Solar Energetic Particles

Remote sensing and in situ observations

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Extraterrestrik @ Kiel university

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- Kiel was a Hanse-city from 1284 till 1518 living mainly from trade.
- Experienced enormous population growth at the end of 19^{th} century.
- Hosts shipyards, marine sciences, etc.,
- Entrance to the Kiel canal, linking the North Sea to the Baltic.
- Kiel was heavily bombed and nearly completely destroyed during World War II.
- Rebuilt as a modern city thereafter, but only few original houses remain.
- Its current population is roughly ¼ of a million (35'000 students)

Extraterrestrik @ Kiel university

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Extraterrestrik @ Kiel university

Well known for Max Planck, Heinrich Hertz, Hans Geiger, and Albrecht Unsöld. (but also for Phillip Lenard...)

About 50 physics majors begin their studies of which about ½ will complete them and ~10 get their PhD.

6 Divisions: Astrophysics, plasma physics, condensed matter physics, surface physics, and theoretical Physics,

The Extraterrestrial Physics Division with some 60 people, incl. students, working on numerous projects (e.g., ACE, Dosimetry, MSL, SOHO, Solar Orbiter, STEREO, Ulysses, AMS 02...).

Charged Particles in the Heliosphere

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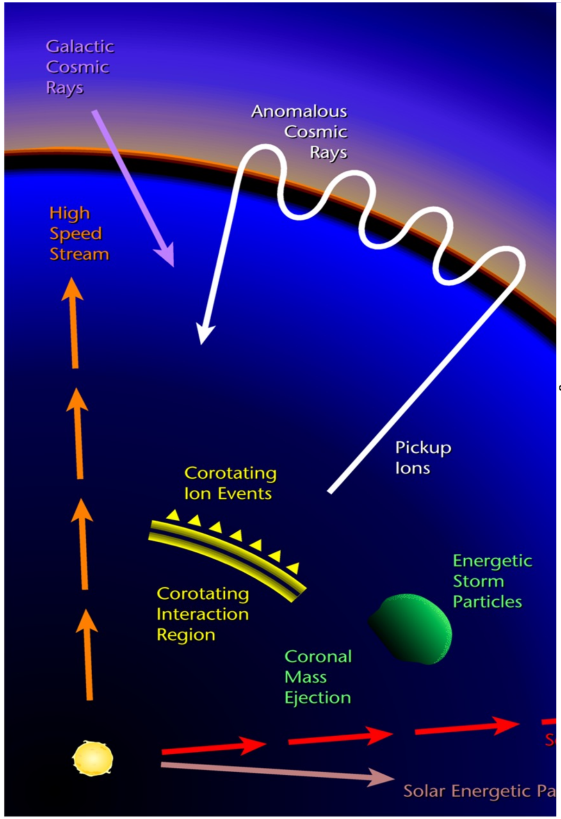

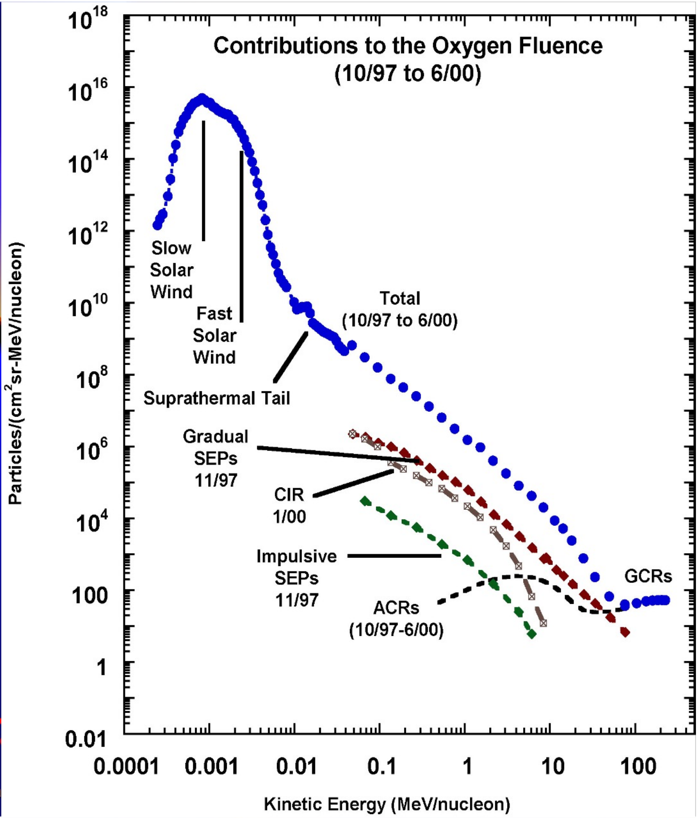

1. Galactic cosmic rays
2. Ions and electrons from Solar Energetic Particle Events (SEPs).
3. Interplanetary particles
4. Magnetospheric particles

From flares to SEPs @Earth

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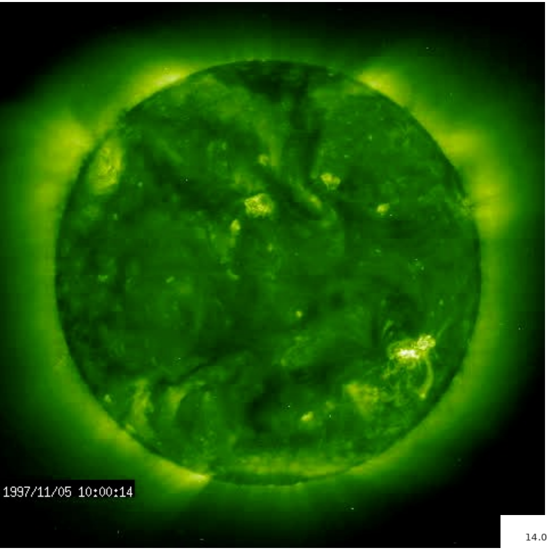

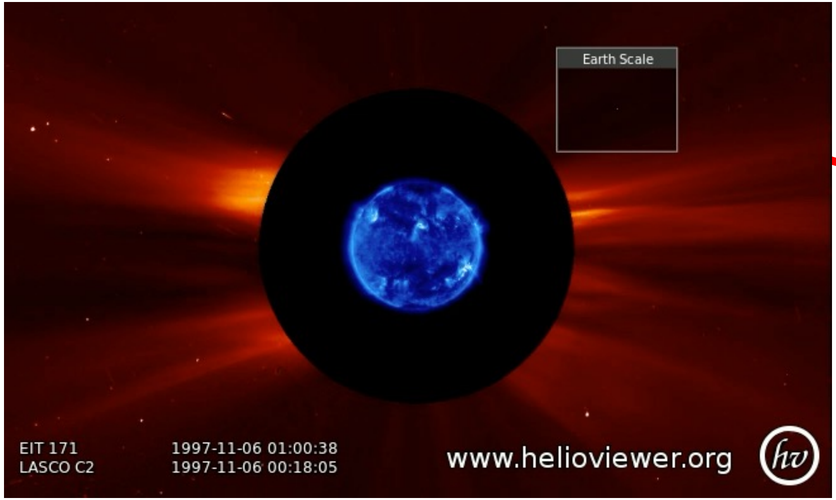

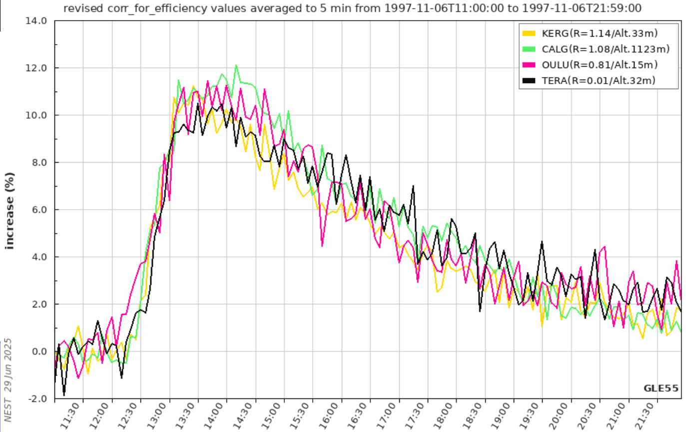

From flares to SEPs @Earth

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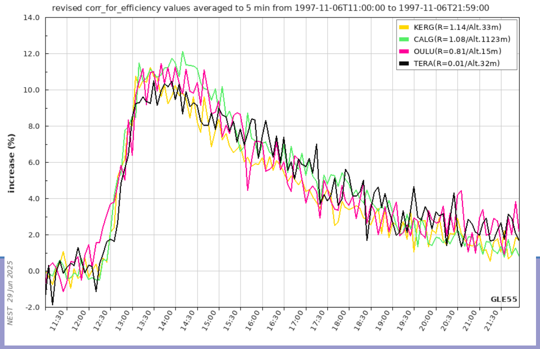
Particle injection to IPM

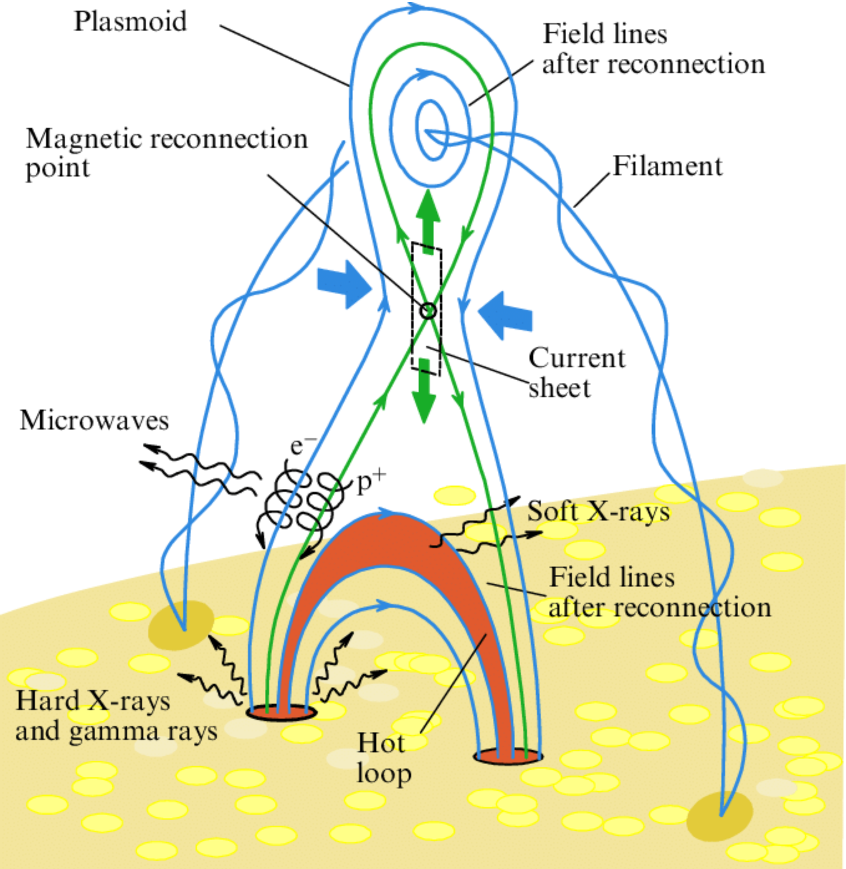
Particle transport within the IPM

Particle Acceleration

Flare vs Shock



Particle acceleration

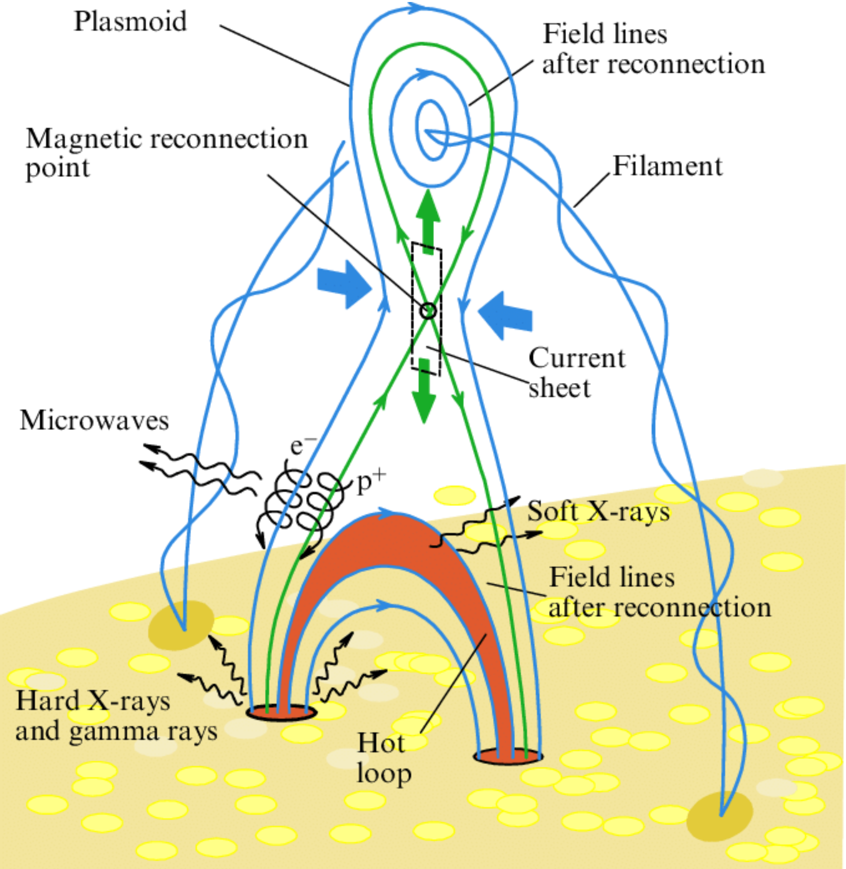


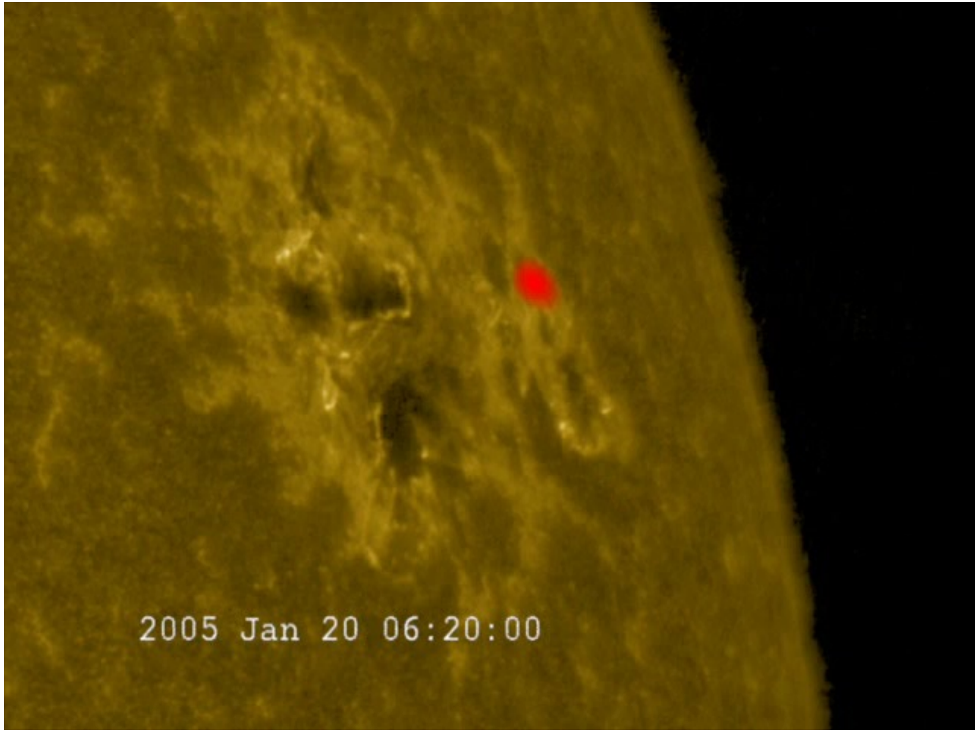
Solar flares

– energy release and particle acceleration

A simple cartoon scenario: energy release and particle acceleration in the corona, loops underneath (magnetic reconnection)

