

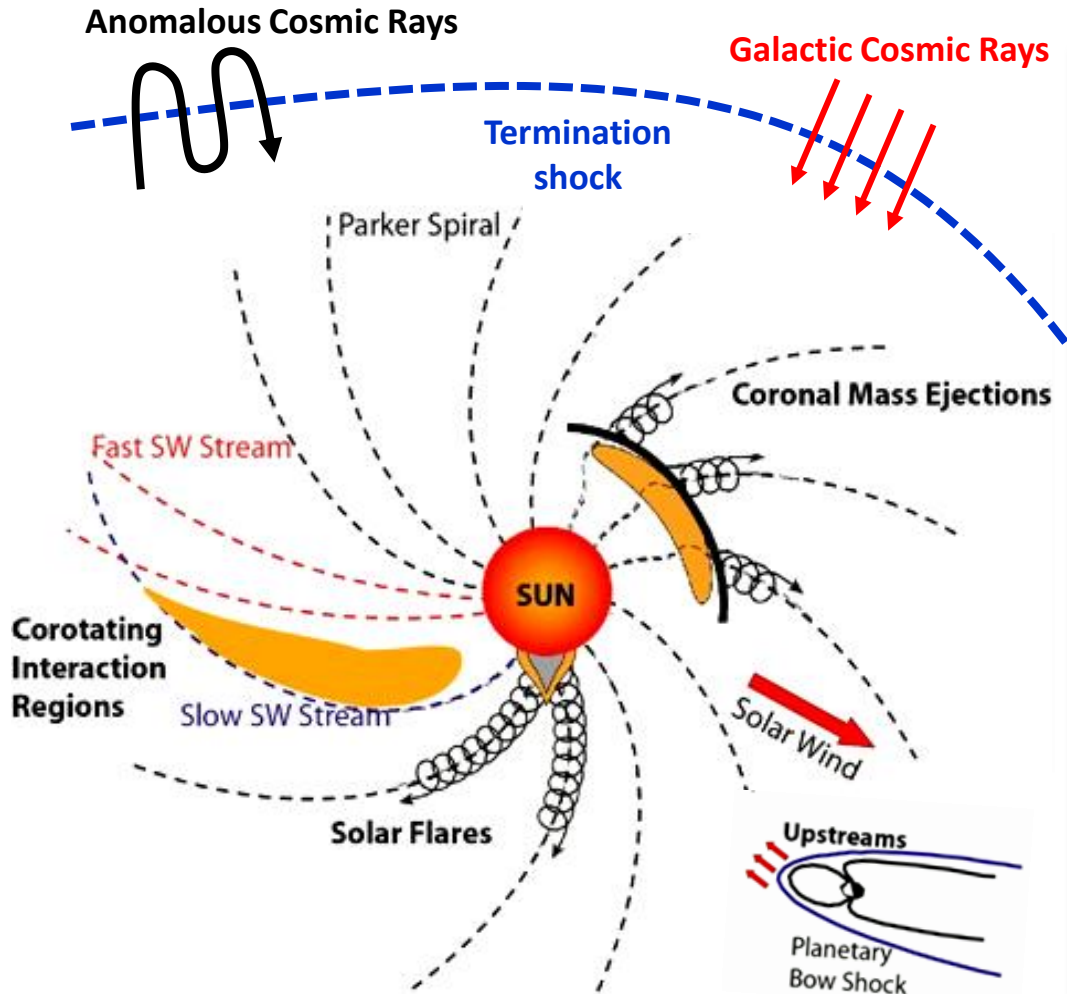
Energetic particles in the heliosphere current understanding and challenges for space weather services

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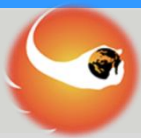
Energetic particle populations in space



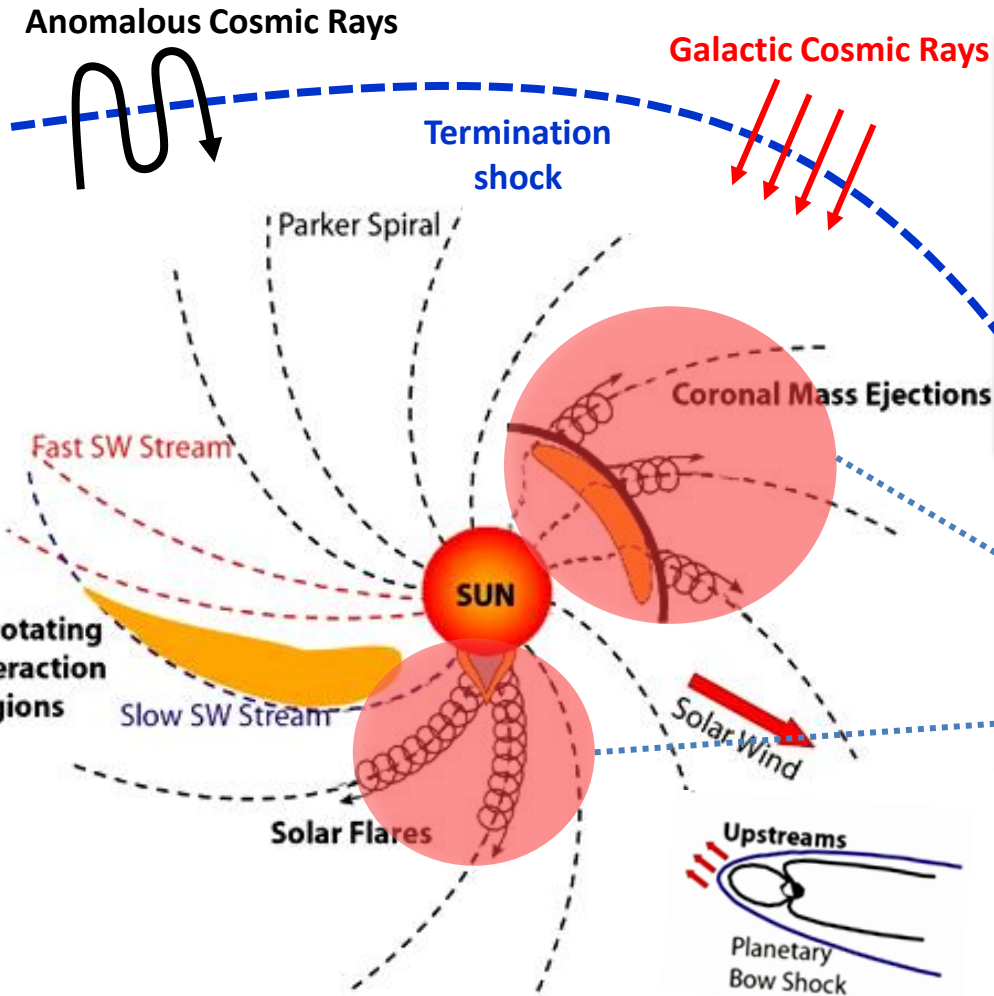
- > **Corotating Interaction Regions (CIRs)** (only < 20 MeV/n ions)
- > **Solar Energetic Particle (SEP)** events (related to *solar flares* and *CMEs*)
- > Other **populations of non solar origin**, however strongly controlled by the large scale structure of the *interplanetary magnetic field* (i.e. modulation).
 - **Galactic Cosmic Rays (GCRs)**
 - **Anomalous Cosmic Rays (ACRs)** (only during solar minimum)
 - *Jovian electrons*

