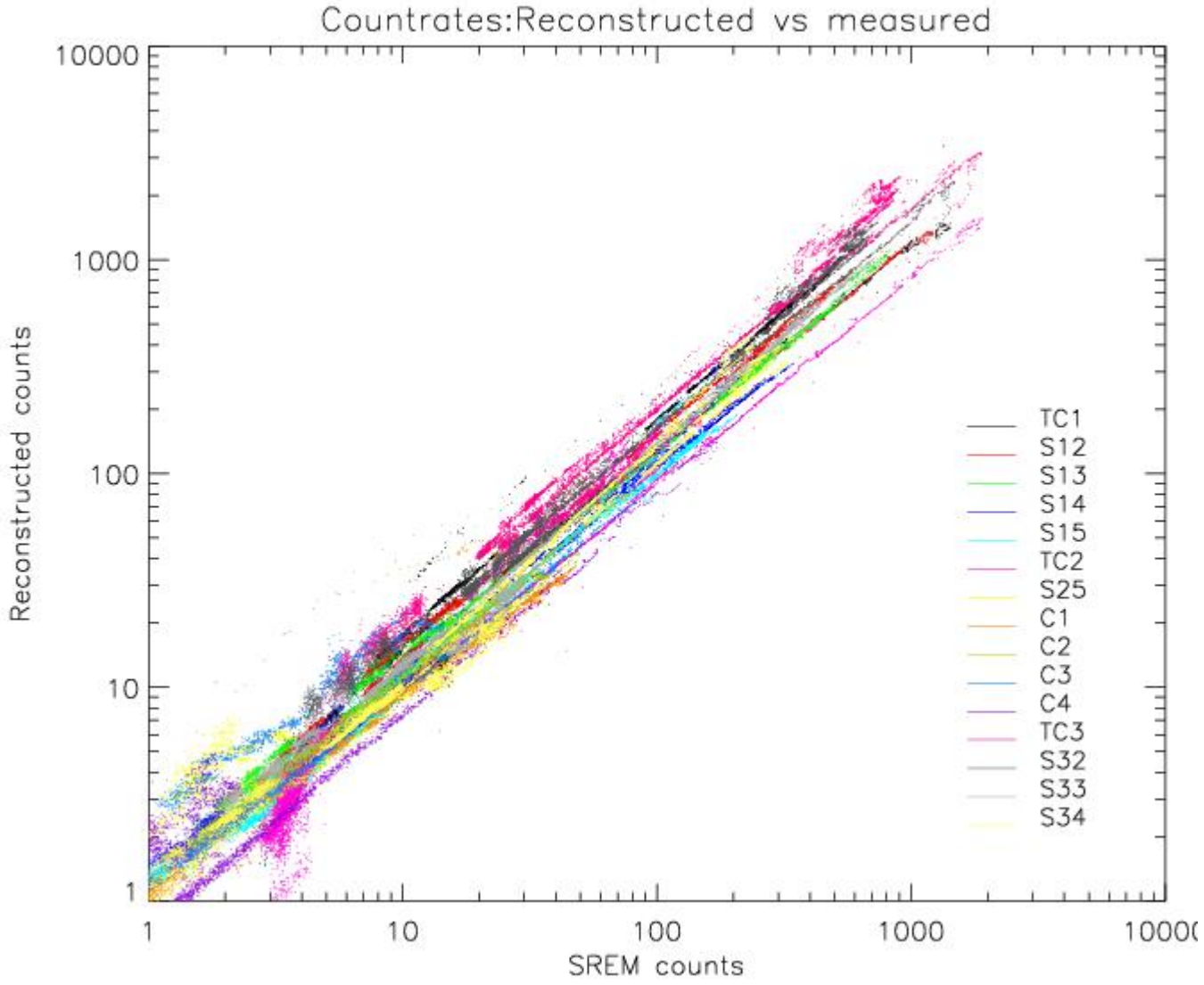
SREM/INTEGRAL data during January 2005



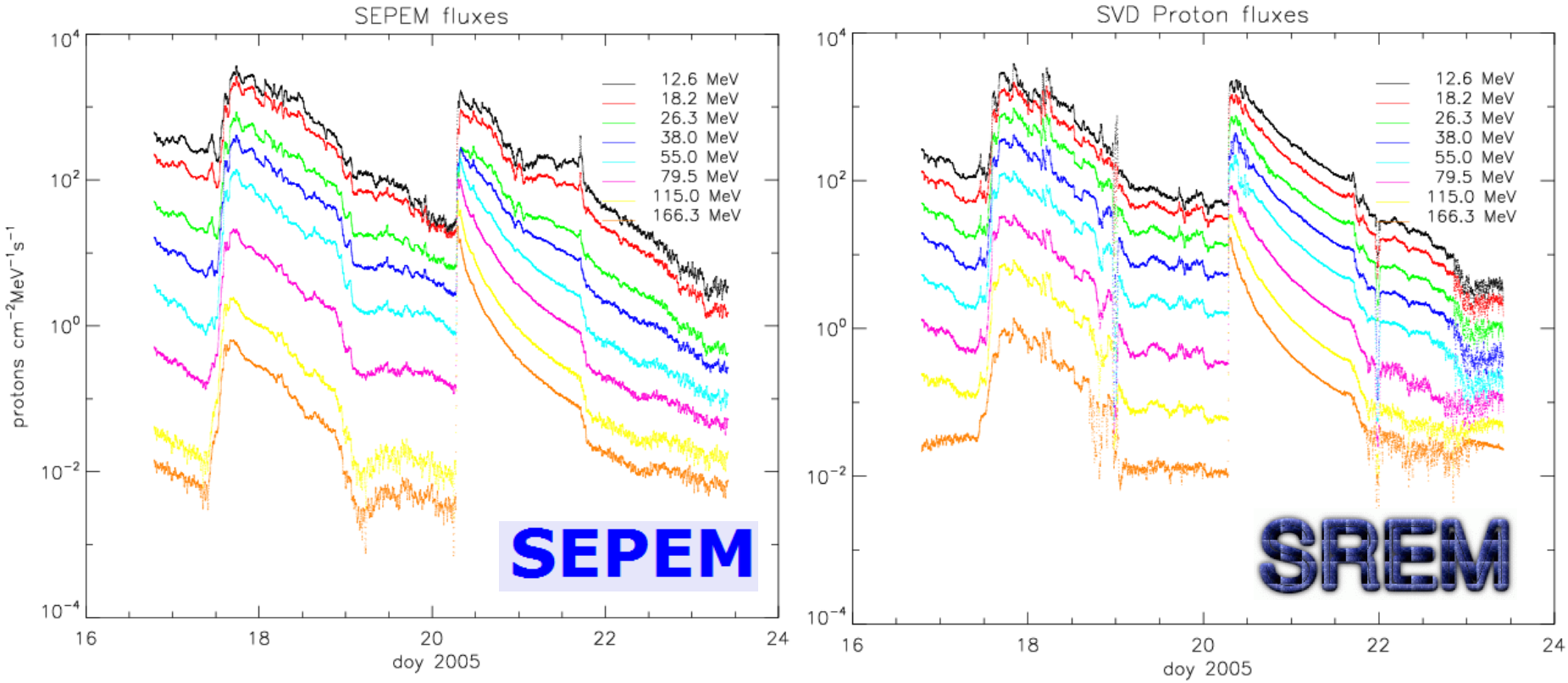