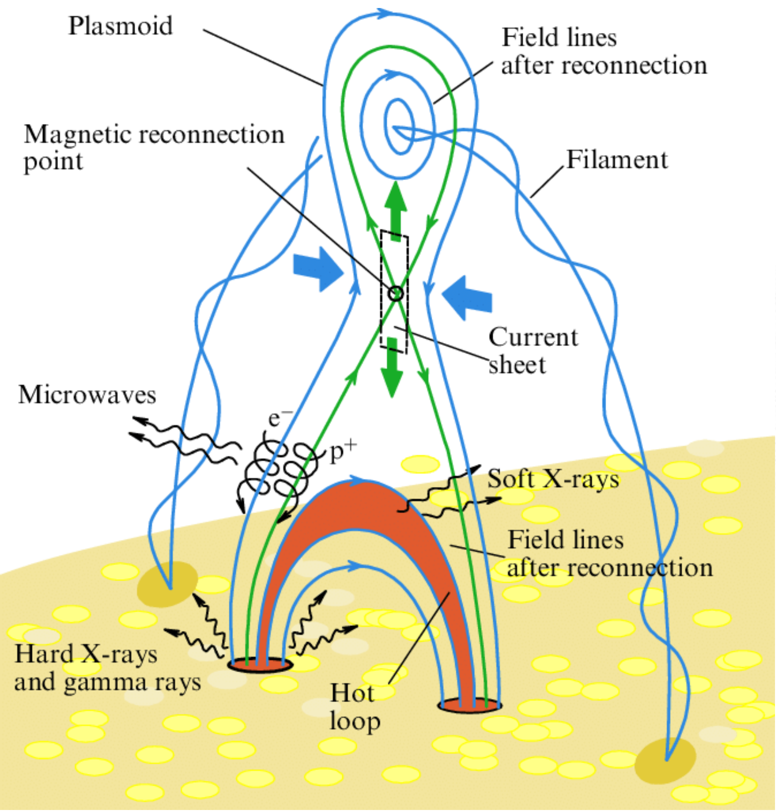
Particle acceleration

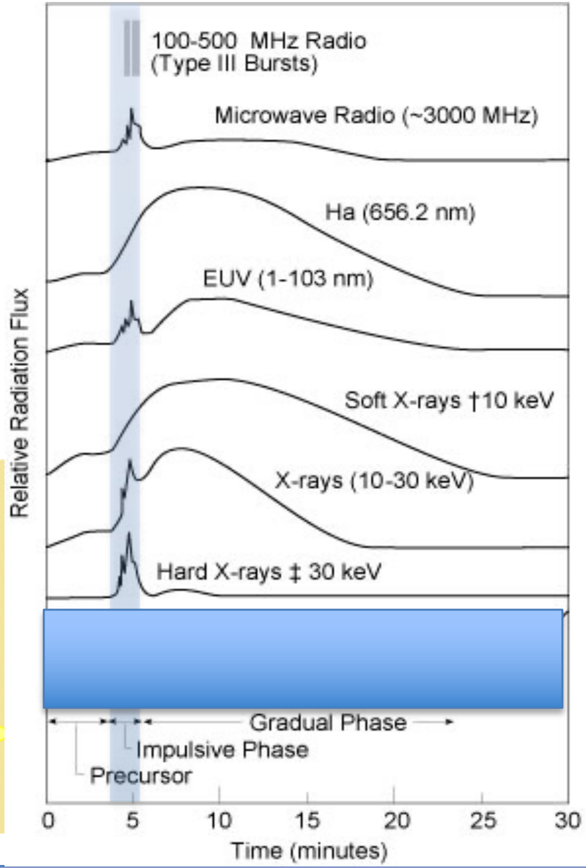




Red: Soft X-ray emission;
Blue: Hard X- and γ-rays emission

Particle acceleration





Gross distinction:

- short & spiky
- (microwaves[1], HXR)
- long-lasting (Hα, SXR)

Phases of a flare:

- impulsive phase
- main phase/gradual phase

Jan. 29, 2015 solar M-class flare

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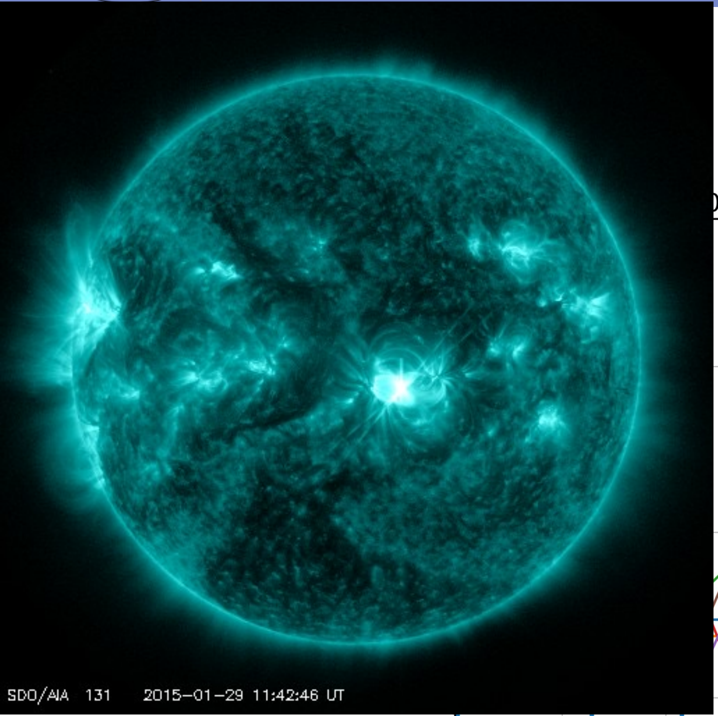

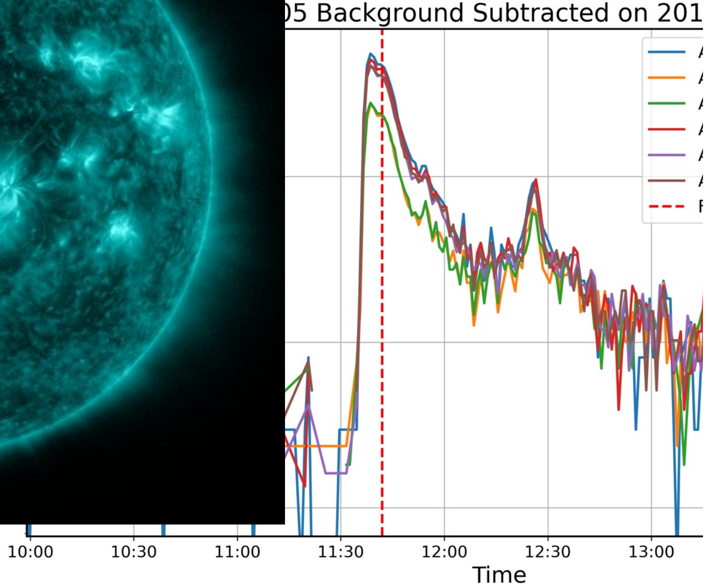

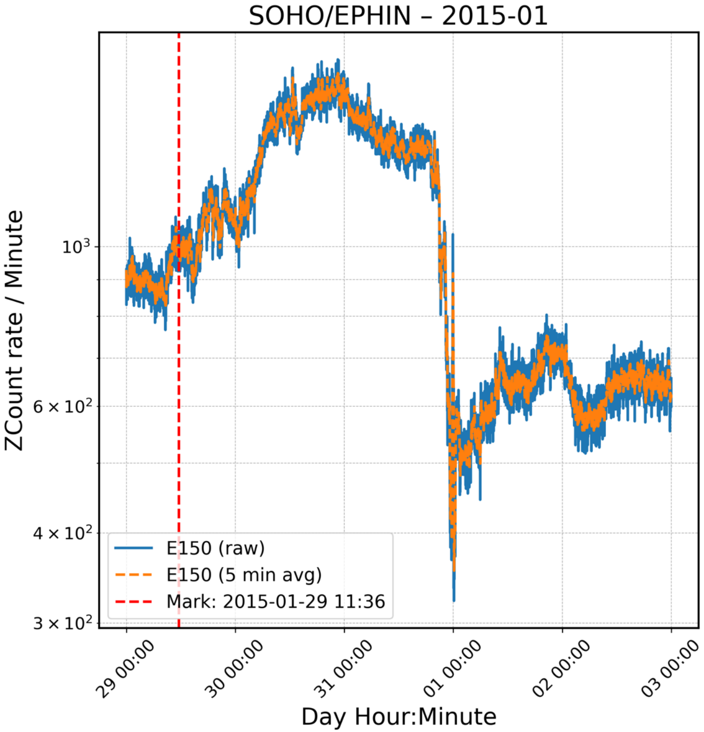

X-ray measurements from SOHO/EPHIN

Electron measurements @ same period

Solar flare but …

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- X-ray measurements from SOHO/EPHIN indicate particles are accelerated and interact with the lower corona
- Measurements from SOHO/EPHIN indicates no significant increase in the electron flux.
- No particles escape from the corona?

From flares to SEPs @Earth

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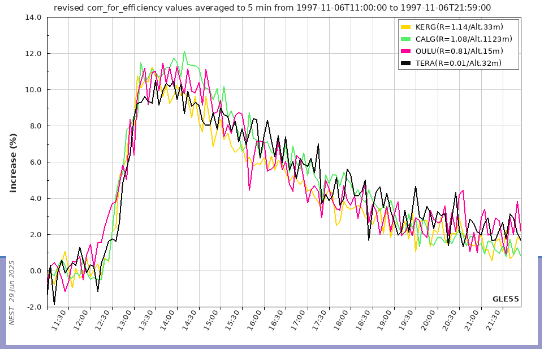
Particle injection to Inter Planetary Medium

Particle transport within the IPM

Particle Acceleration
Flare vs Shock



Solar flare but …

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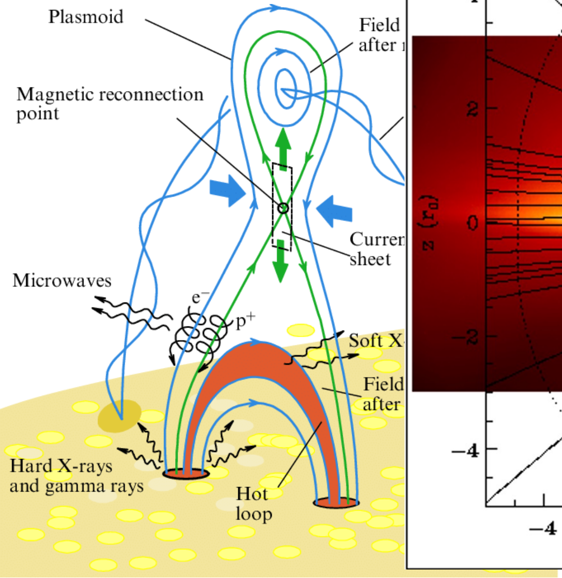
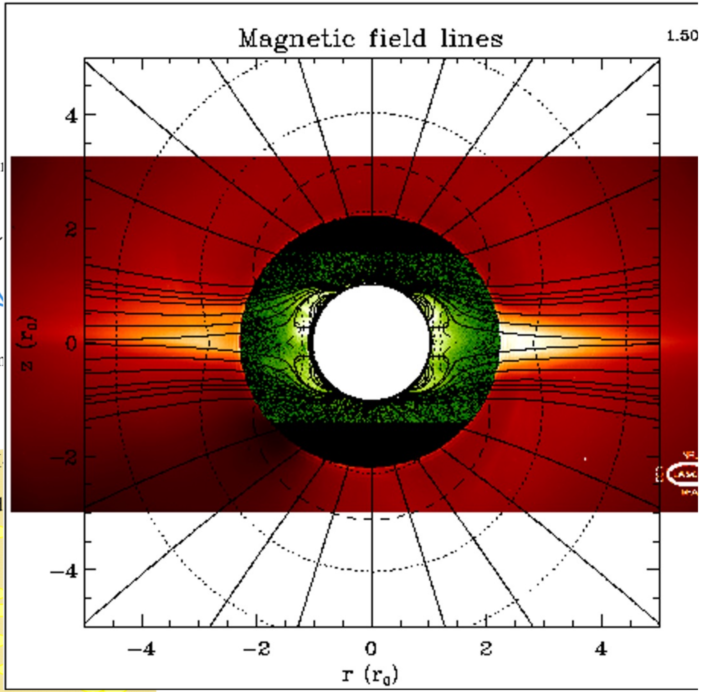
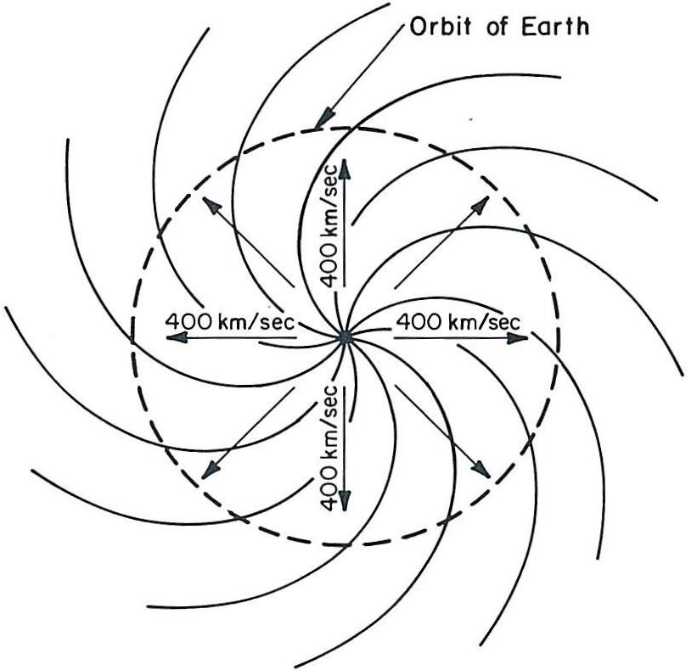