Credit: Adapted from M. Desai

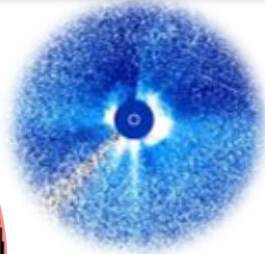
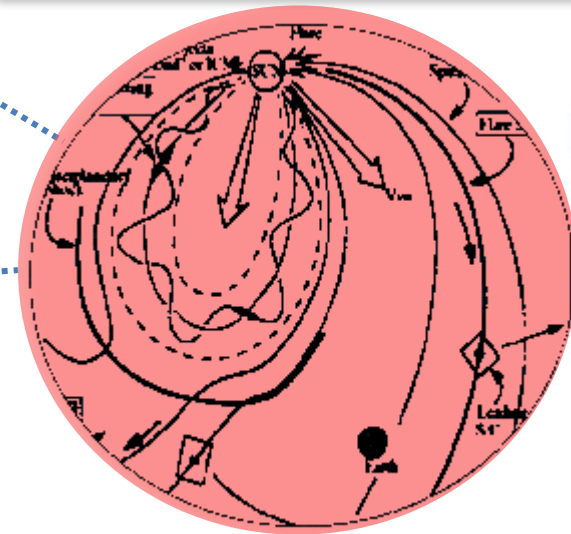
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Energetic particle populations in space



> Outside the shield offered by the magnetosphere, the most relevant Space Weather Effects are due to **Solar Radiation Storms** (i.e. *elevated levels of radiation* that occur when the number of **Solar Energetic Particles (SEPs)** increases)



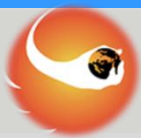
Credit: Adapted from M. Desai

Vainio et al, SSRv, 2007

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Solar Energetic Particle (SEP) events

The origin of SEP events

> Since the 90s:

Distinction of 2 classes of events:

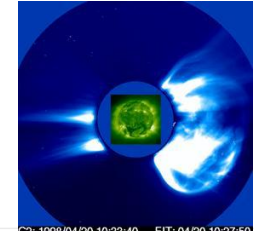
- **Impulsive** (small, frequent, presumably flare related)
- **Gradual** (large, rare, presumably fast CME related)
- The *separation scheme is not that clear* (mixed contributions, hybrid events)

Impulsive

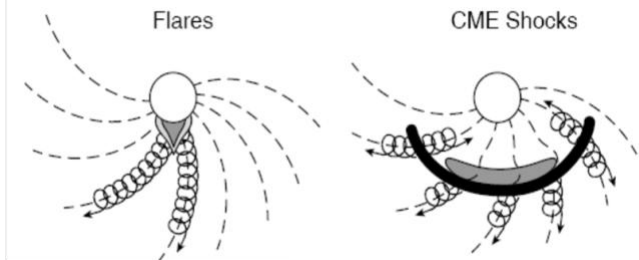


Flares

Gradual



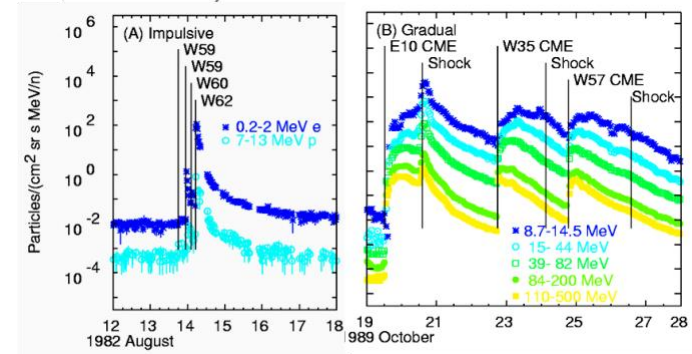
CME Shocks



Impulsive	Gradual
Flare-related	CME-driven Shock
Fe/O ~ 1	Fe/O ~ 0.1
$^3\text{He}/^4\text{He} \sim 0.1 - 1$	$^3\text{He}/^4\text{He} < 0.01$
$Q_{\text{Fe}} \sim 20$	$Q_{\text{Fe}} \sim 10-14$
Narrow injection cone	Broad injection cone
Radio type III	Radio type II & IV
> Lower intensity, short duration events	> Higher intensity, longer duration

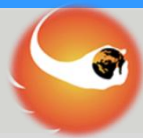
⇒ Less severe

⇒ Significant



Credit: SOHO / NASA / ESA

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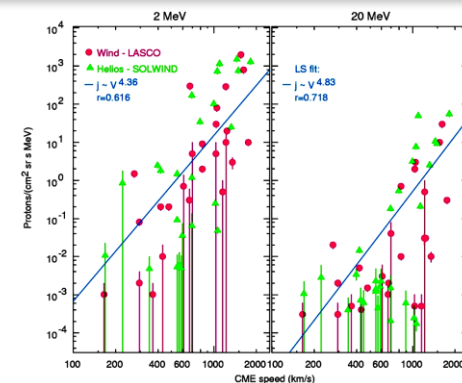
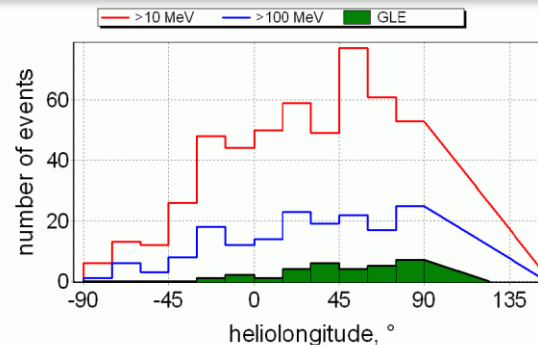
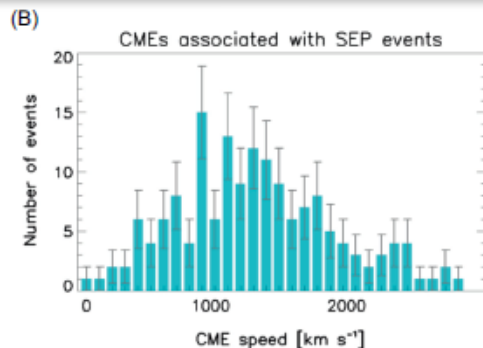
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Reames, SSRv, 1999
Papaioannou et al., J. SWSC, 2016