January 2005 SEPE: Proton fluxes



January 2005 SEPE: Reconstruction



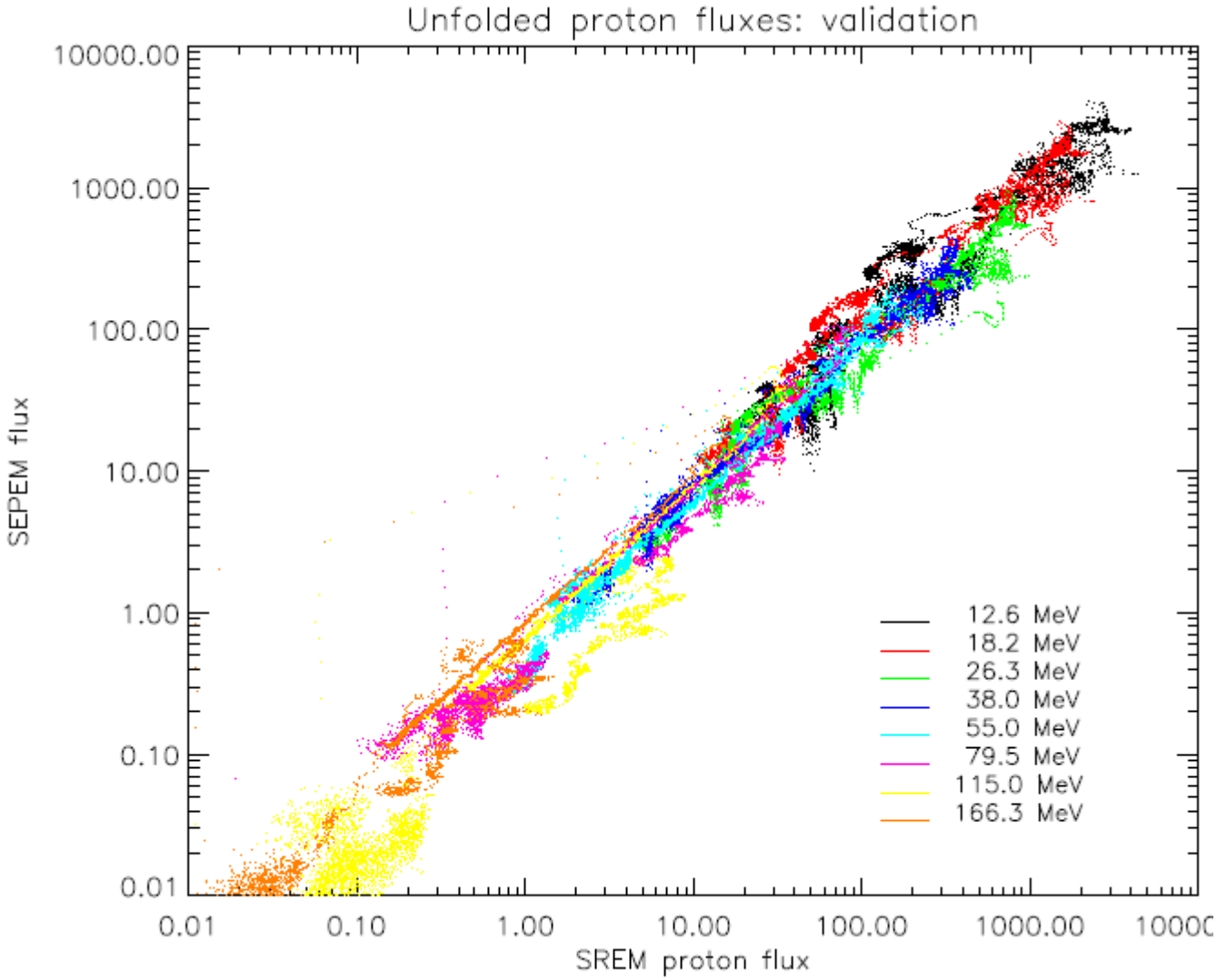