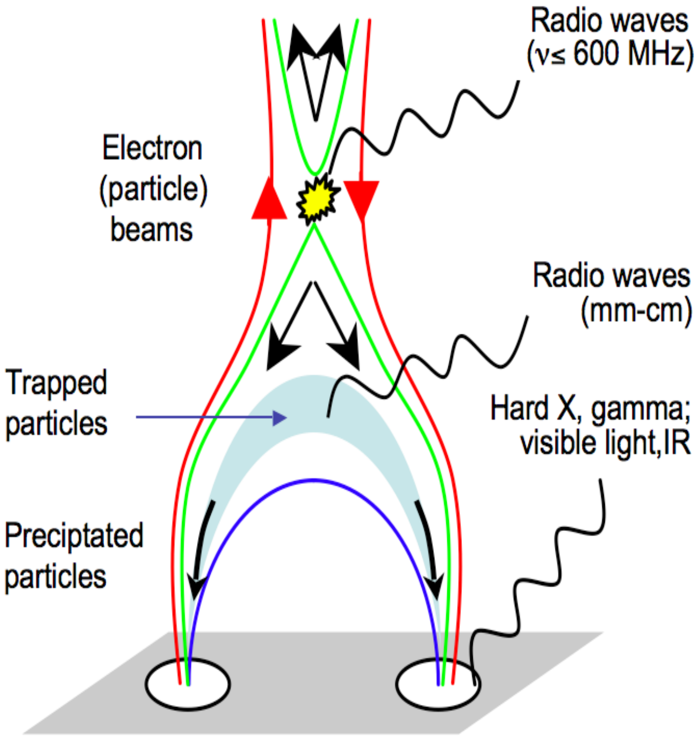


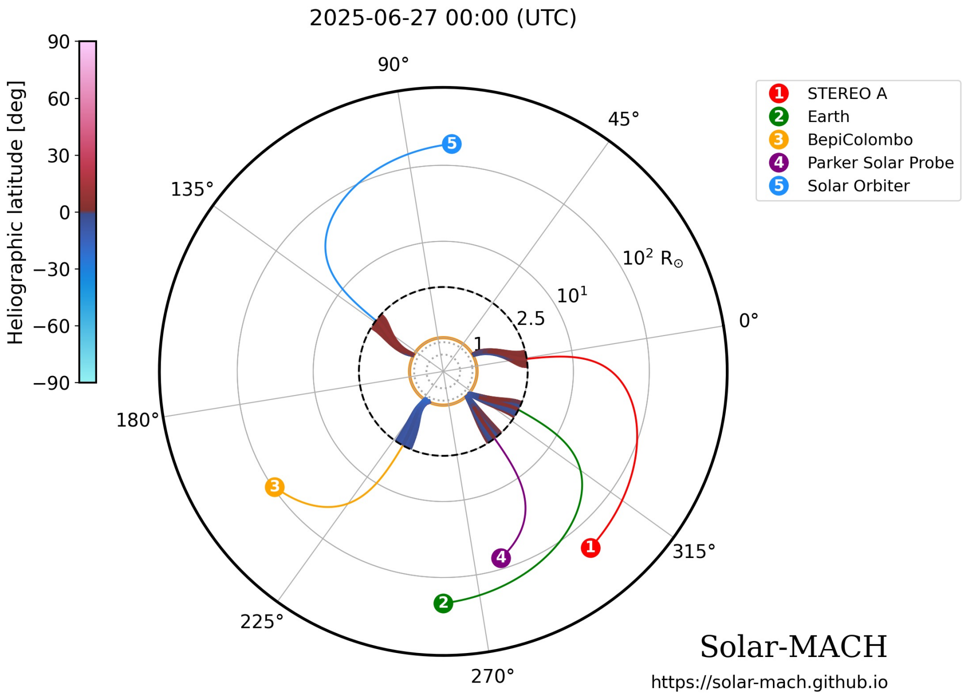


PFSS computation of the coronal solar magnetic files incl. closed field lines

Model of the interplanetary magnetic field

Solar flare but …





Coronal shocks
ed to eruptions

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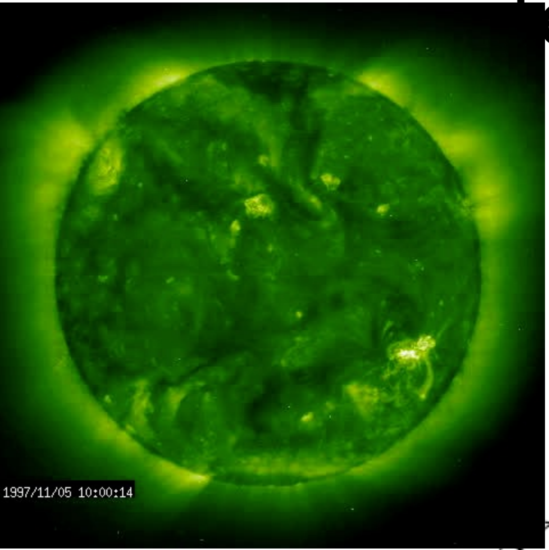
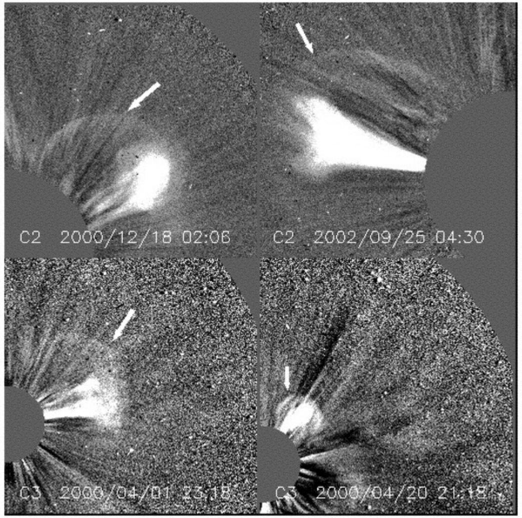
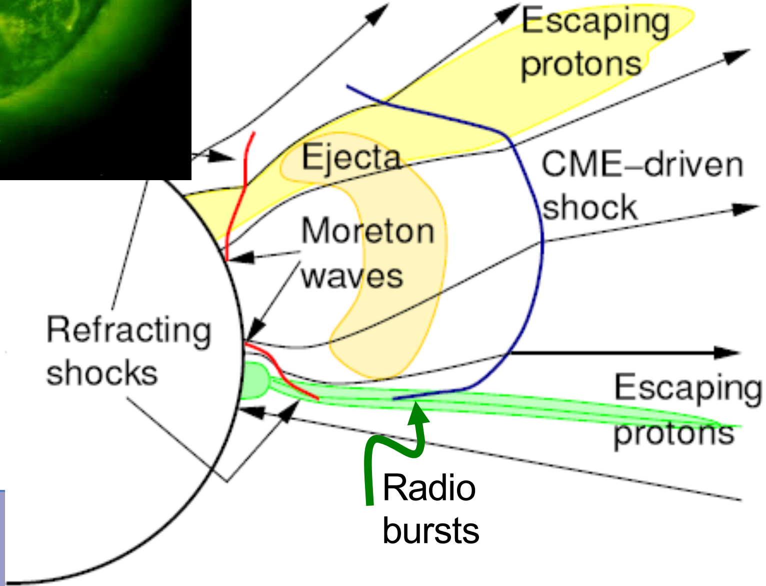
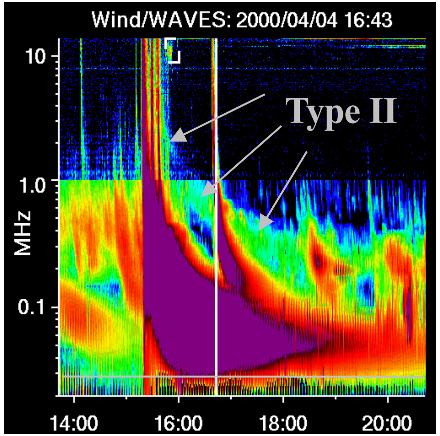




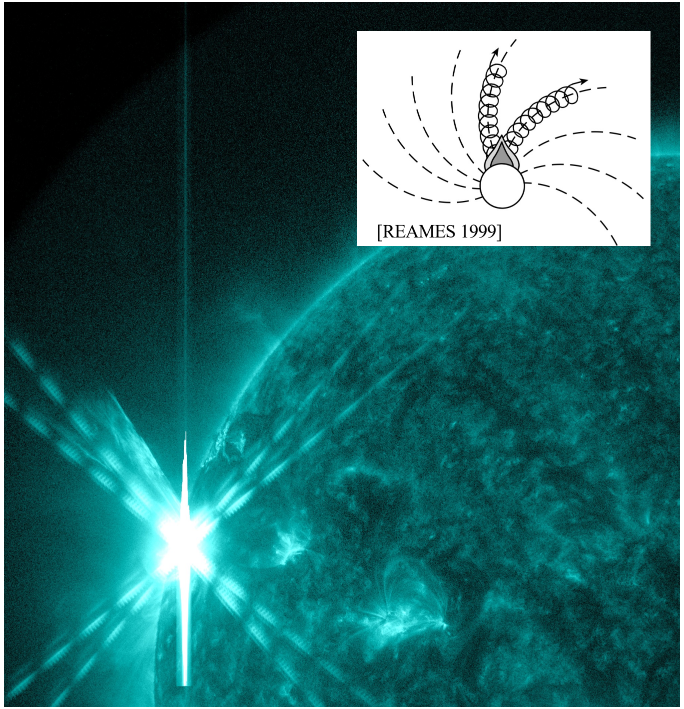




$$f_p(\text{kHz}) = 9\sqrt{n_e(\text{cm}^{-3})}$$

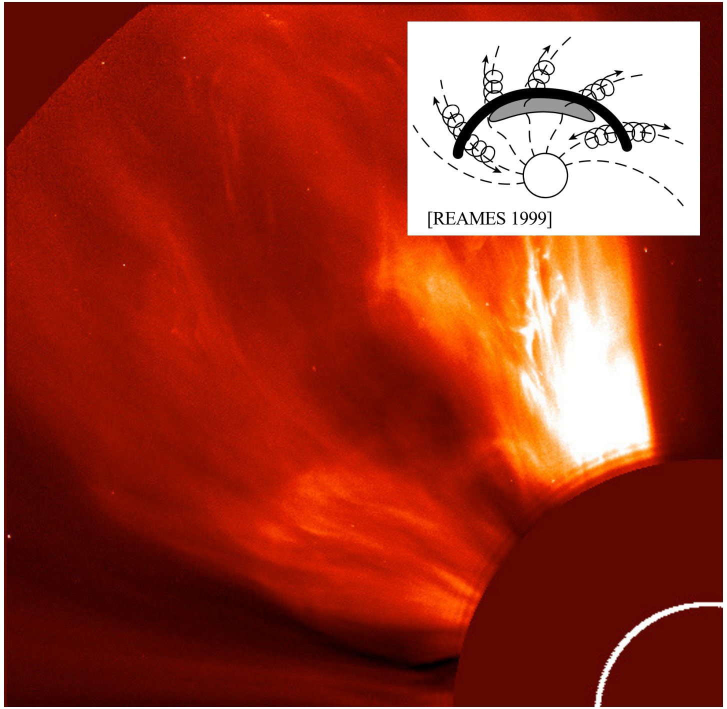
Sources of SEPs

Solare Flares, discussed here



SDO/AIA – 13.1 nm 05.05.2015

Shock waves associated with (CMEs)

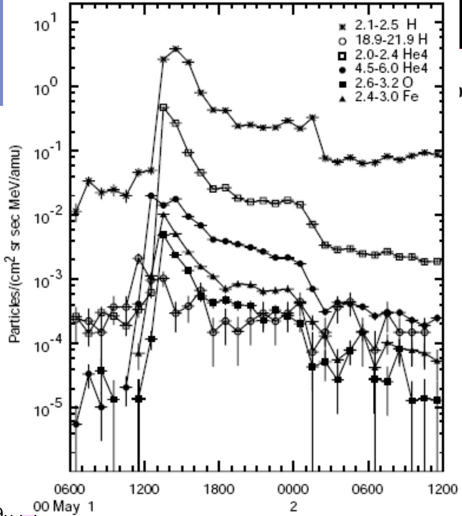


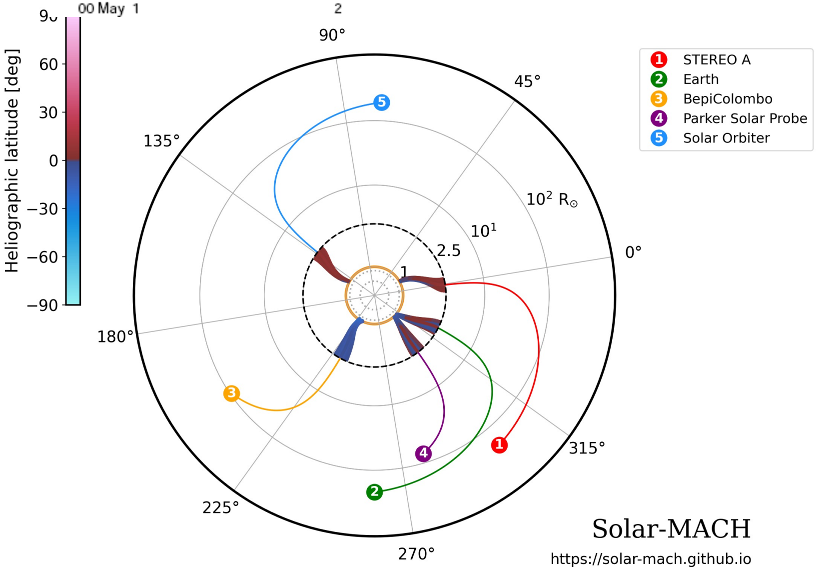
SOHO/LASCO C2 05.05.2015

TABLE 1. Properties of Impulsive and Gradual Events

	Impulsive	Gradual
Particles:	Electron-rich	Proton-rich
3He/4He	~1	~0.0005
Fe/O	~1	~0.1
H/He	~10	~100
QFe	~20	~14
Duration	Hours	Days
Longitude Cone	<30 deg	~180 deg
Radio Type	III, V (II)	II, IV
X-rays	Impulsive	Gradual
Coronagraph	-	CME (96%)
Solar Wind	-	IP Shock
Events/year	~1000	~10