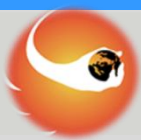
Forecasting SEP events

- > The *occurrence rate* of **SEP events** is related to the *solar cycle*, however short-term forecasting is **difficult**:
 - “**Strong flares** and **fast CMEs** give ground to SEP events” but what does *strong* and *fast* really means ?
 - Prediction of the **ICME/shock transit time** to 1 AU and the importance of the possible *Energetic Storm Particles (ESPs)* spike is also complicated
- > However, **correlations & dependencies** between **SEP occurrence rates**, **intensities** and **SF** or **CME** properties have been found



⇒ **Data Driven Methods**

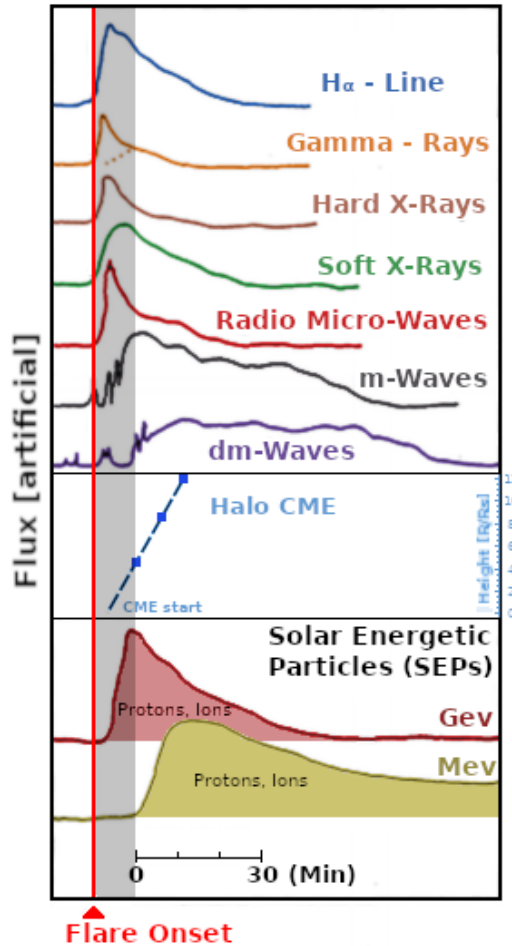
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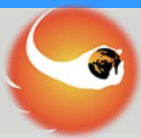
Forecasting SEP events

Data-driven methods

Anastasiadis et al, RSTA, 2019



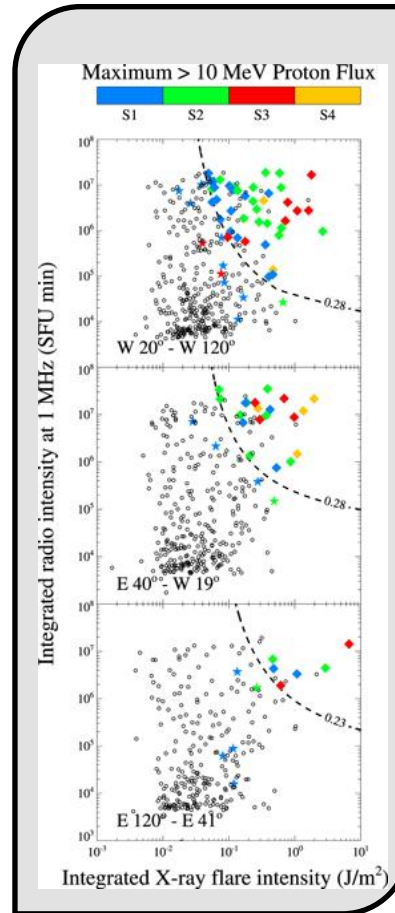
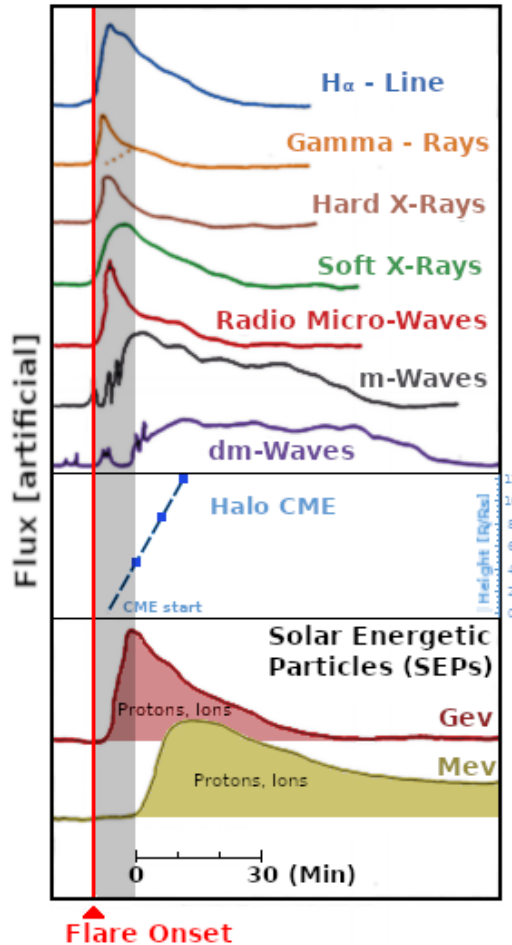
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Forecasting SEP events