January 2005 SEPE: Comparison



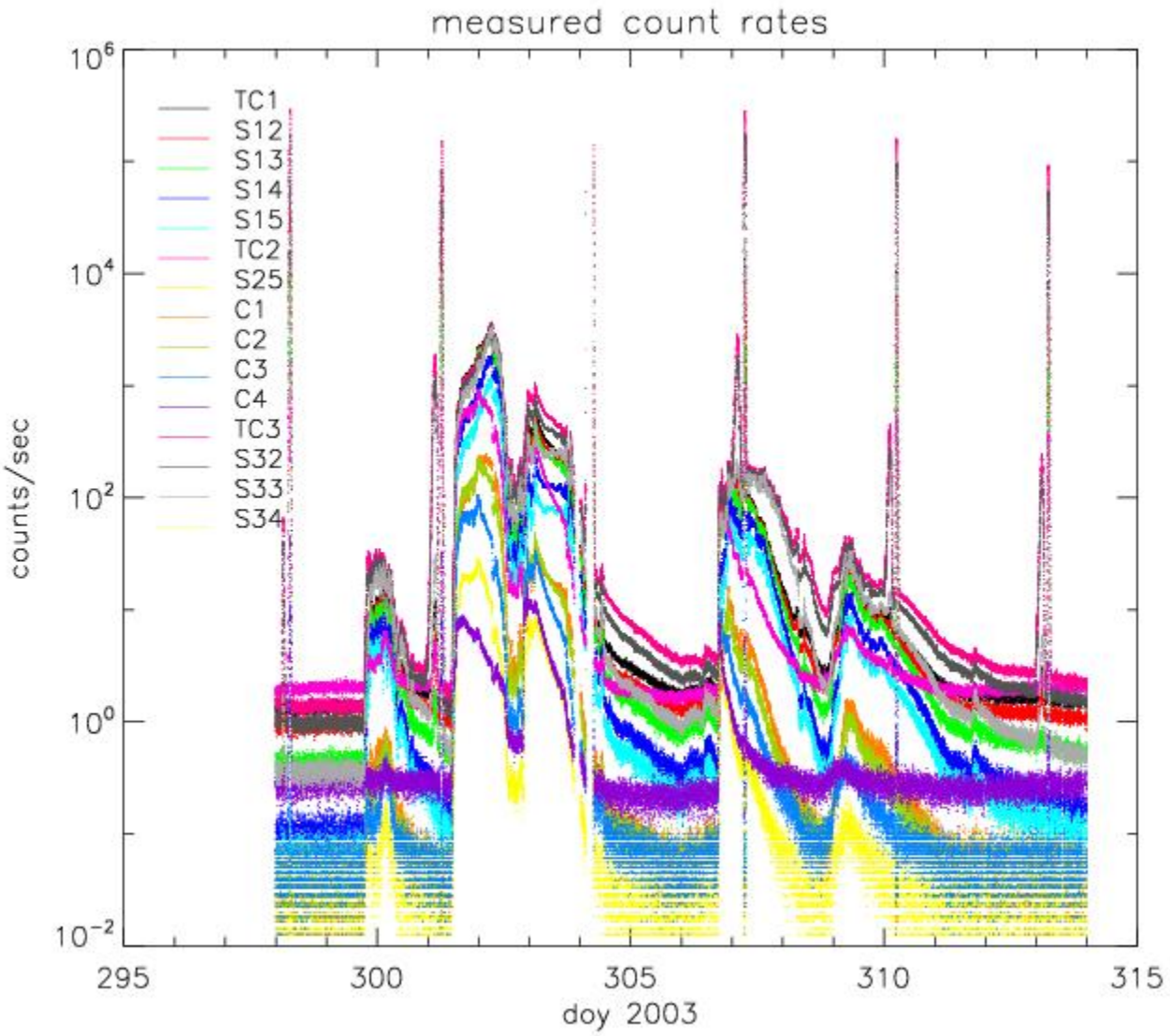
SEPEM: ESA Solar Energetic Particle Environment Modelling database