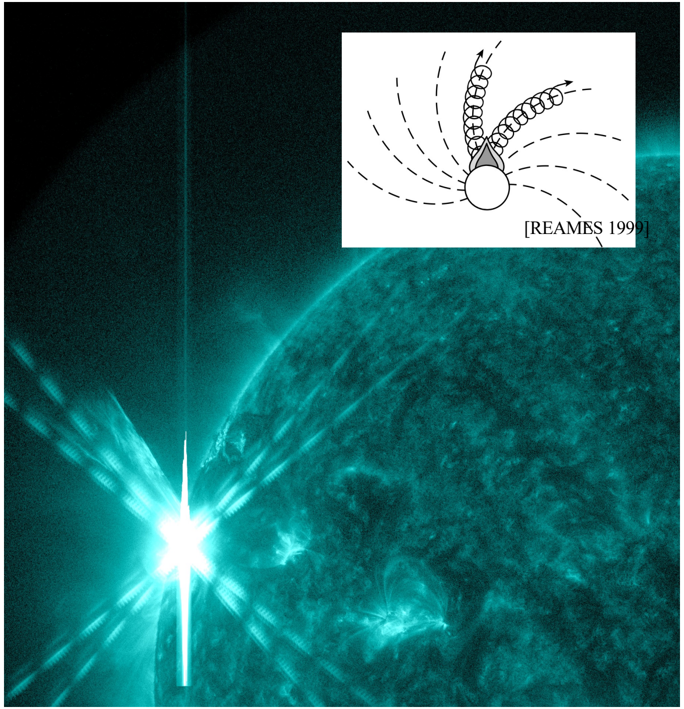
- 0.05





Impulsive flares

Solare Flares, discussed here

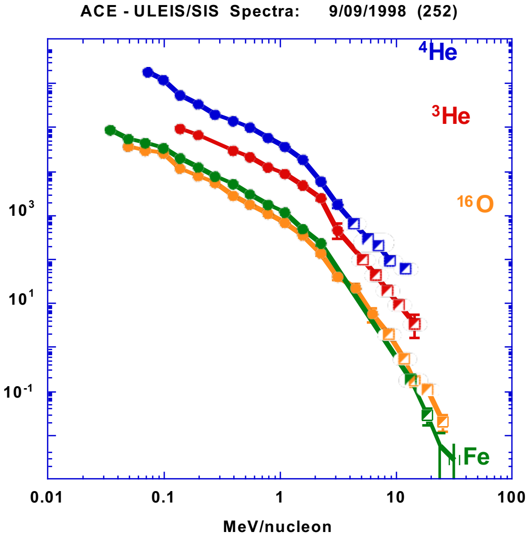


SDO/AIA – 13.1 nm 05.05.2015

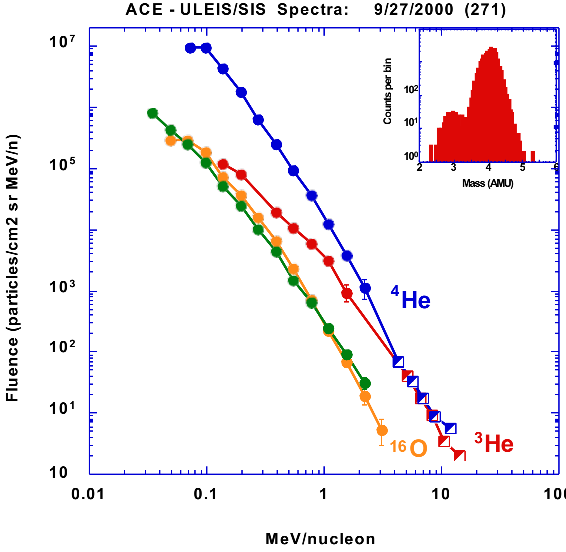
- Thought to be a result of flare acceleration only
- Characteristics
  - $^{3}He/^{4}He$ enhanced by large factors (x10^4)
  - Enhanced Ne-Si and Fe over CNO as compared to gradual SEP events
  - Enhancement of ‘ultra heavy’ ions ($Z \geq 30$)
  - electron rich
  - small intensities and short duration (flares and SEPs)

Impulsive flares: ^{3}He importance

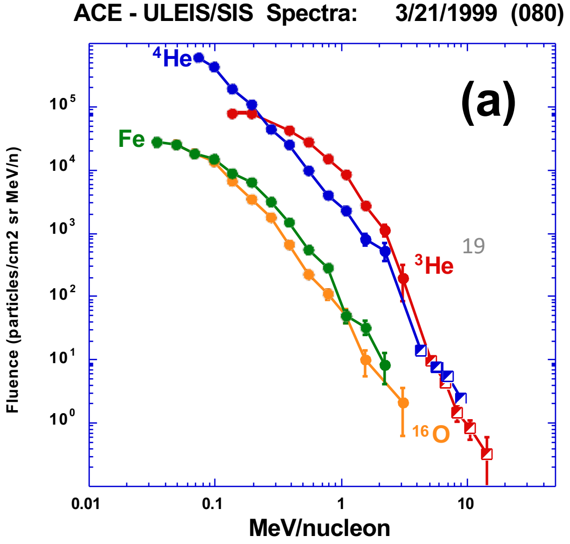
All similar



Only ^{3}He broken



^{3}He & Fe rounded



Mason et al., 2002

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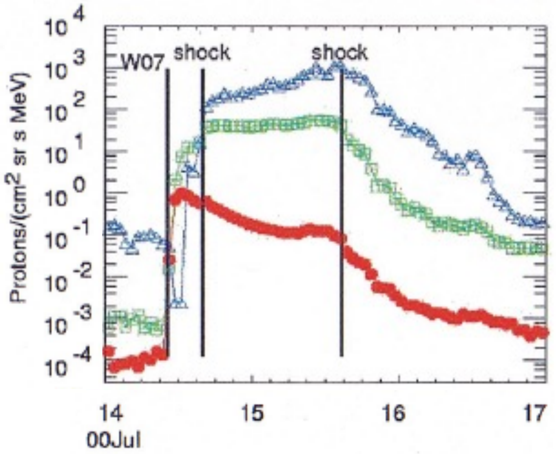
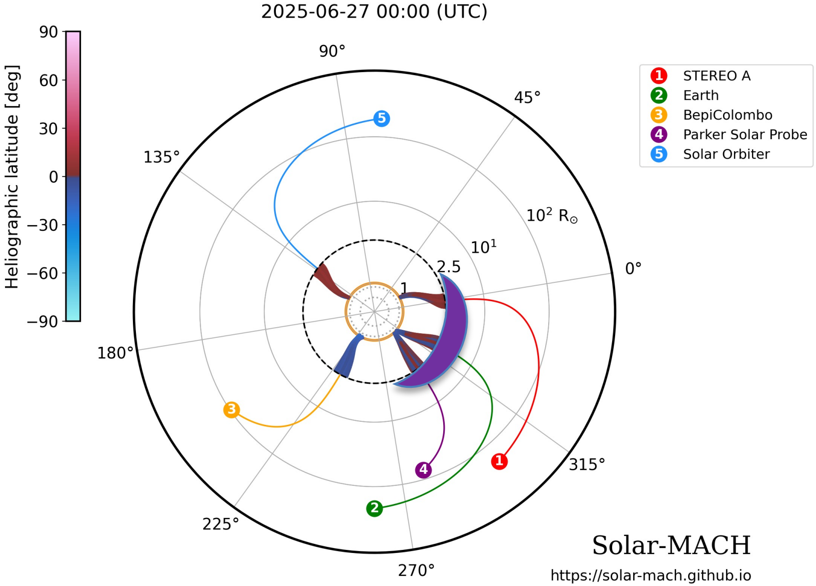
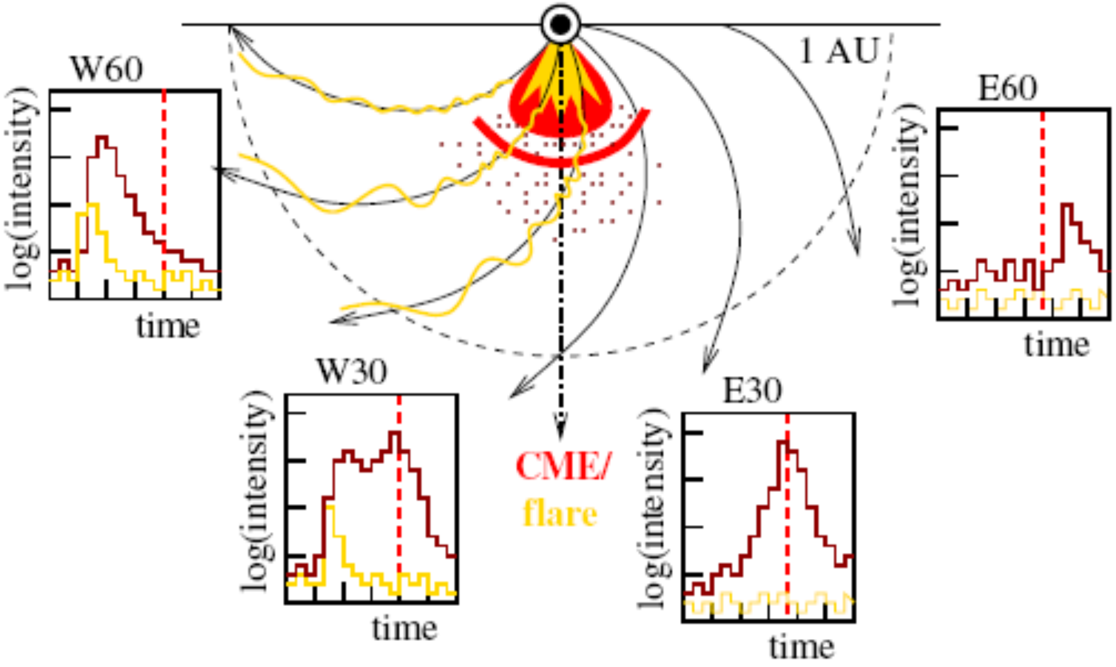


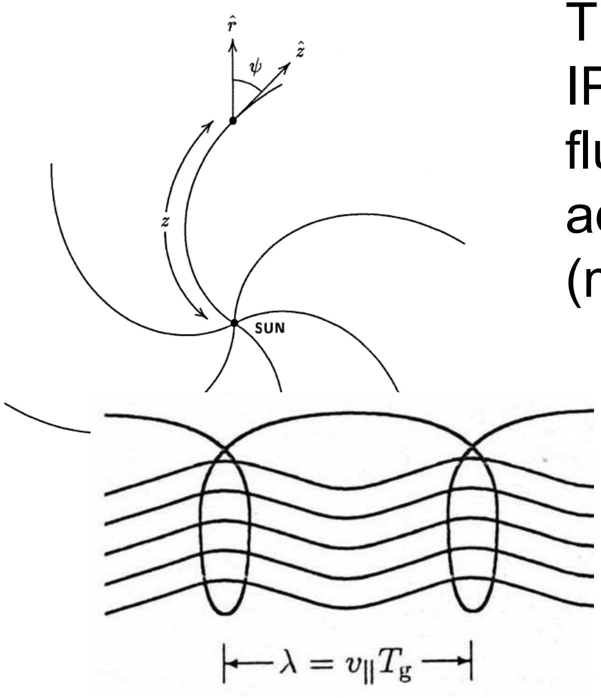


Longitude distribution of SEP events: flares vs. CMEs



- W60: Particles only from the Corona
- W30: Particles from the corona plus ESP.
- E30: Only ESP's
- E60: Only ESP's transported in the IPM reach the spacecraft

Transport in the IPM



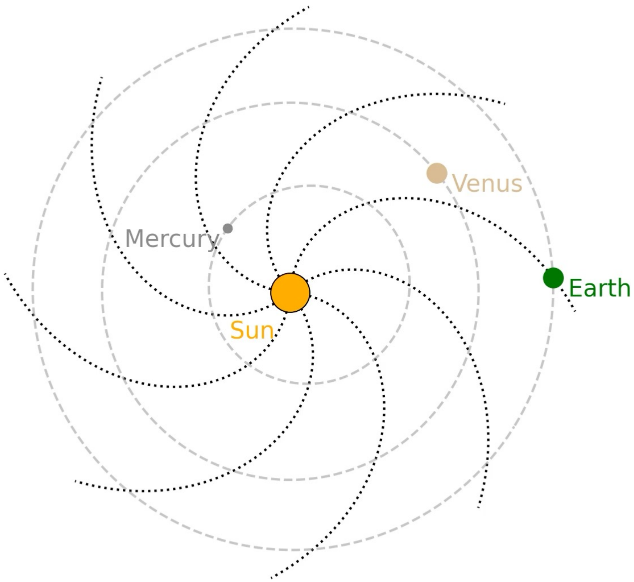
The simplest model of transport applicable to the IPM conditions assumes static magnetic fluctuations superposed on a Parker IMF. In addition the effect of adiabatic focusing (mirroring) has to be taken into account

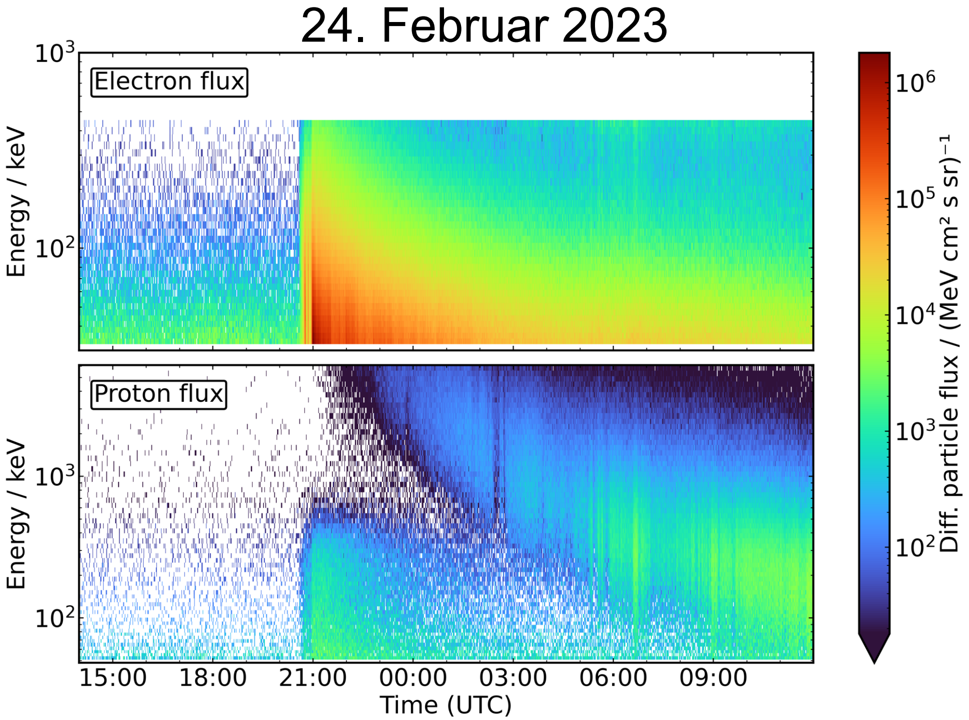
$$\dot{\mu} = \frac{1-\mu^2}{2L} v \quad \frac{1}{L} = -\frac{\partial \ln B}{\partial Z}$$

$$\boxed{\frac{\partial F}{\partial t} + v\mu \frac{\partial F}{\partial Z} + \frac{1-\mu^2}{2L} v \frac{\partial F}{\partial \mu} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial F}{\partial \mu}\right)}$$