Data-driven methods

Anastasiadis et al, RSTA, 2019



ESPERTA

Empirical model for Solar Proton
Event Real Time Alert

- > Time-integrated soft X-ray flux,
- > Time-integrated radio intensity @ 1 MHz

Laurenza et al., Space Weather, 2009

Alberti et al., Astrophys. J, 2017

Laurenza et al., Astrophys. J, 2019

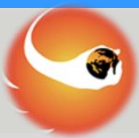
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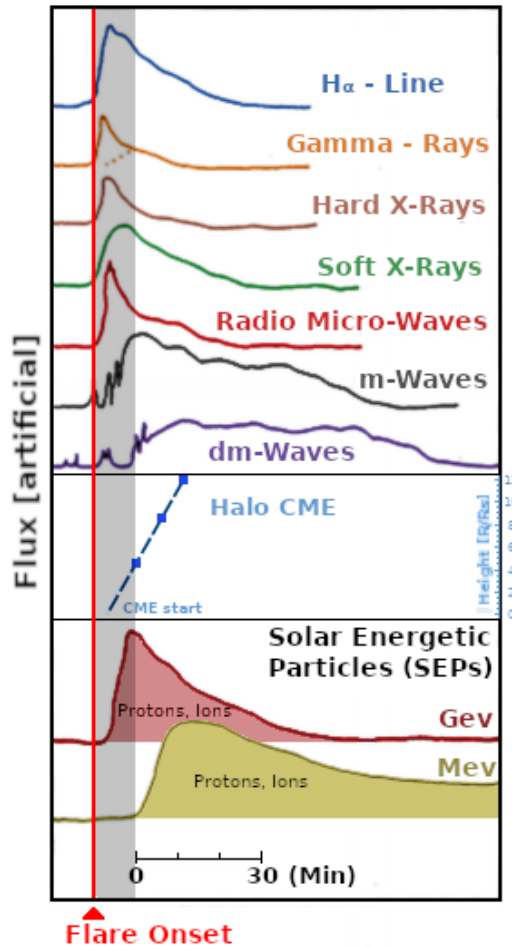
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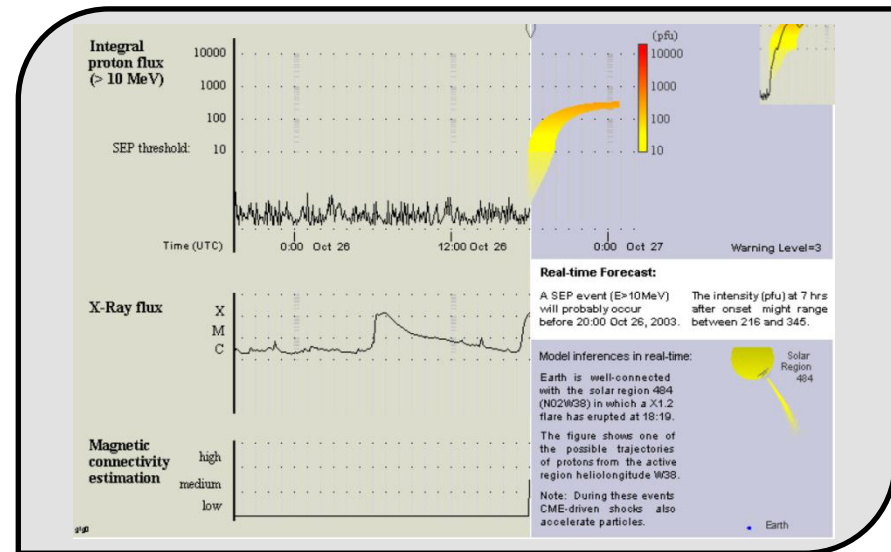
Forecasting SEP events

Data-driven methods

Anastasiadis et al, RSTA, 2019



UMASEP



- > Soft X-ray flux (derivative)
- > Proton flux at various energies (derivative)

Núñez, Space Weather, 2011; 2015; 2017

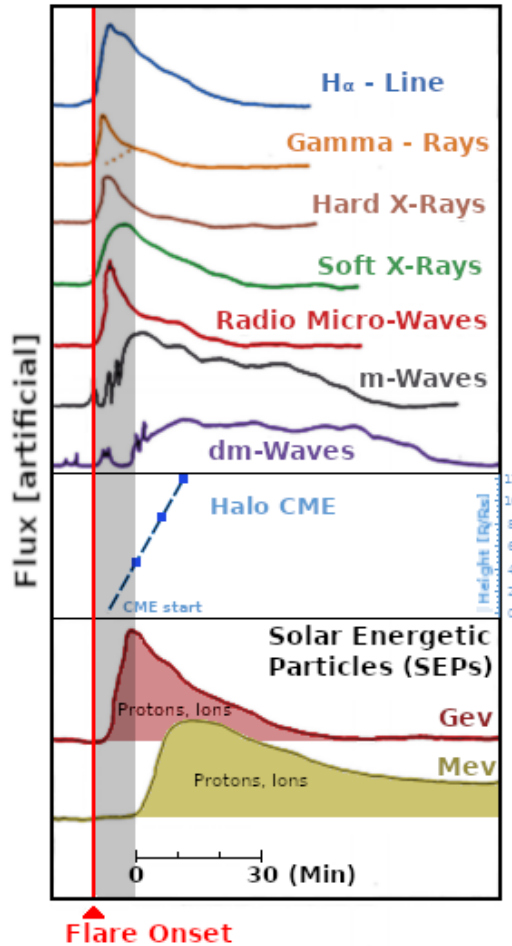
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Forecasting SEP events