http://sepem.aeronomie.be/

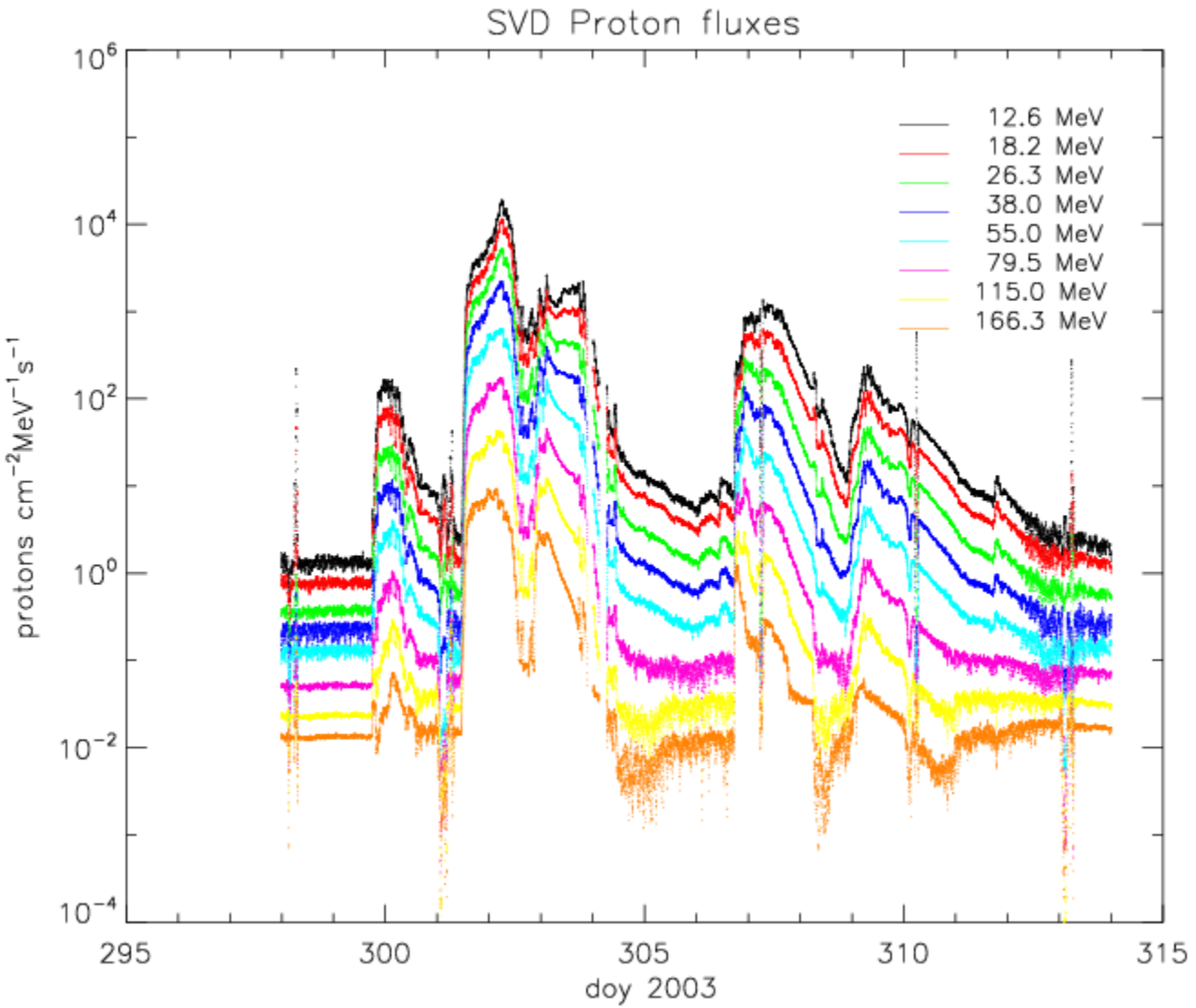
January 2005 SEPE: Validation



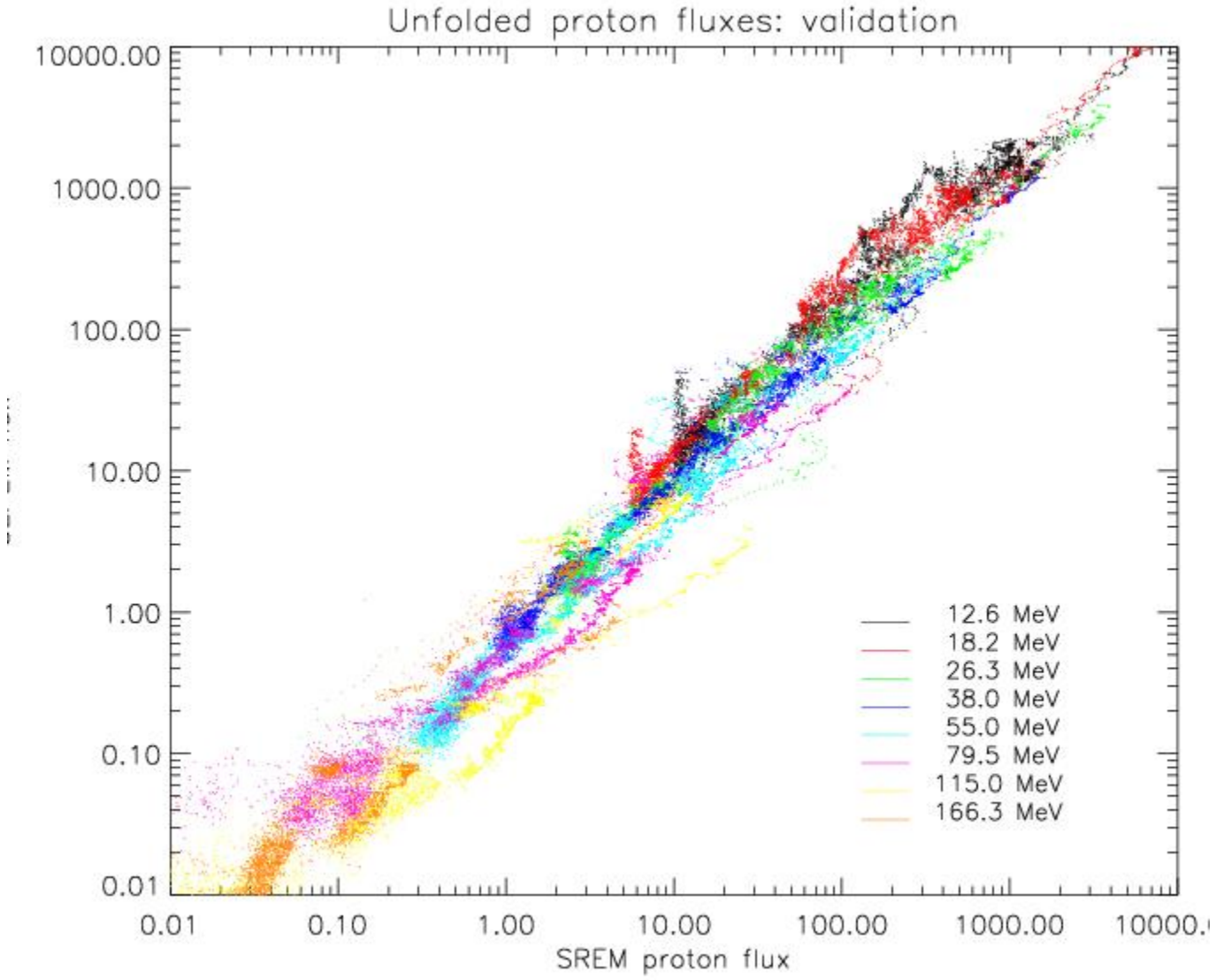
SREM/INTEGRAL data during October-November 2003