Focused transport equation

Velocity dispersion: No scattering





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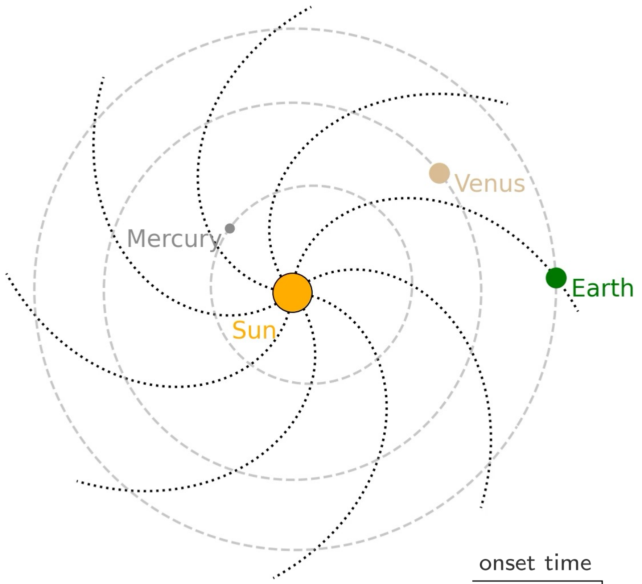
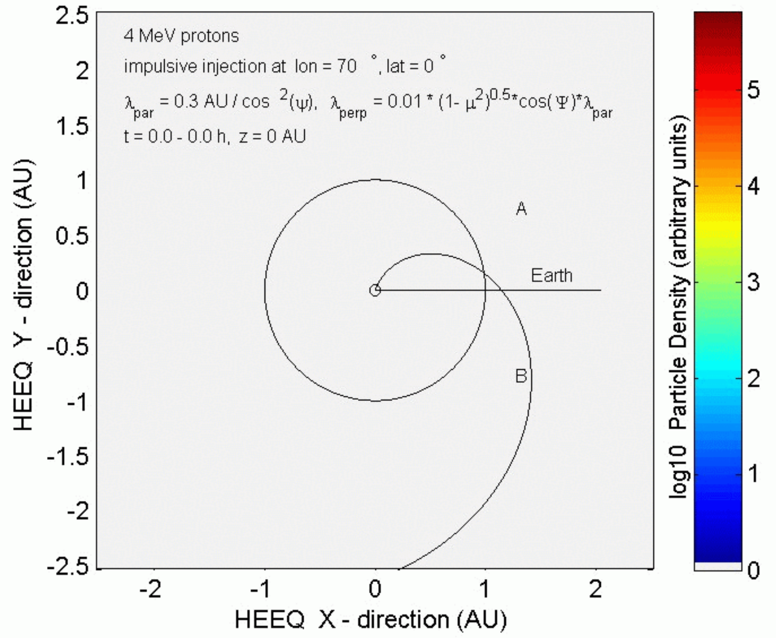


onset time

$$t(E) = t_{\mathrm{Sun}} + \boxed{\frac{s}{v(E)}}$$

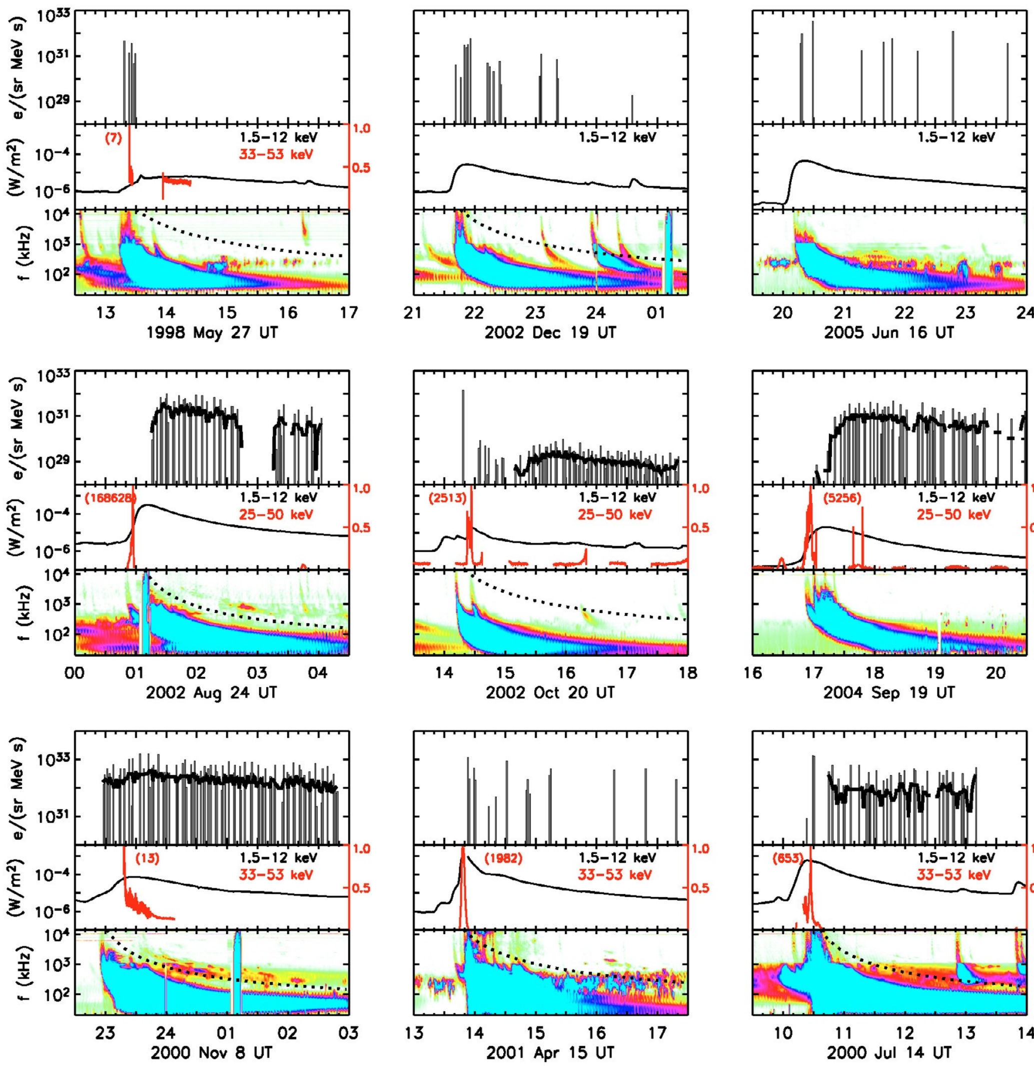
injection time

propagation time



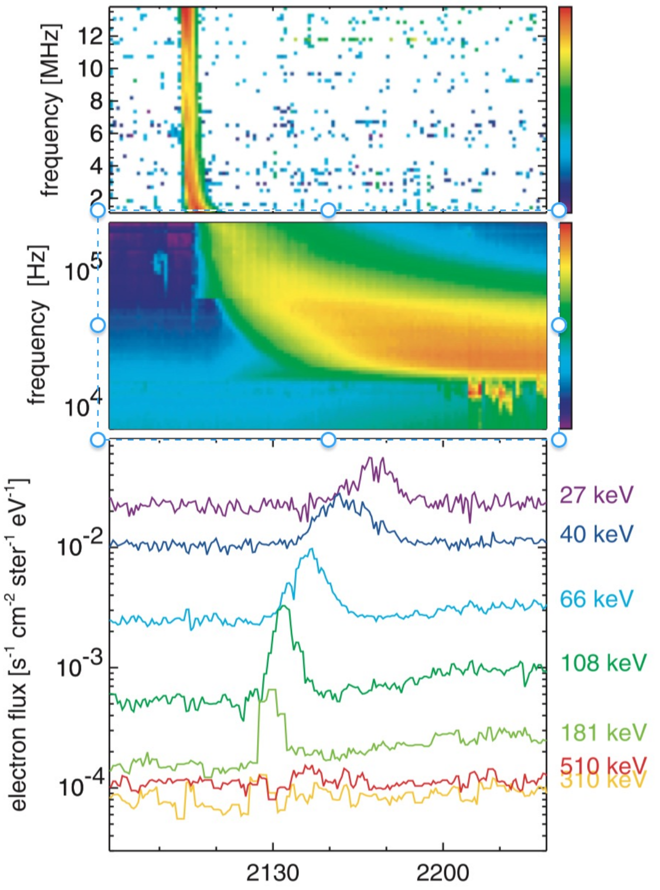
Application:

For well connected events the inversion of the focused transport equation we can derive the injection function that can be compared to radio measurements: Works for STEREO/Wind/Solar Orbiter



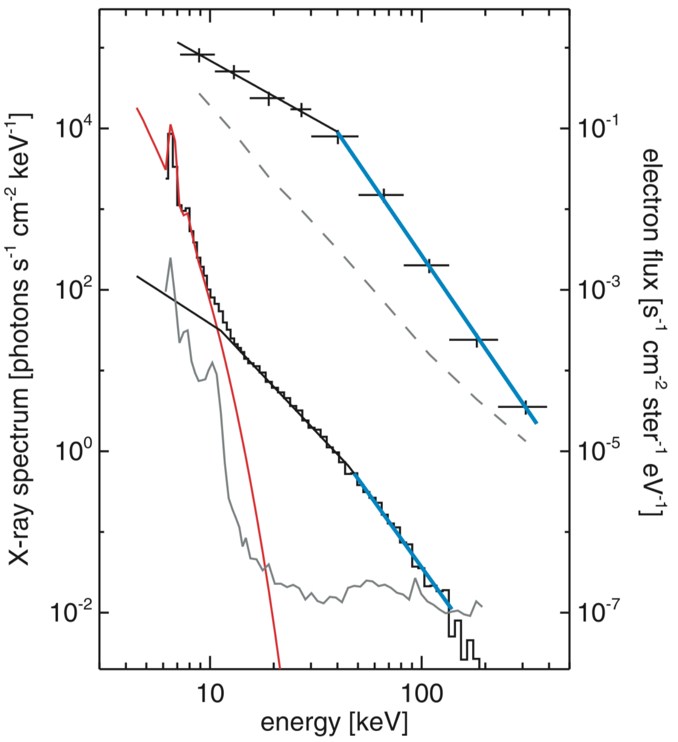
Correlation X-ray spectra and well-connected events (Krucker, Dresing, …)

- Well connected: Type III reaches local plasma frequencies.
- Prompt events rapid rise strong anisotropies

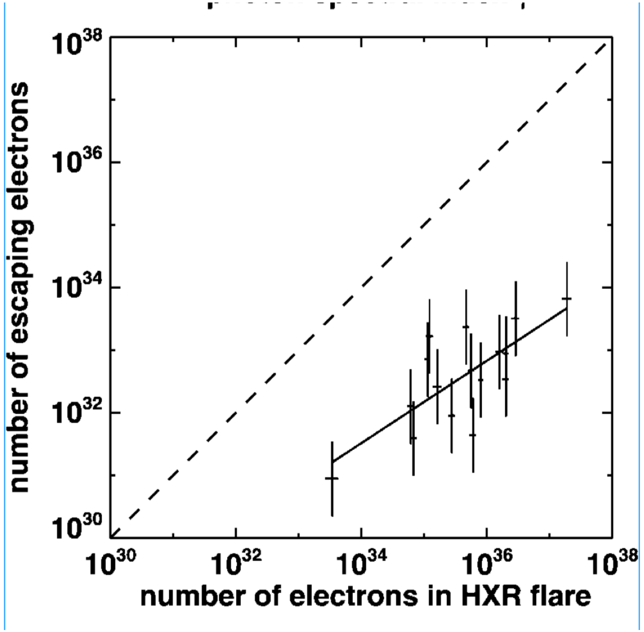


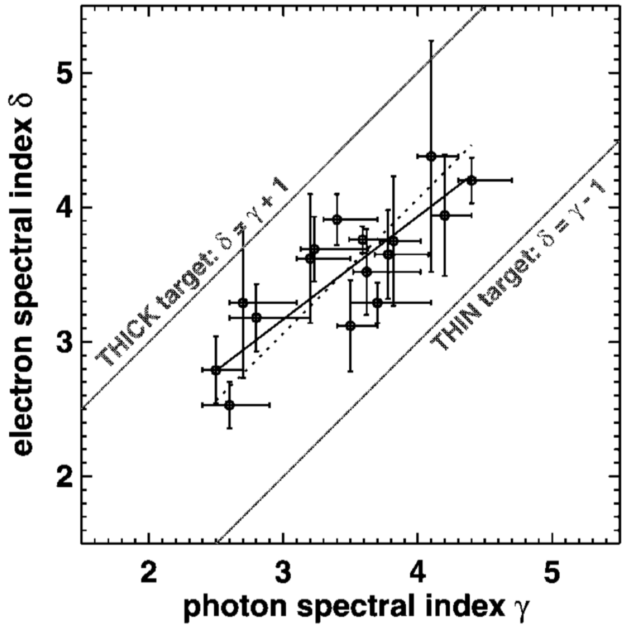
Correlation X-ray spectra and well-connected events (Krucker, Dresing, …)

- Well connected: Type III reaches local plasma frequencies.
- Energy spectra of photons from RHESSI
- Energy spectra form Wind 3DP or STEREO SEPT



Correlation X-ray spectra and well-connected, prompt events (Krucker, Dresing, …)