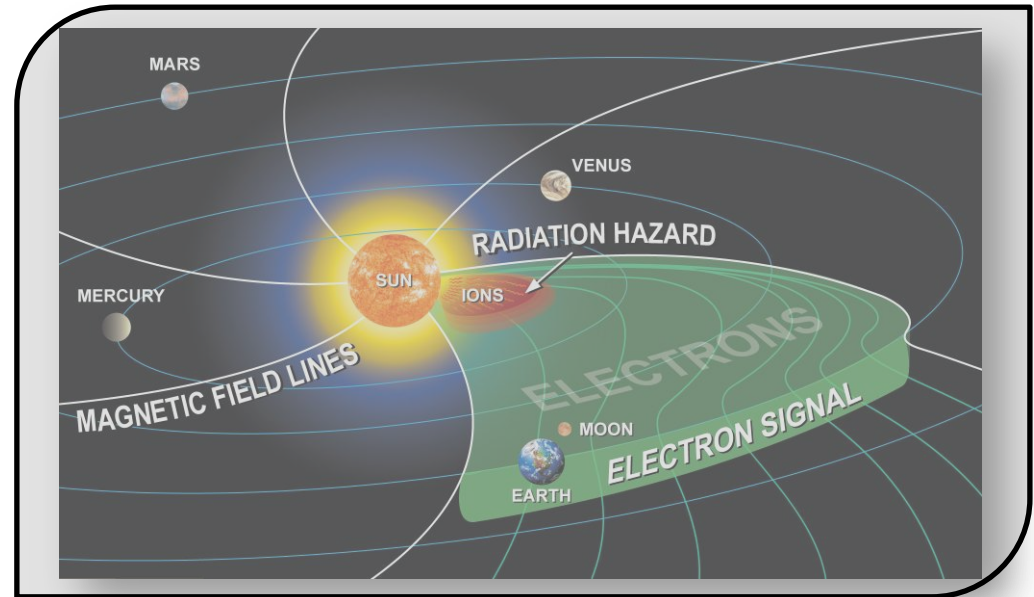
Data-driven methods

Anastasiadis et al, RSTA, 2019



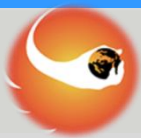
RELeASE

Relativistic Electron Alert System for Exploration



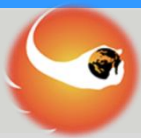
Posner, Space Weather, 2009

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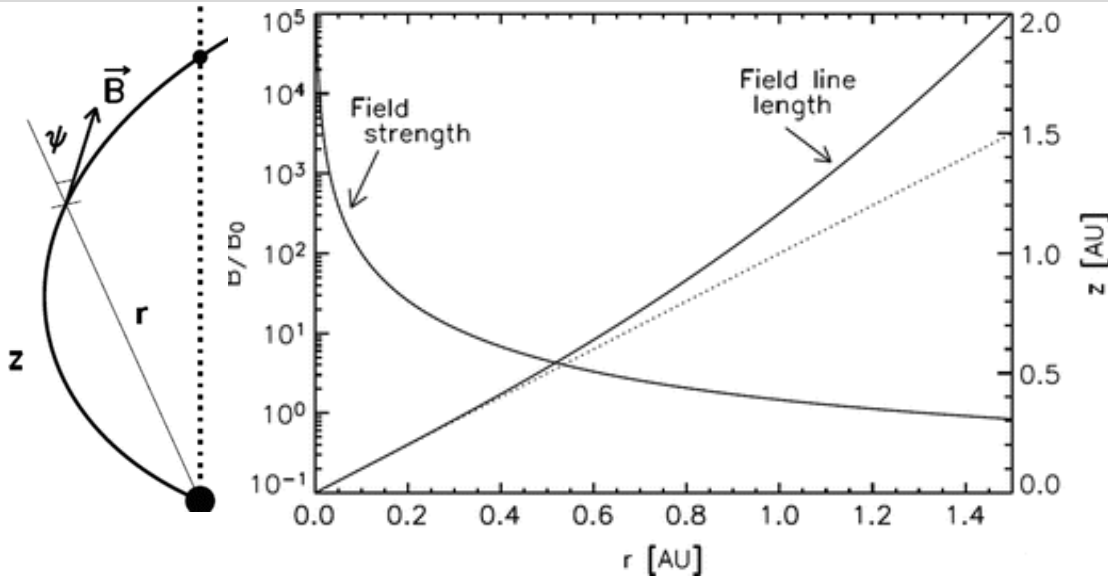


Forecasting SEP events

- > In order to *improve* the **forecasting quality**, we need to *better understand* the **physical processes** that **govern the particle acceleration, injection and propagation**. In particular, we need to understand:
 - **Acceleration and injection processes** near the Sun
 - **SEP interplanetary transport (diffusive models)**

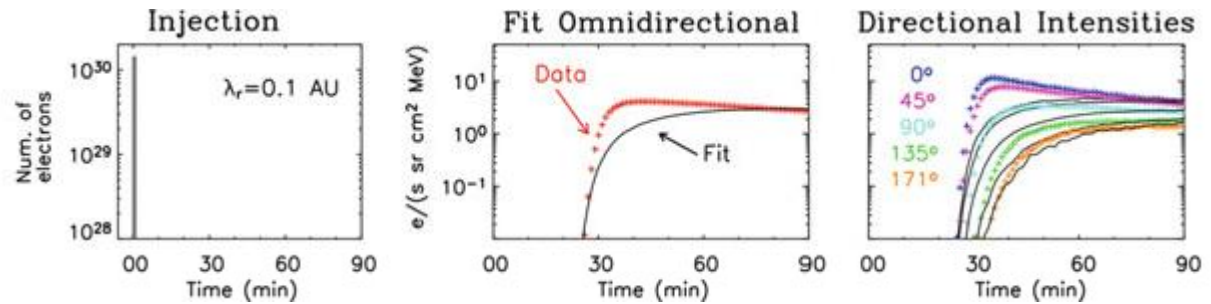


Focused Transport



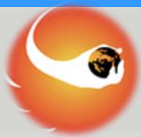
Mirror force	Particle scattering
$F_{\parallel} = -\frac{\gamma m v_{\perp}^2}{2B} \frac{\partial B}{\partial z} \quad + \quad \nu_c = \frac{\pi}{2} \Omega \frac{\delta B_k^2}{B^2}$	
= Focused transport	

Impulsive injection
+
Focused transport

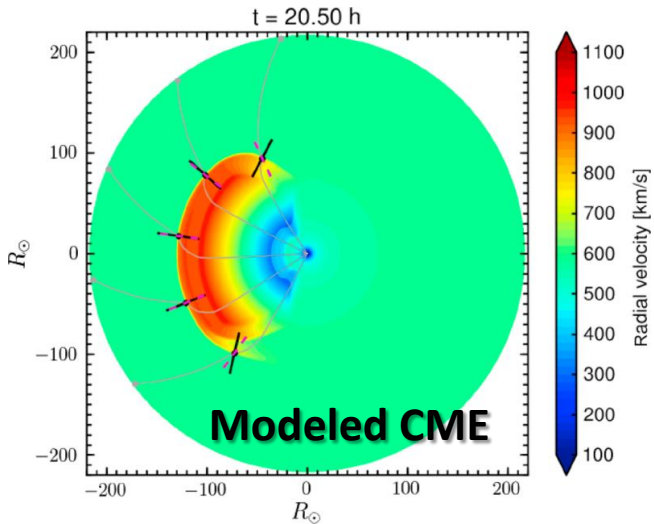


Aran et al., *Charged Particle Transport in the Interplanetary Medium*, ASSL, Springer, 2018