October-November 2003 SEPEs

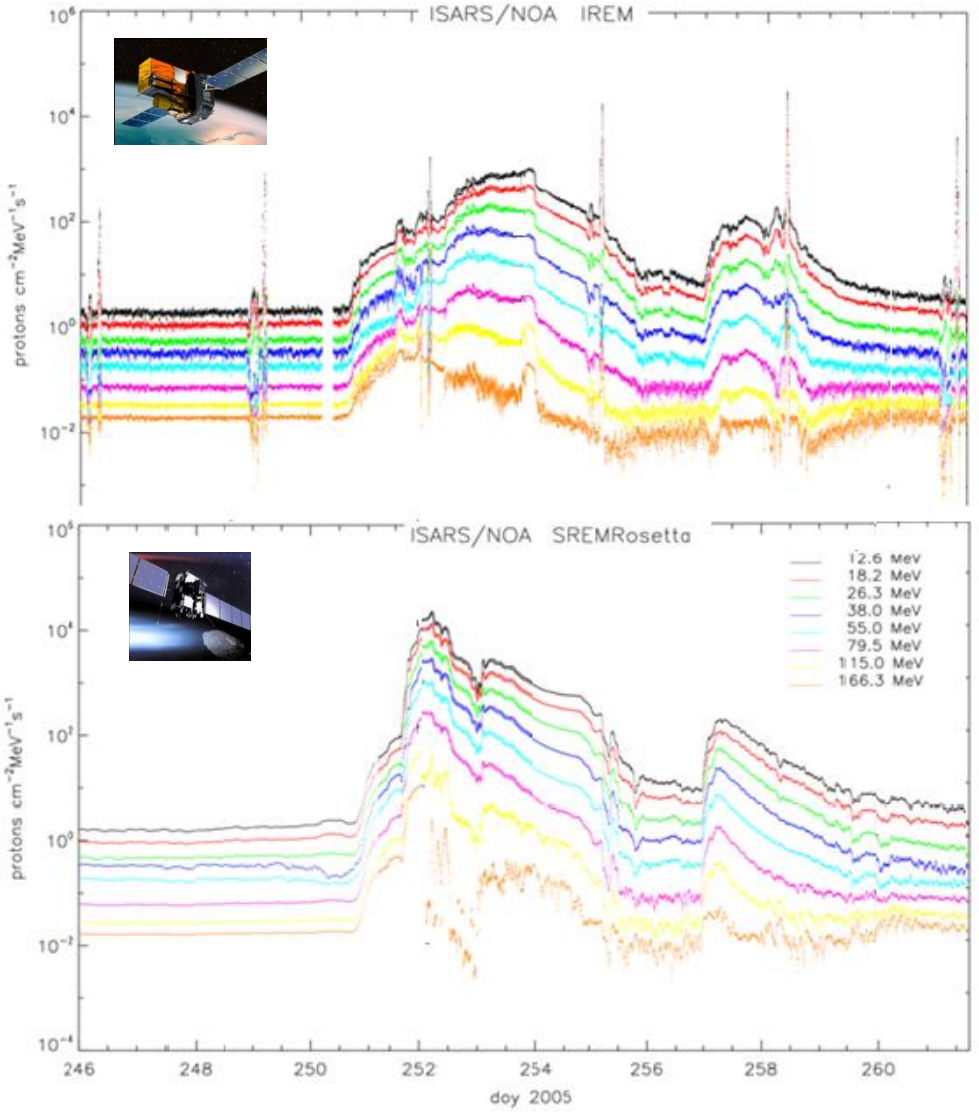


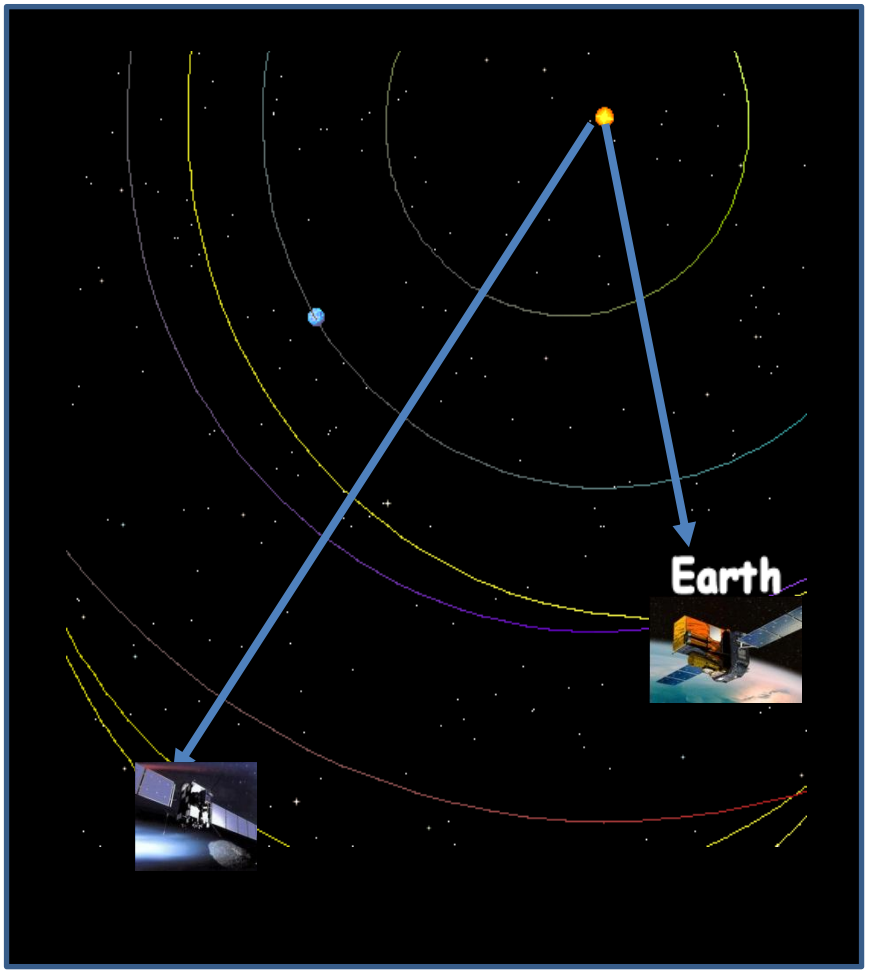
October-November 2003 SEPEs



SEP multipoint measurements I

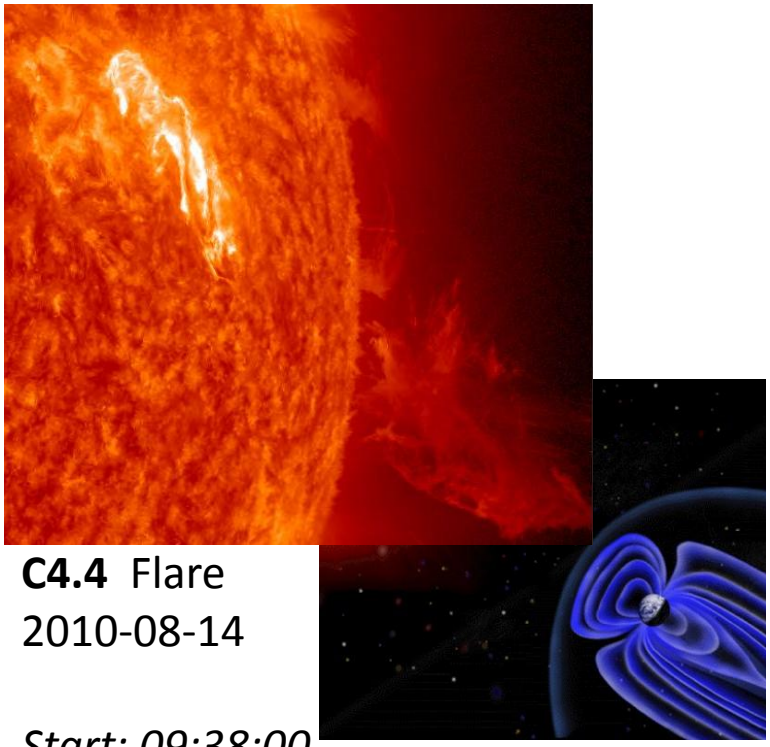
Magnetic connectivity effects: September 2005 SEPEs