Number of escaping electrons

Spectral index

The REleASE scheme: How it works

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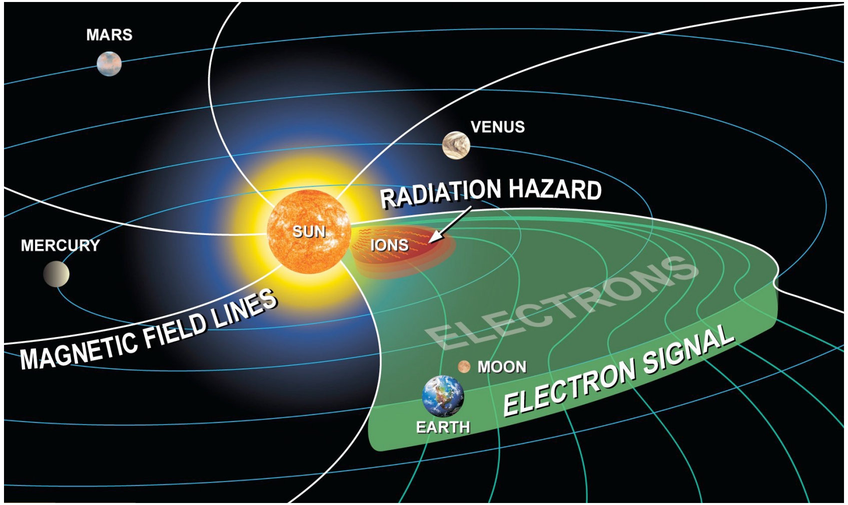

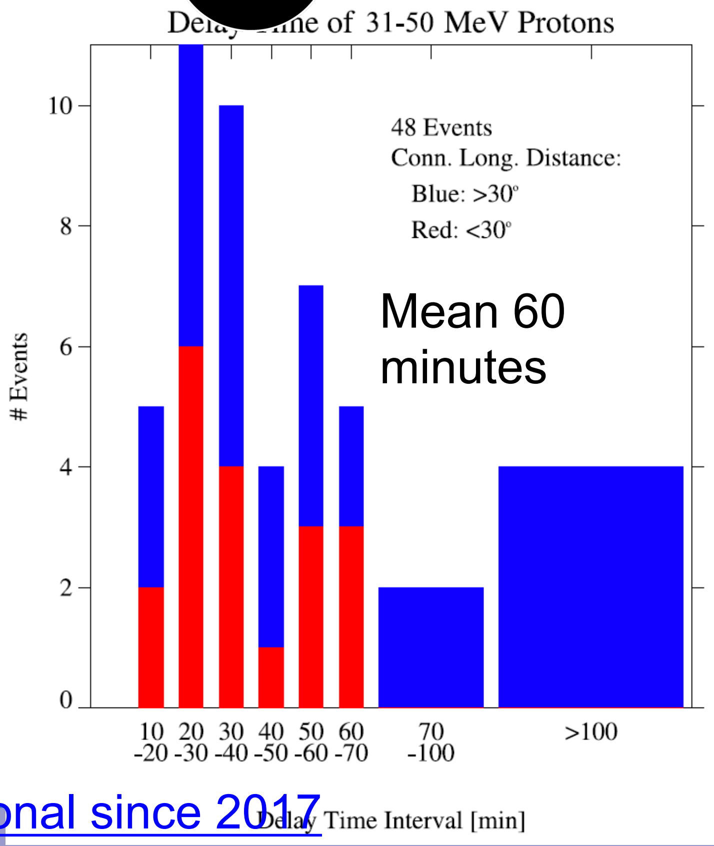

Electrons:

1 MeV -> 0.94c -> Travel time 10.6 min

Protons:

30 MeV → 0.25c → Travel time 40 min

50 MeV → 0.31c → Travel time 32 min

It is operational since 2017

The REleASE scheme: How it works.

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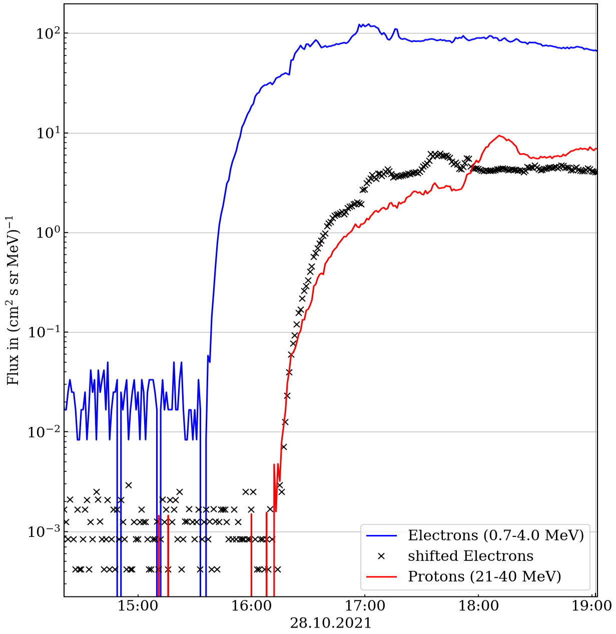

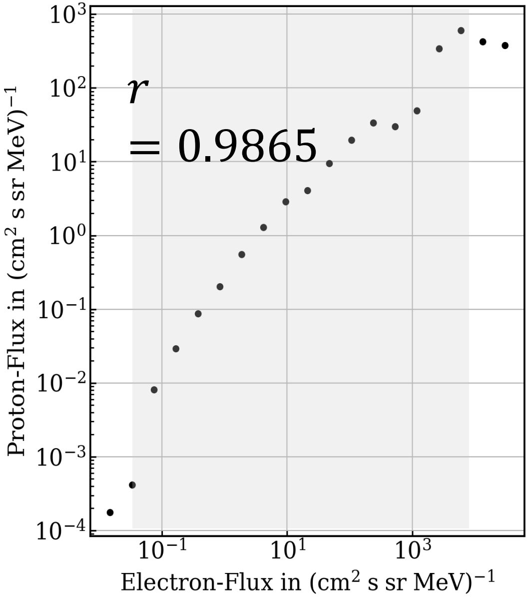

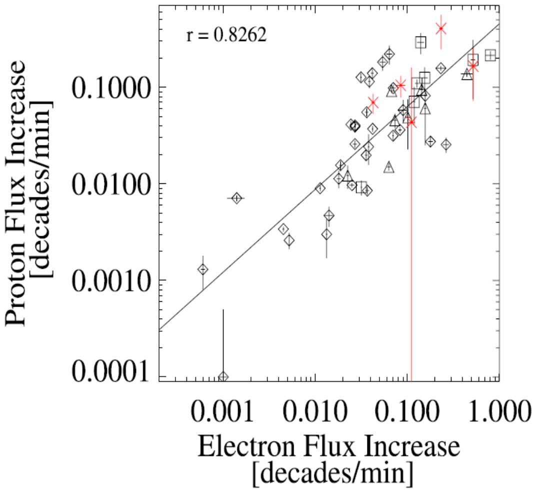

STEREO HET electrons
STEREO HET protons
Electrons shifted by 38 minutes

Electron-proton-flux correlation

Correlation of electron proton increase rate

The REleASE scheme: Computation of Forecast Matrix

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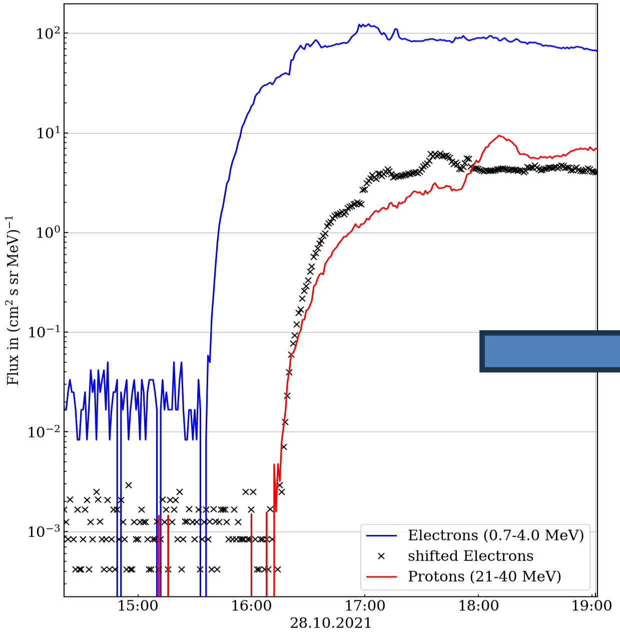
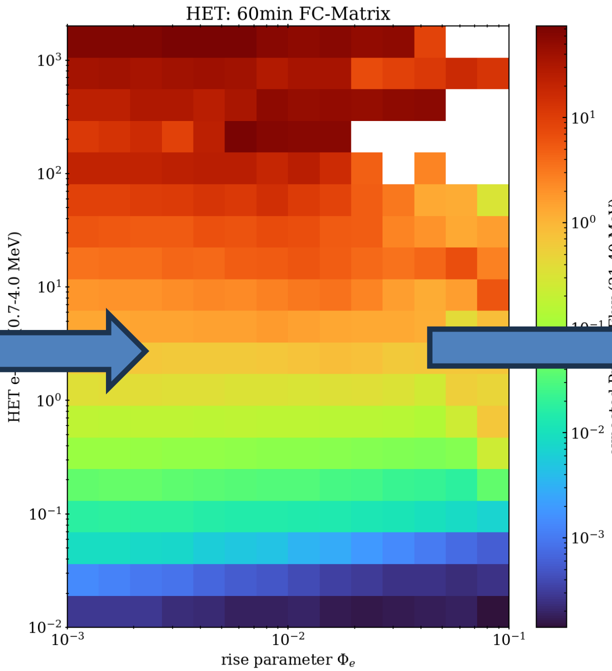
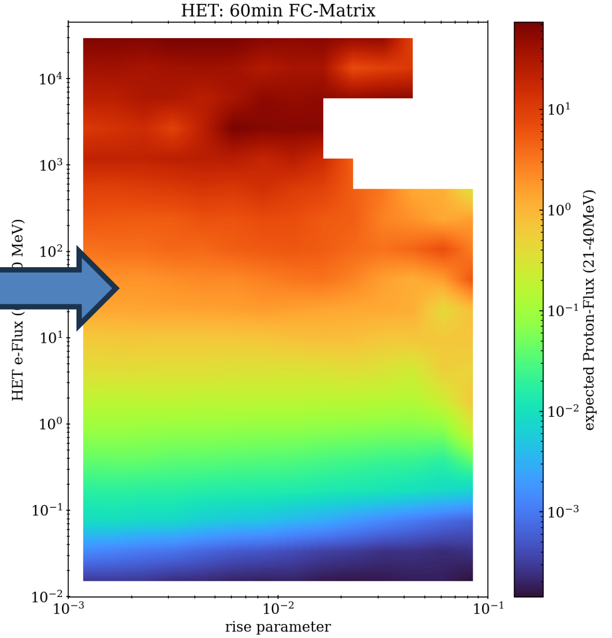






STEREO HET electrons

STEREO HET protons

Electrons shifted by 38 minutes

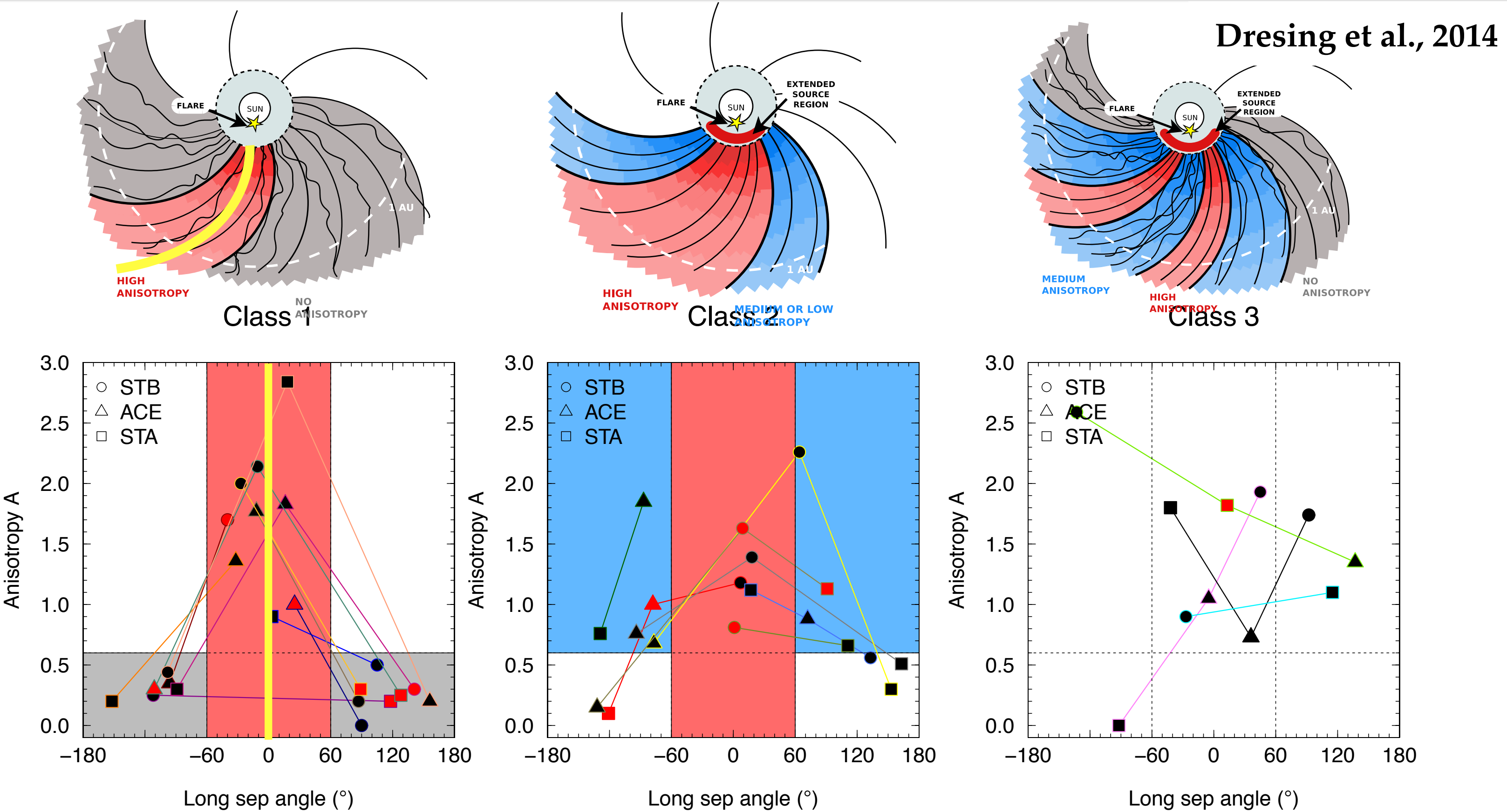
Matrix from 15 years of STEREO HET (electrons and protons)

discrete and interpolated on the left and right, respectively.