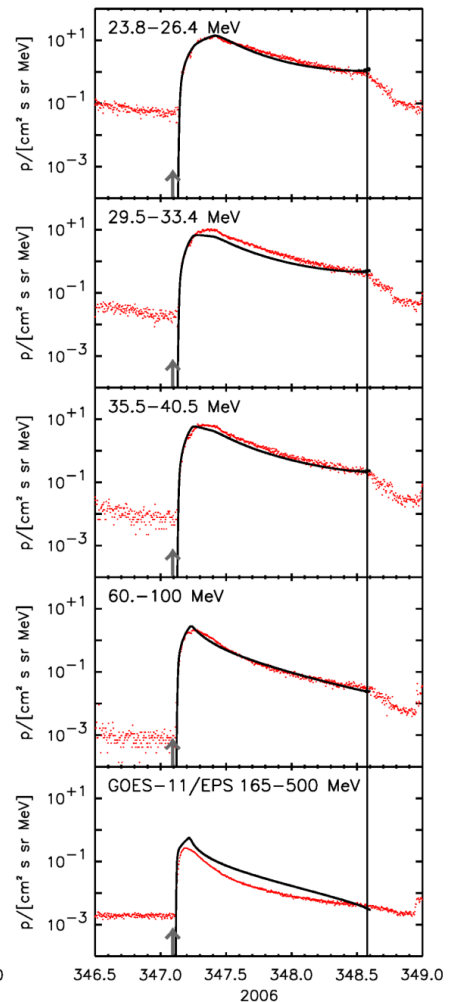
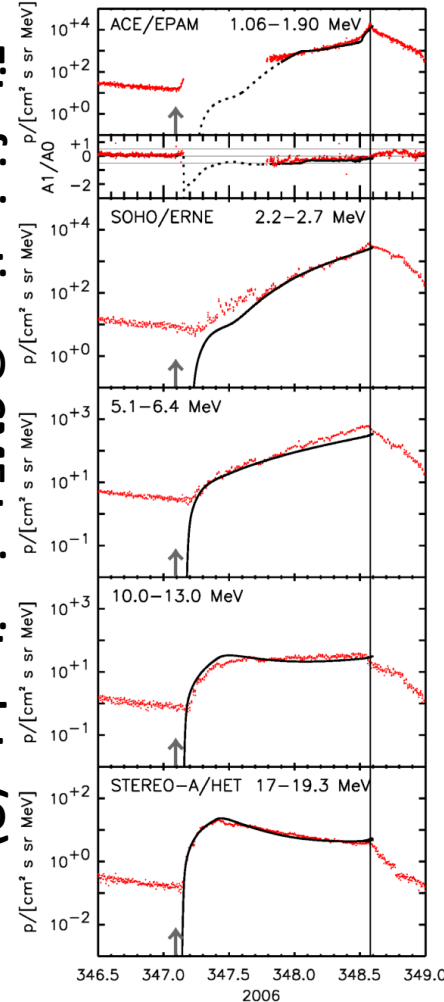
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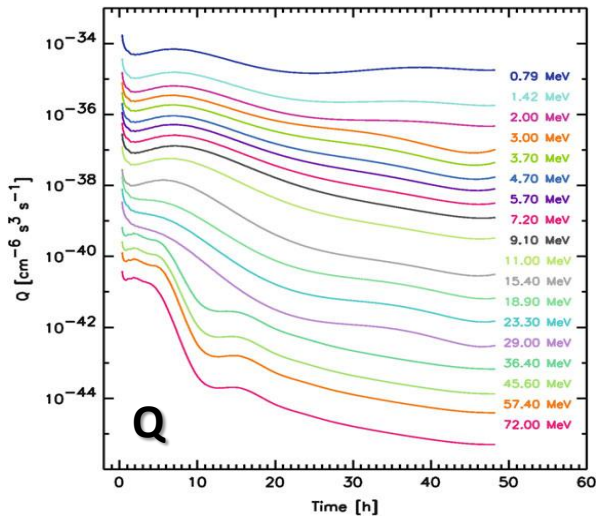
Focused Transport



Fit of injection @ CME to in-situ data (Q)