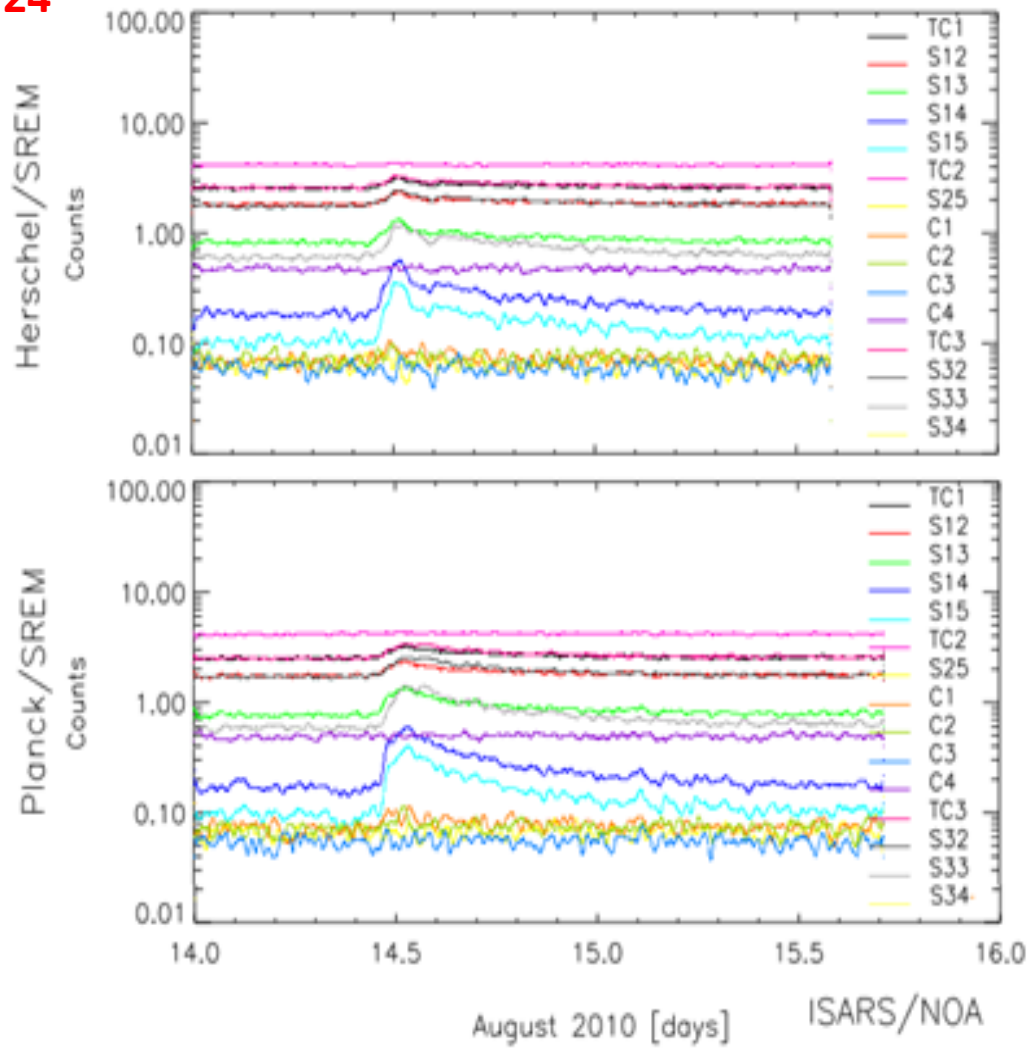
SEP multipoint measurements II

August 14, 2010: 1st SEP of Solar Cycle 24



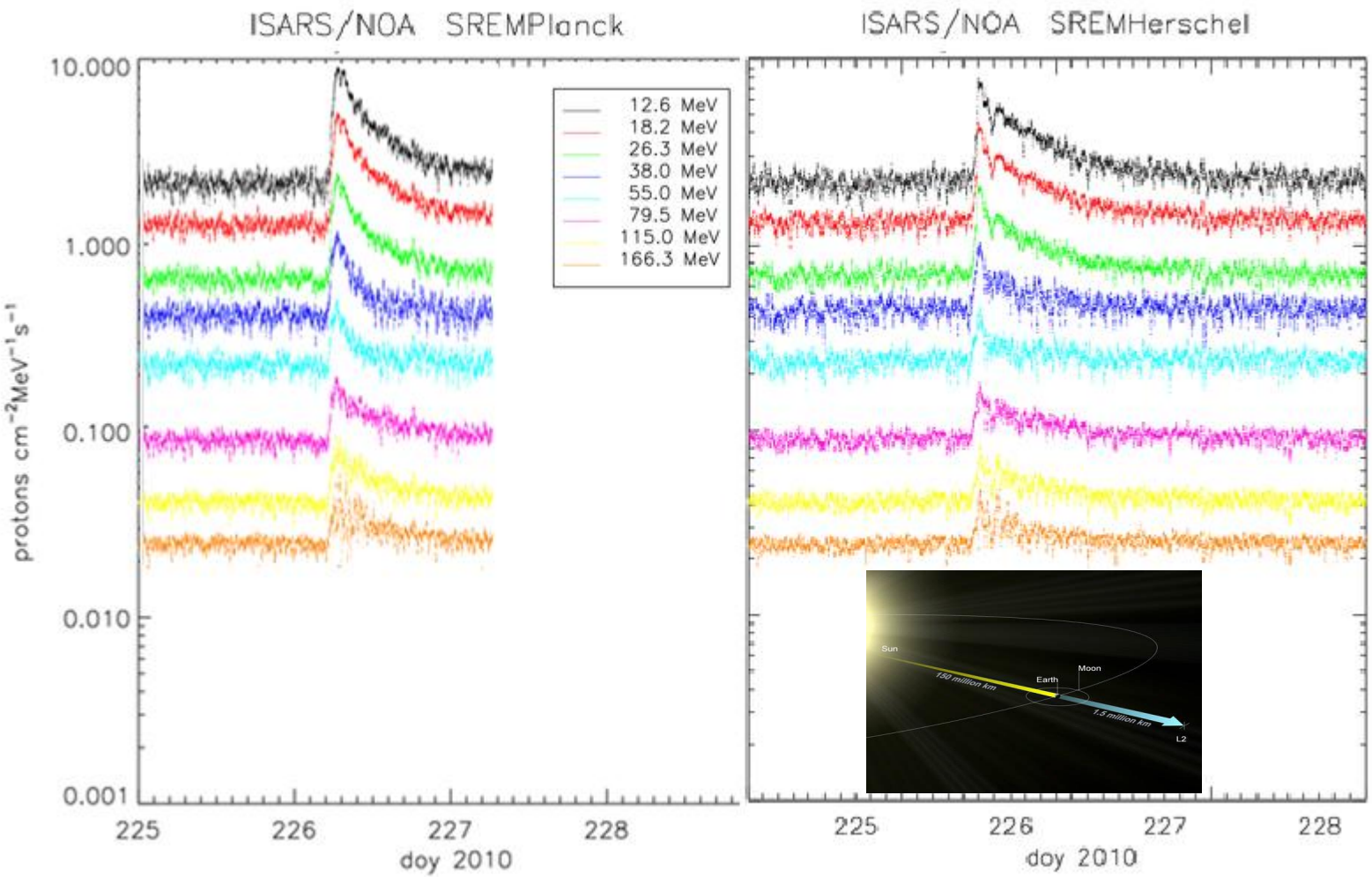
C4.4 Flare
2010-08-14

Start: 09:38:00
Peak: 10:05:00
End: 10:31:00
Location: N17 W52



SEP multipoint measurements II

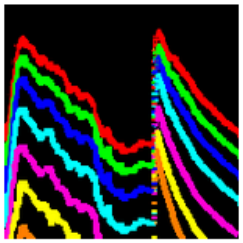
Halo Effects



ISARS/NOA SREM activities

- provide proton flux profiles to Herschel team on a weekly basis since begin of 2011
- provide calculations of the total fluence of Rosetta mission
- develop and operate SEPF tool
- Derive SREM proton flux database for INTEGRAL, Rosetta, Herschel and Planck missions

SEPF tool



SEPF tool

Solar Energetic Proton Fluxes

using ESA SREM data

SEPF beta phase

The Solar Energetic Proton Flux (SEPF) tool provides solar energetic proton fluxes at various locations in space. The SEPF tool uses a linear algorithm solver developed by ISARS/NOA for the inverse problem of calculating fluxes through multipoint count-rate measurements of the ESA Standard Radiation Environment Monitor (SREM) units on-board INTEGRAL, Herschel, Planck, and Rosetta. The SEPF tool downloads SREM data, calculates the differential proton fluxes and displays the most recent results for the current year and the past week on a daily basis. Results of the method have been validated for selected number of historic solar energetic particle events using measurements from other proton monitors.