Velocity dispersion: No scattering

The longitudinal distribution of anisotropies

Dresing et al., 2014

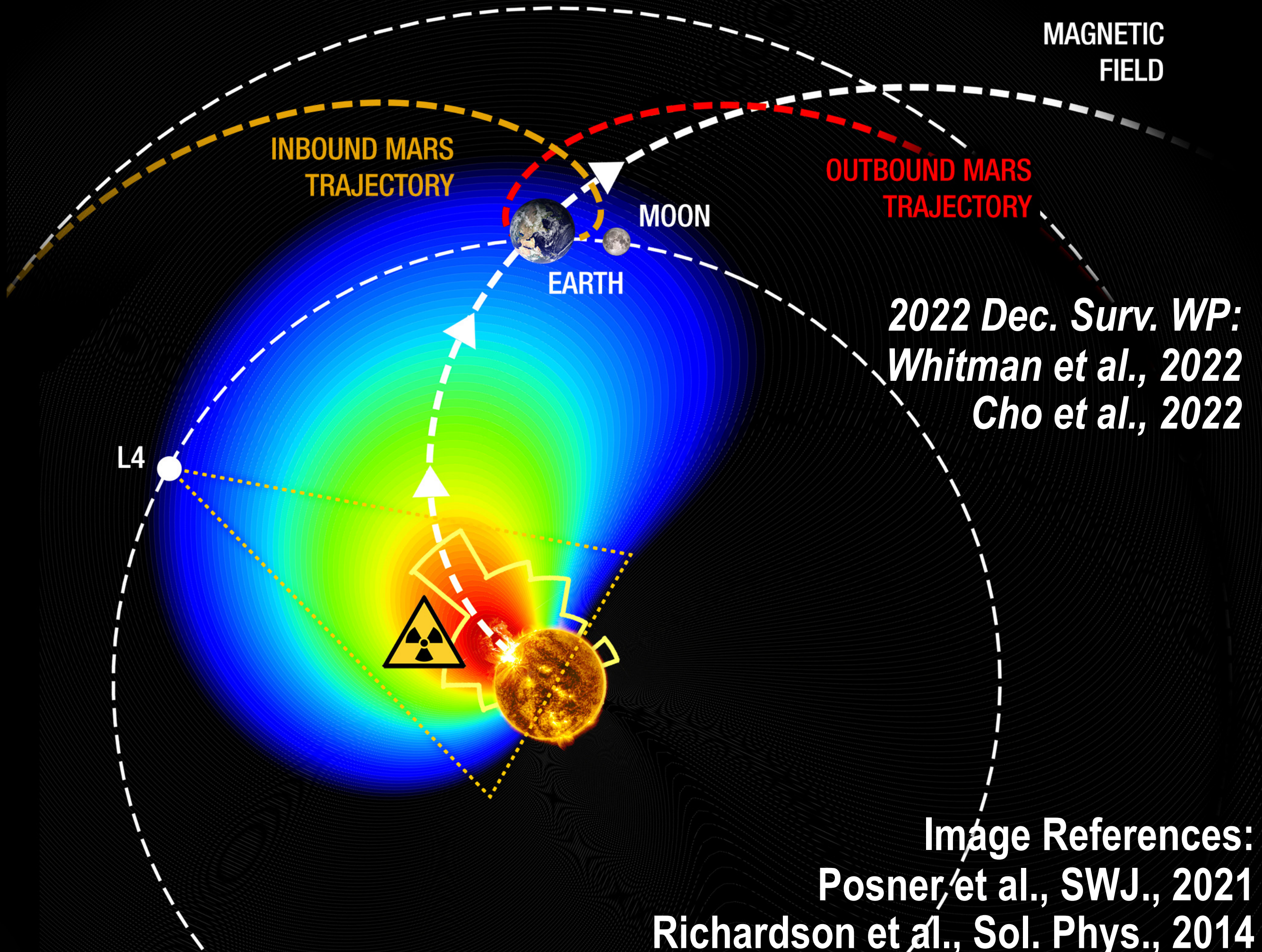


Traveling to Moon and Mars

Trips to the Moon and especially to Mars are long duration flights

Dose contribution by Galactic Cosmic Rays (GCRs) as well as Solar Energetic Particles.

Orbit to and from Mars in a coordinate system with Sun-Earth fixed.



2022 Dec. Surv. WP:
Whitman et al., 2022
Cho et al., 2022

Image References:
Posner et al., SWJ., 2021
Richardson et al., Sol. Phys., 2014

STEREO A, SOHO and Mars (01.09 to 31.11.2024)

C | A | U
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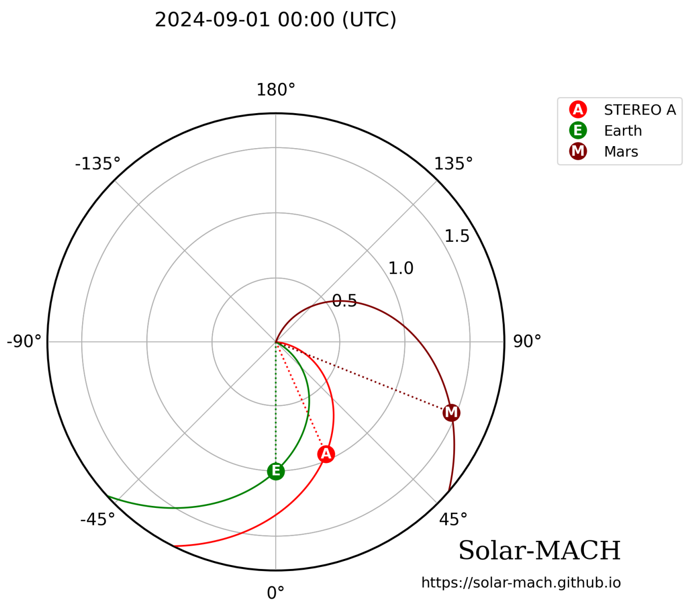
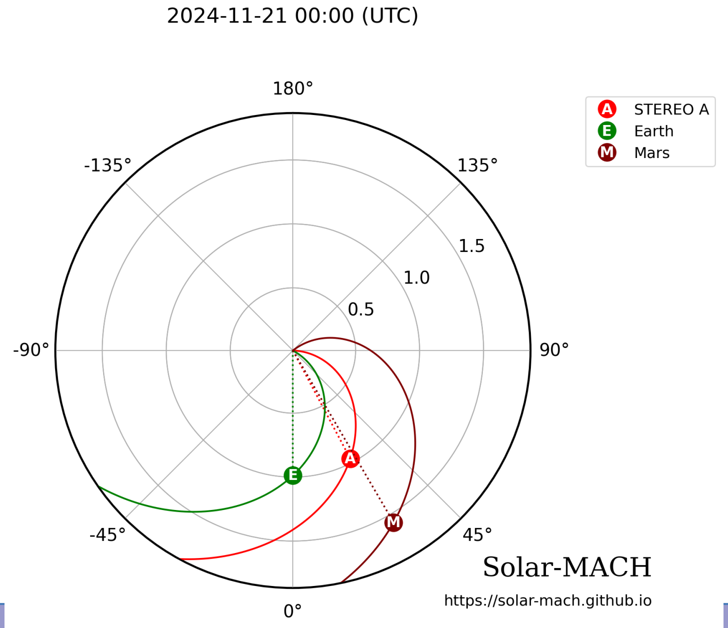
From September to December 2024 Mars and STEREO A are ahead of the Earth



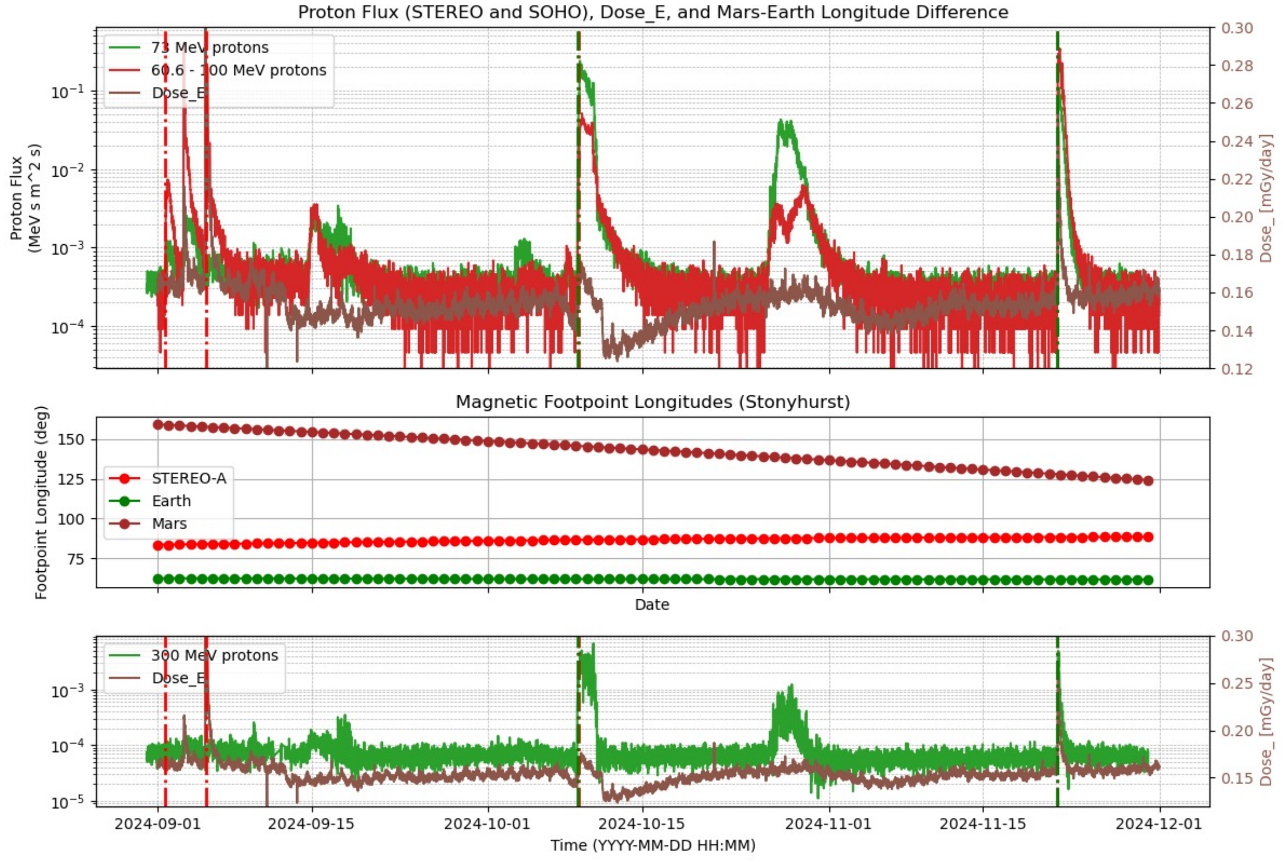


5 SEP events are seen by MSL/RAD

Nr.	Date
1	2024-09-03
2	2024-09-05 2024-10-05‘
4	2024-10-09
5	2024-11-21

STEREO A, SOHO and Mars events: Overview

Christian-Albrechts-Universität zu Kiel



5 SEPE's @MSL/RAD

@70 MeV protons

- 10 SEPE's @STEREO A
- 9 SEPEs @SOHO

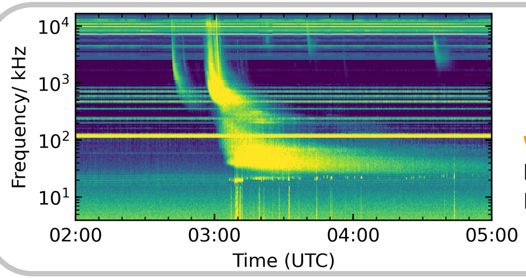
@300 MeV protons

- 4 SEPEs @SOHO

Propagation tool plus hard X-ray and radio observations can lead:

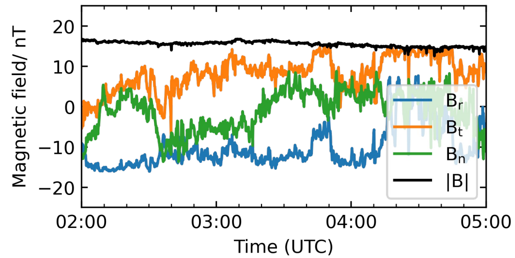
1. To the derivation of the injection spectra of electrons (timing and spectral shape)
2. Propagation tool can predict the expected electron onset for different particle propagation conditions.
3. Tracking the pitch angle resolved measurements narrows the propagation parameters
4. Correlation studies for protons allow to estimate the proton onset and the flux increase.

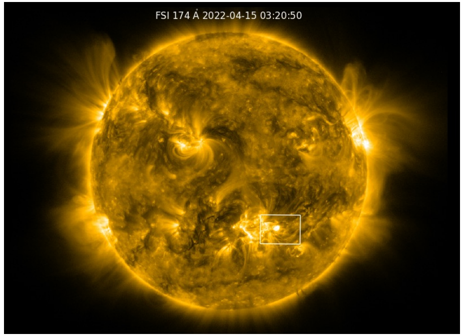
Instrumentation of Solar Orbiter is ideally suited to do so. So L4 should be able to fulfill this too.