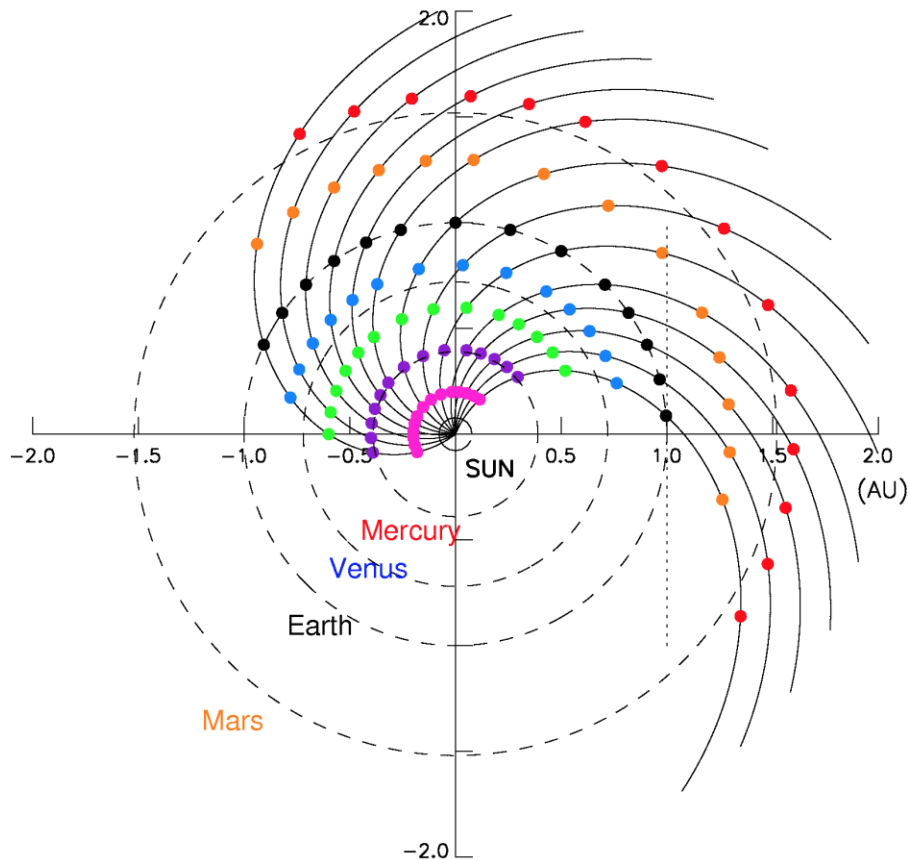
Pomell et al., JSWSC, 2015



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SOLPENCO2



Q vs. shock properties

+

Shock model

+

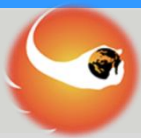
Focused transport model

→ Synthetic SEP event at various r

Aran et al., ESWW16, Session 8

http://sepem.eu/help/solpenco2_intro.html

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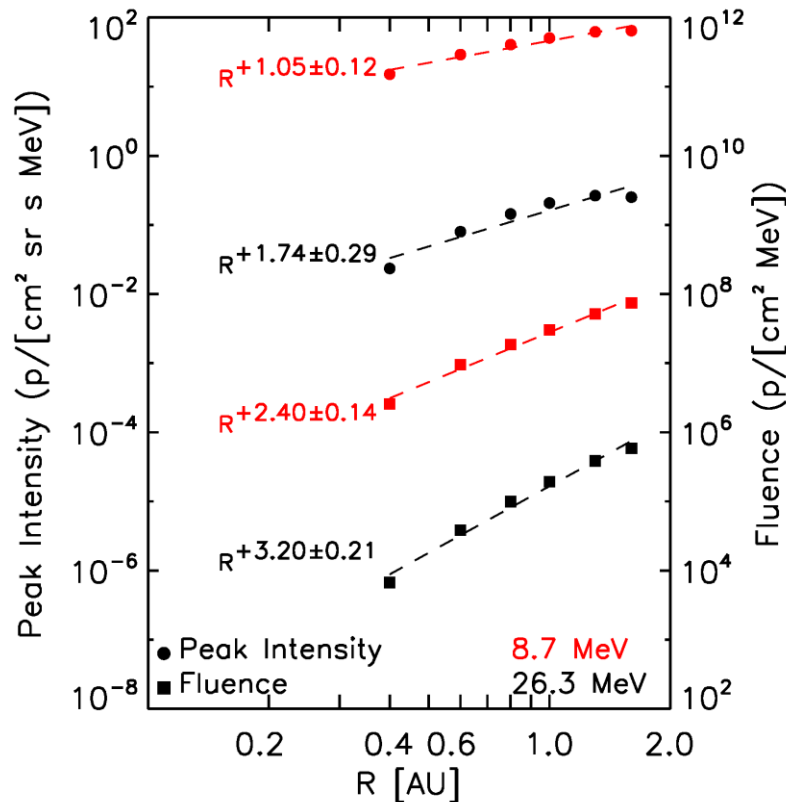
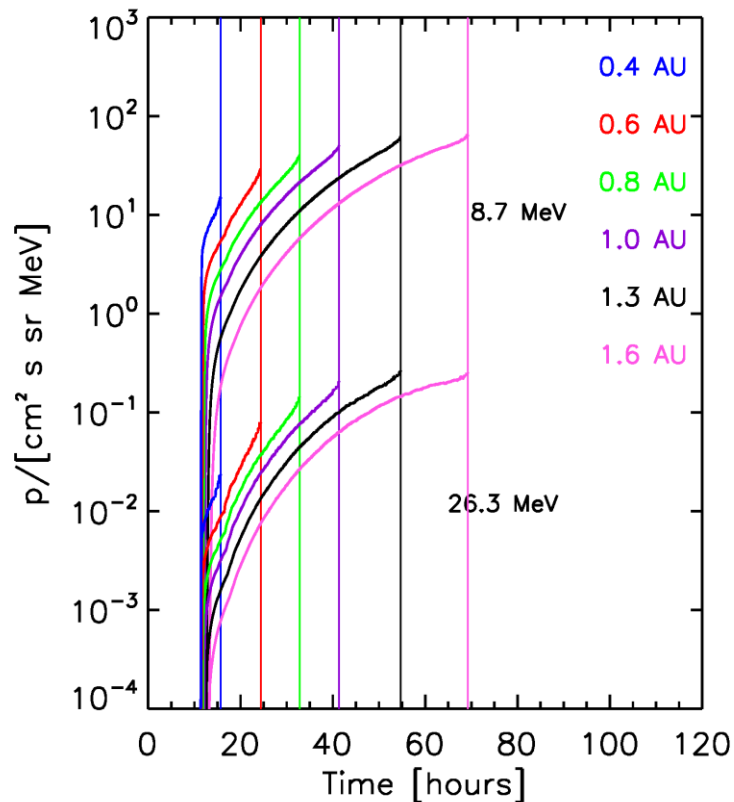


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SOLPENCO2

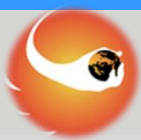
June 6, 2000 SEP event



Aran et al., ESWW16, Session 8

http://sepem.eu/help/solpenco2_intro.html

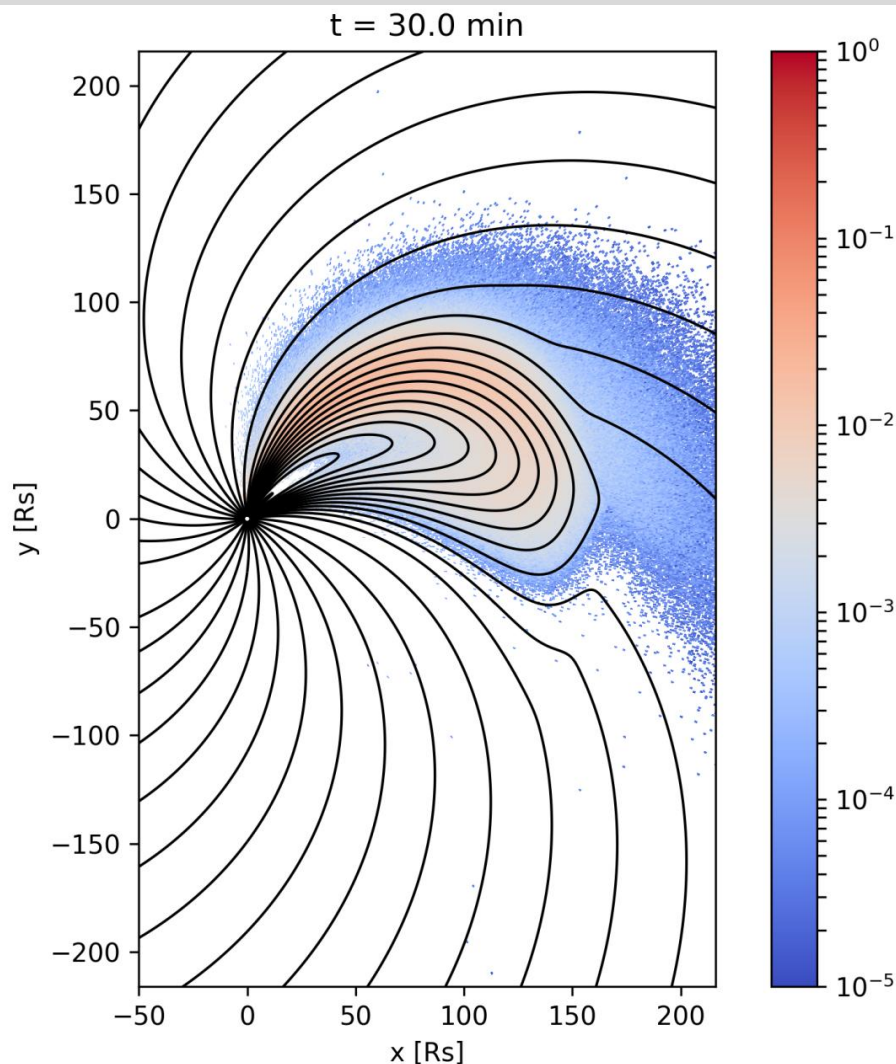
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Beyond the Archimedean spiral IMF