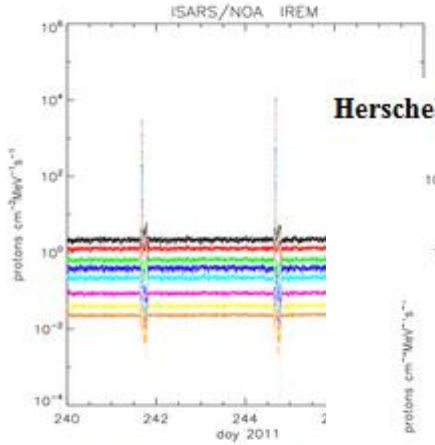
SREM PROTON FLUXES

- INTEGRAL/SREM Proton Fluxes
- Herschel/SREM Proton Fluxes
- Planck/SREM Proton Fluxes
- Rosetta/SREM Proton Fluxes

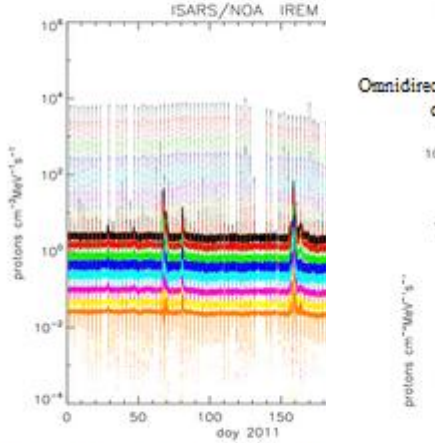
http://proteus.space.noa.gr/~srem/SEPF/

SEPF tool

INTEGRAL/SREM Proton Fluxes

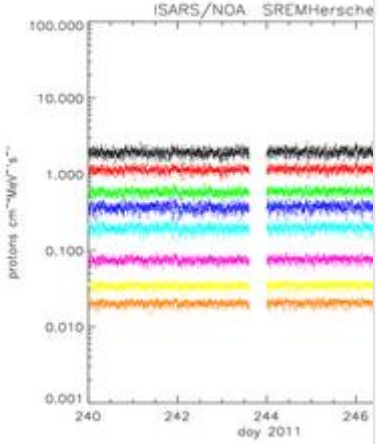


Omnidirectional differential proton fluxes from INTE
days. The INTEGRAL spacecraft is in an elliptical
enhancements are attributed to ra

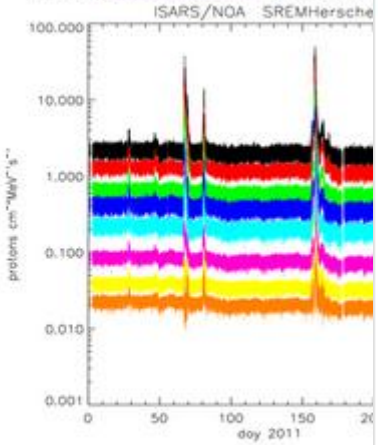


Omnidirectional differential proton fluxes from IN
January 2011. The occasional sharp flux enhancement

Herschel/SREM Proton Fluxes

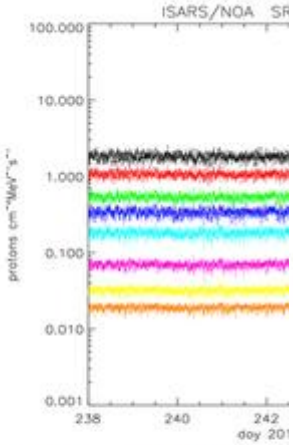


Omnidirectional differential proton fluxes from Hersch
days. The Herschel spacecraft operates at the

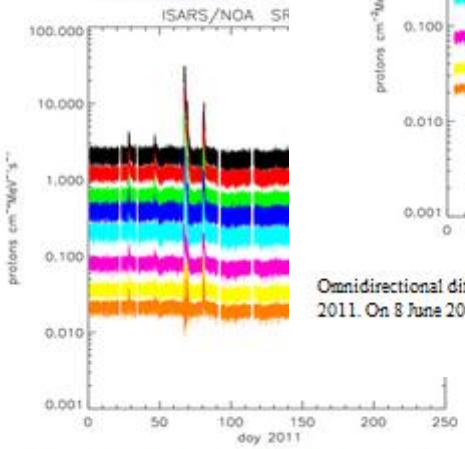


Omnidirectional differential proton fluxes from Hersche
2011.

Planck/SREM Proton Fluxes



Omnidirectional differential proton fluxes fro
The Planck spacecraft operate



Omnidirectional differential proton fluxes from Planck/SREM measurements since 1 January 2011.