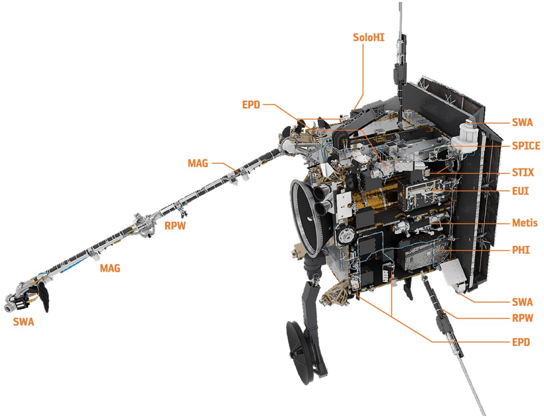
RPW Radio and Plasma Waves
beobachtet
Radioemission

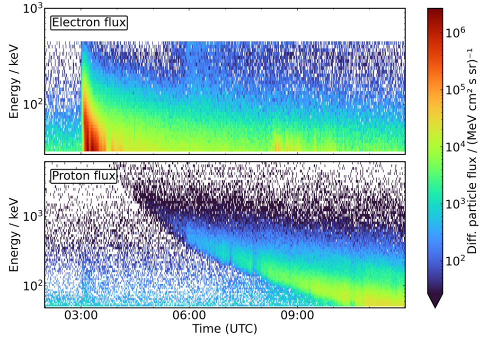
MAG Magnetometer
beobachtet
lokales Magnetfeld



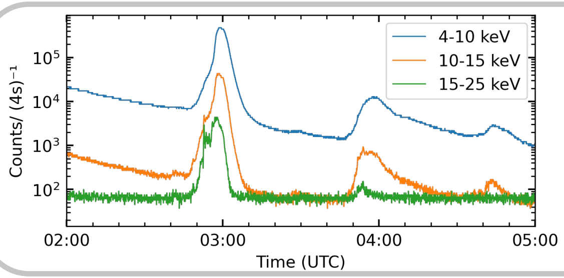


EUI - Extreme Ultraviolet Imager
beobachtet Ultraviolettemission



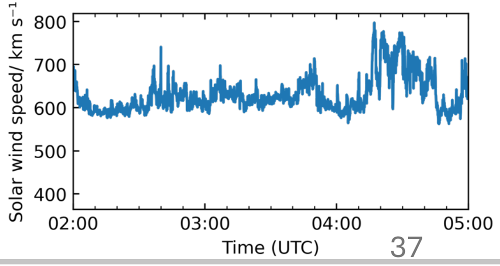


EPD Energetic Particle Detector
beobachtet energiereiche Teilchen



STIX Spectrometer Telescope for Imaging X-rays
beobachtet
Röntgenemission

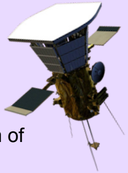
SWA Solar Wind Plasma Analyser
beobachtet
lokalen
Sonnenwind



The first widespread solar energetic particle event observed by Solar Orbiter on 2020 November 29

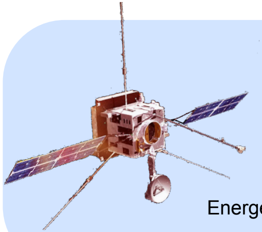
(Kollhoff et al. 2021)

Parker Solar Probe



ISOIS
Integrated Science Investigation of the Sun

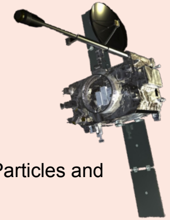
Solar Orbiter



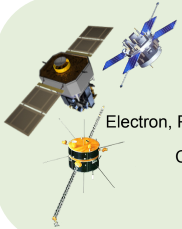
EPD
Energetic Particle Detector

©ESA

Stereo-A

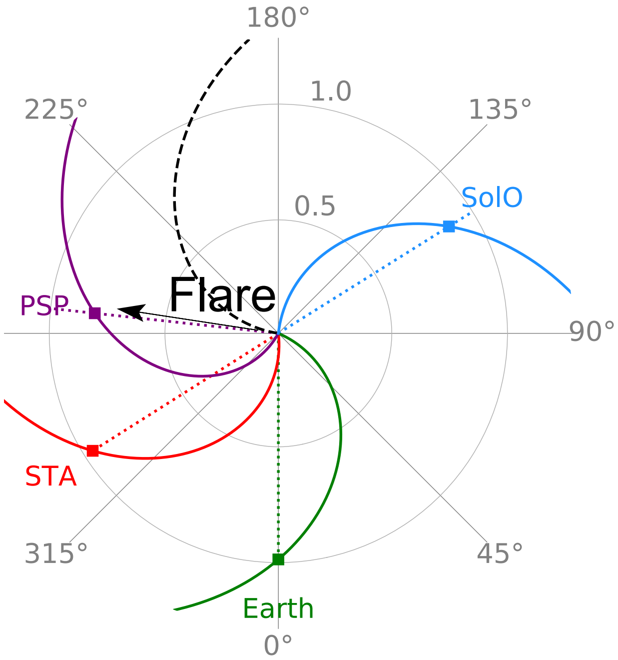


IMPACT
In-situ Measurements of Particles and CME Transients



ACE, SOHO, Wind

EPAM
Electron, Proton, and Alpha-particle Monitor
COSTEP
Comprehensive Suprathermal and Energetic Particle Analyzer
3DP
3D Plasma Analyzer



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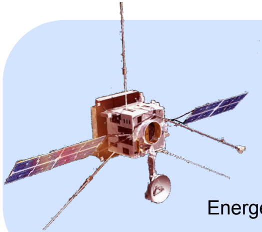

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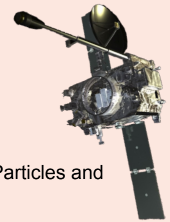
©ESA

Stereo-A



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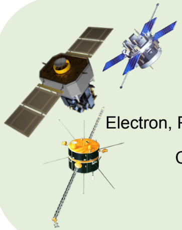
In-situ Measurements of Particles and CME Transients

ACE, SOHO, Wind



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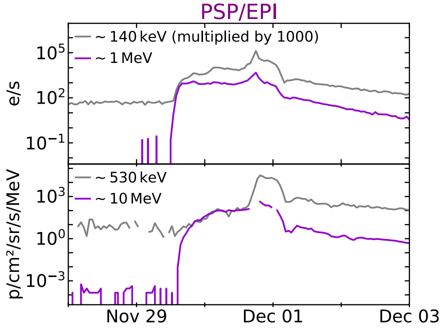
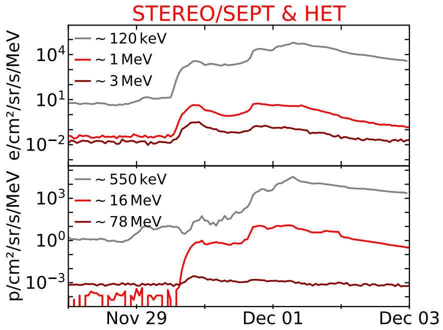
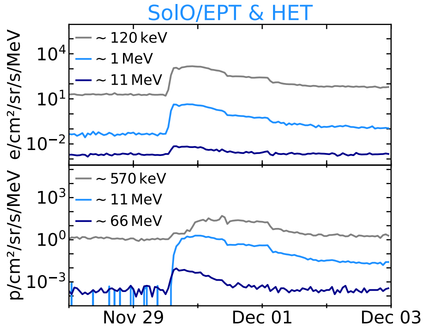
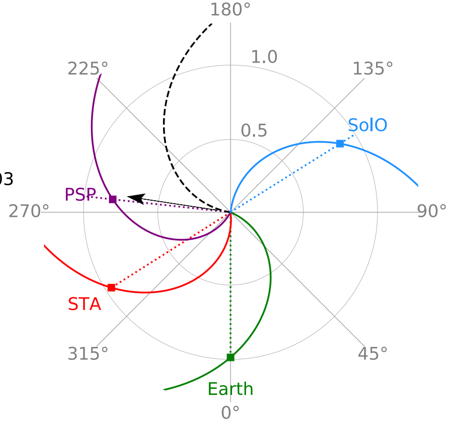
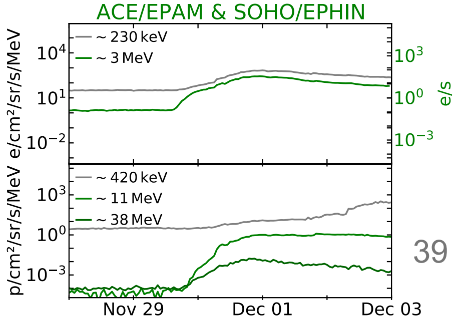


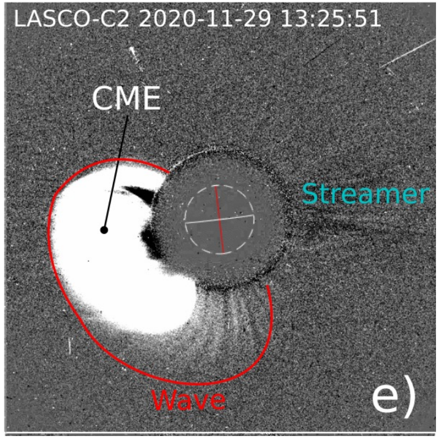


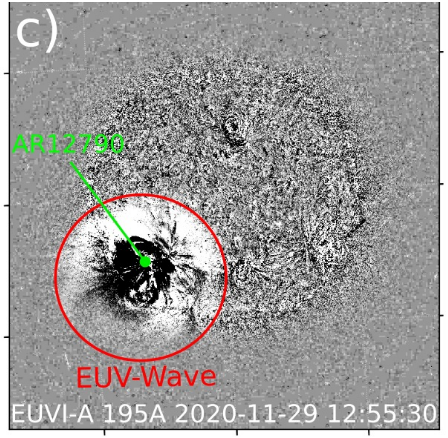


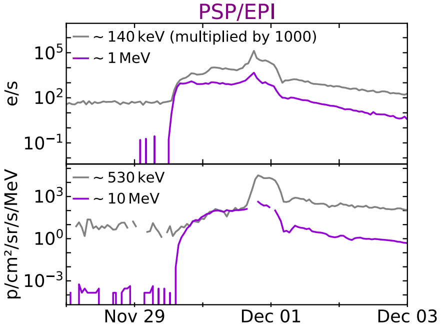


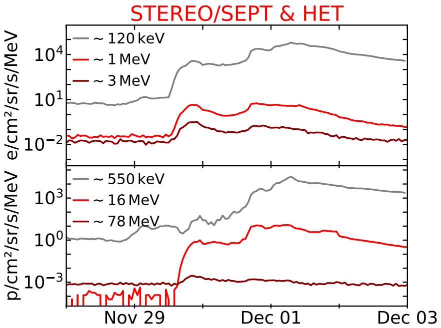


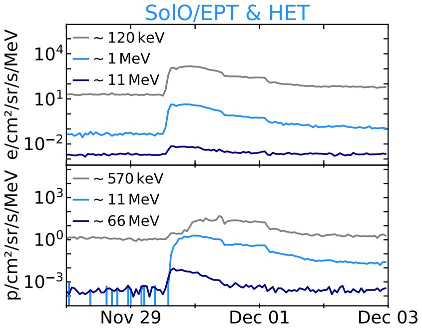
29. Nov. 2020 SEP-Event – CME and EUV-Wave

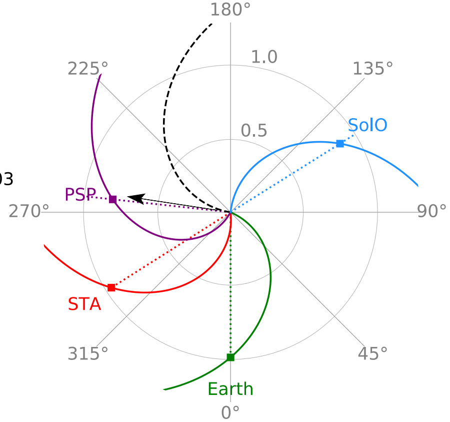


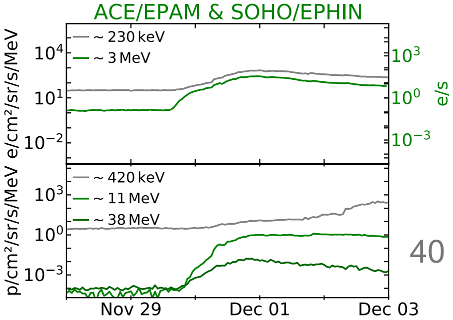












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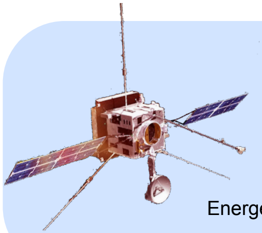

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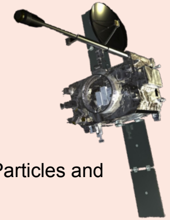
Stereo-A



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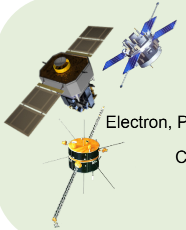

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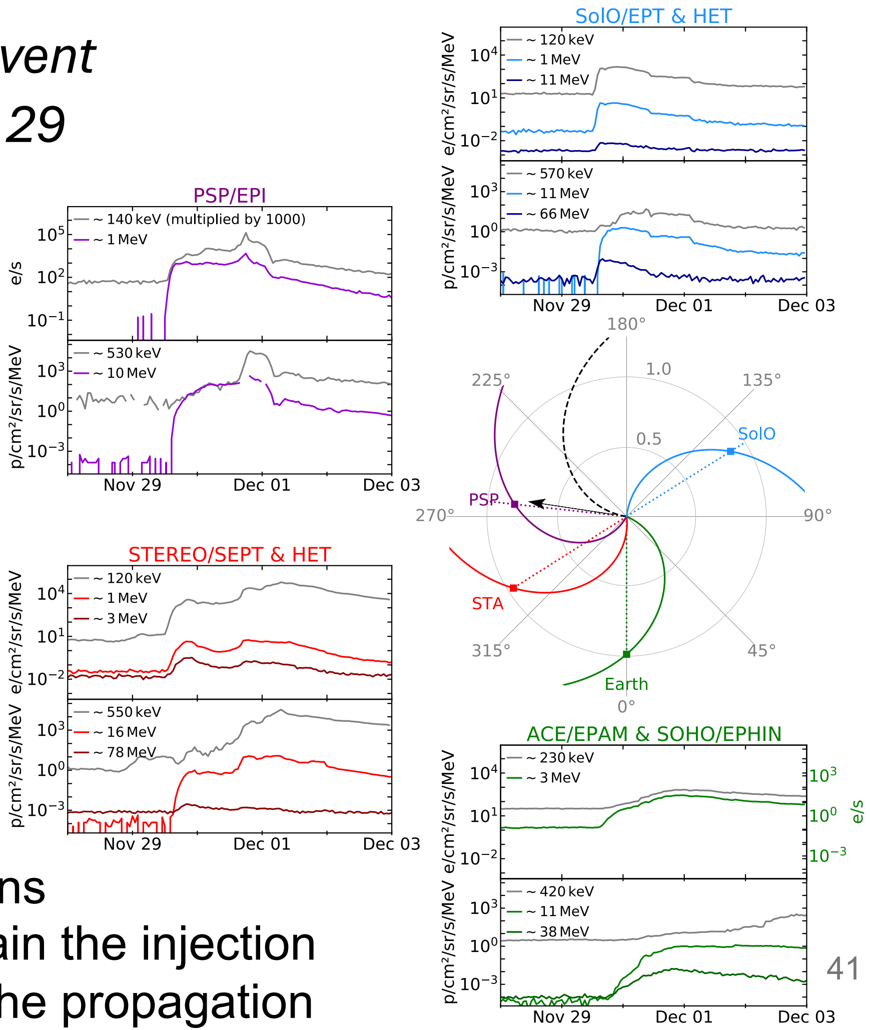

- ➢ Different injection times of protons and electrons
- ➢ Shock propagation in the corona can not explain the injection
- ➢ Anisotropies are important for understanding the propagation

29. Nov. 2020 SEP-Event – Anisotropies