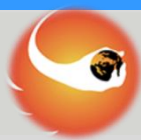


> During the **active Sun**, the IMF has a *non-spiral structure*

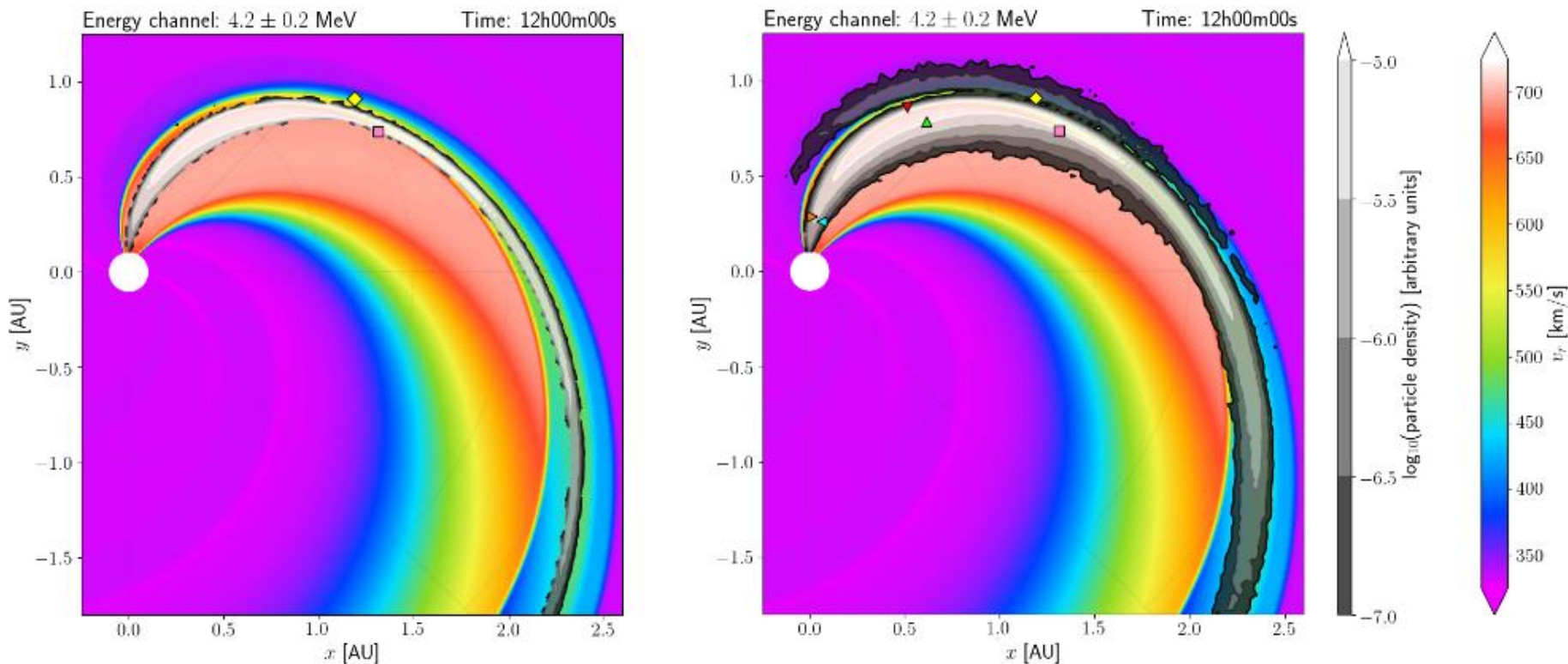
> **Transport** in, e.g., *closed magnetic fields* (magnetic clouds), also *perpendicular to the mean field*

Afanasiev et al., ESWW16, Poster | S5.p21

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MHD + transport modeling



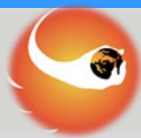
> MHD background (*EUHFORIA code*) + 3D Particle Transport Modeling applied to a CIR

Wijzen et al. , *Astron. Astrophys.*, 2019

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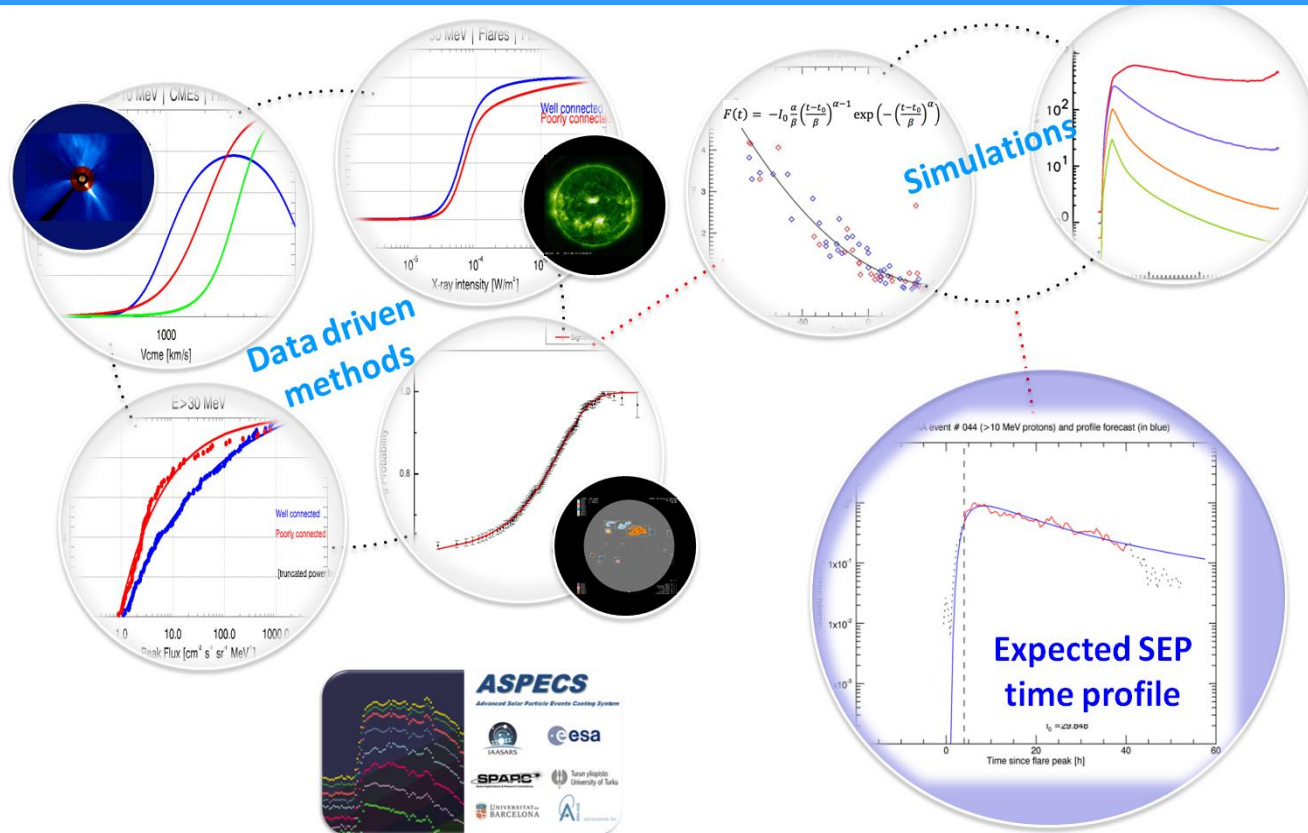
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A novel hybrid tool

Coupling Data-driven + Physics based models

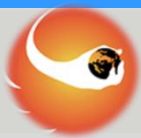


TDM today [!] @ 14:00 Mozane 789

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Conclusions

- > Outside the protective barrier of the magnetosphere **the most important contribution to radiation risk** comes from **gradual SEP events**
- > **Forecasting models and tools** progressively become more reliable. With the coupling of **Data-driven** and **Physics based models** *being already achieved*.
 - Better understanding of the physical processes is needed (acceleration, propagation, transport) for better **forecasting quality**.

⇒ **Such understanding will be (hopefully) achieved by new missions during the upcoming years: Solar Orbiter, Parker Solar Probe, BepiColombo ...**

Thank you for your attention

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