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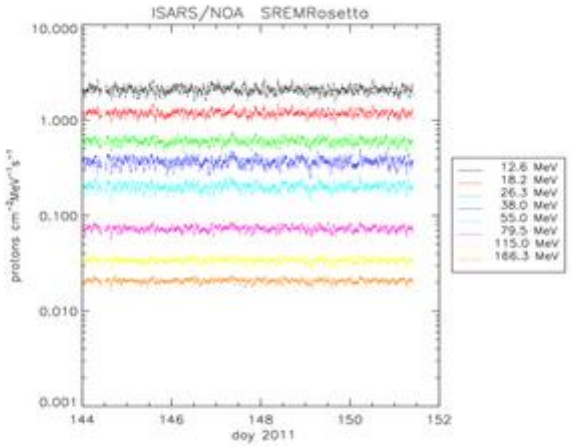
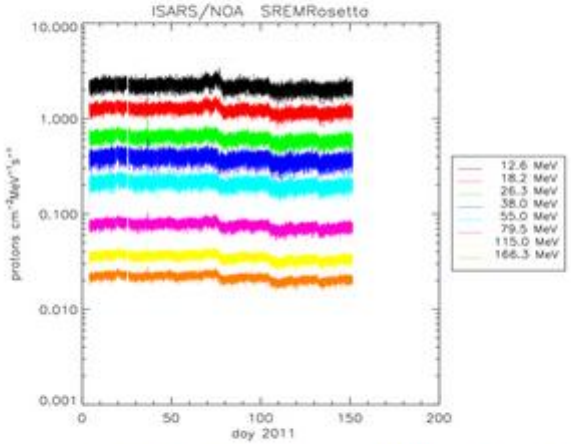
Rosetta/SREM Proton Fluxes



Omnidirectional differential proton fluxes from Rosetta/SREM measurements for the past
Rosetta is an interplanetary mission, heading to an encounter with comet 67P/Churyu
Gerasimenko.



Omnidirectional differential proton fluxes from Rosetta/SREM measurements since 1 Ja
2011. On 8 June 2011, Rosetta mission controllers switched ESA's comet-hunter into
space hibernation for 31 months.

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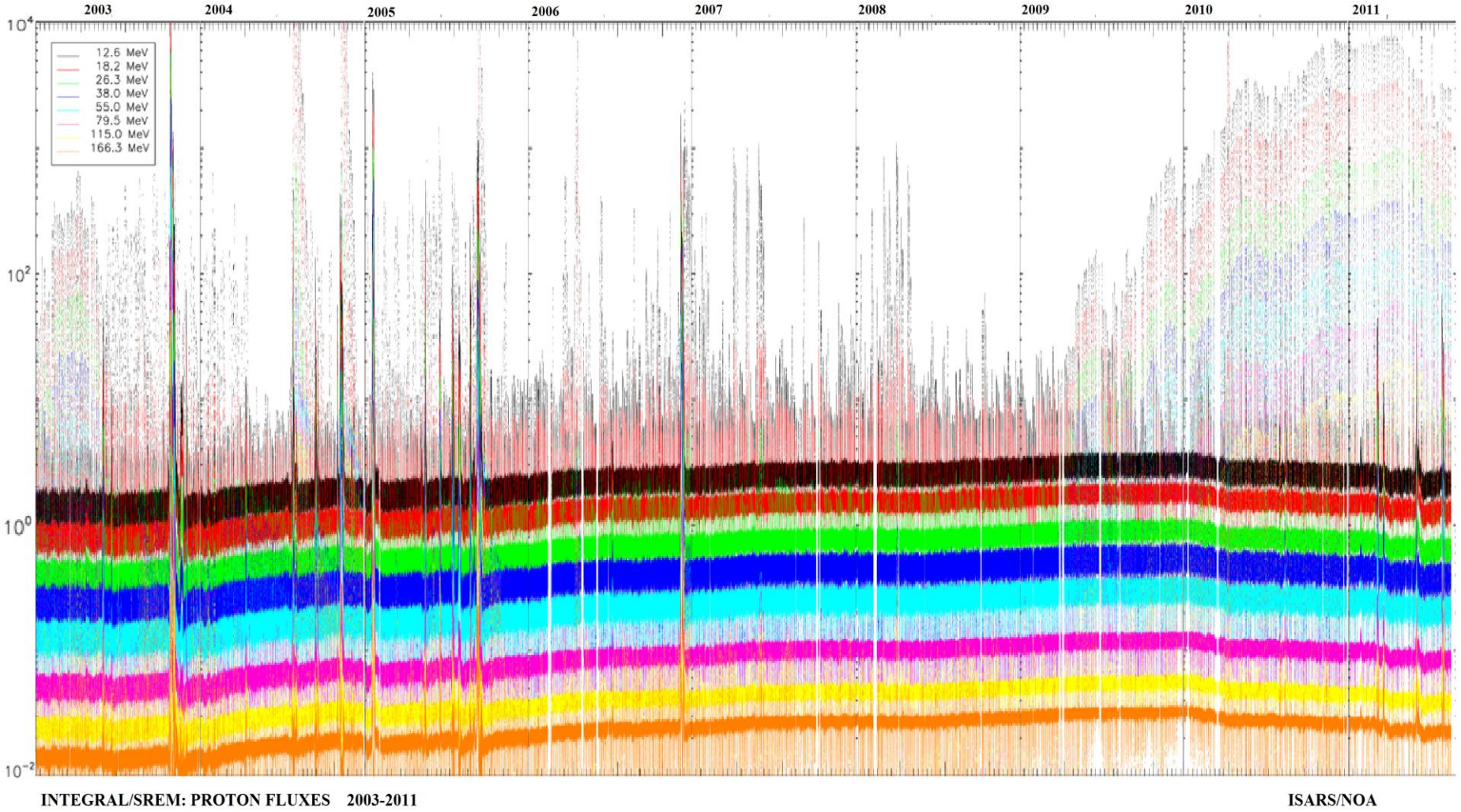
SREM proton fluxes: database



Summary-Conclusions

- Data from SREM units on-board multiple ESA spacecraft offer a unique opportunity for multipoint observation of SEPE
- A novel method for unfolding SREM data has been developed
- The derived proton flux datasets have been validated with fully processed, corrected, cleaned, inter-calibrated, scientific datasets
- SEPF: A near-real time monitor of solar proton fluxes has been released and operated by ISARS/NOA
- The proton flux SREM database is under preparation containing multipoint measurements (MEO,LEO,L2,HEO,IP)
- Novel properties of past and coming SEPEs will be revealed