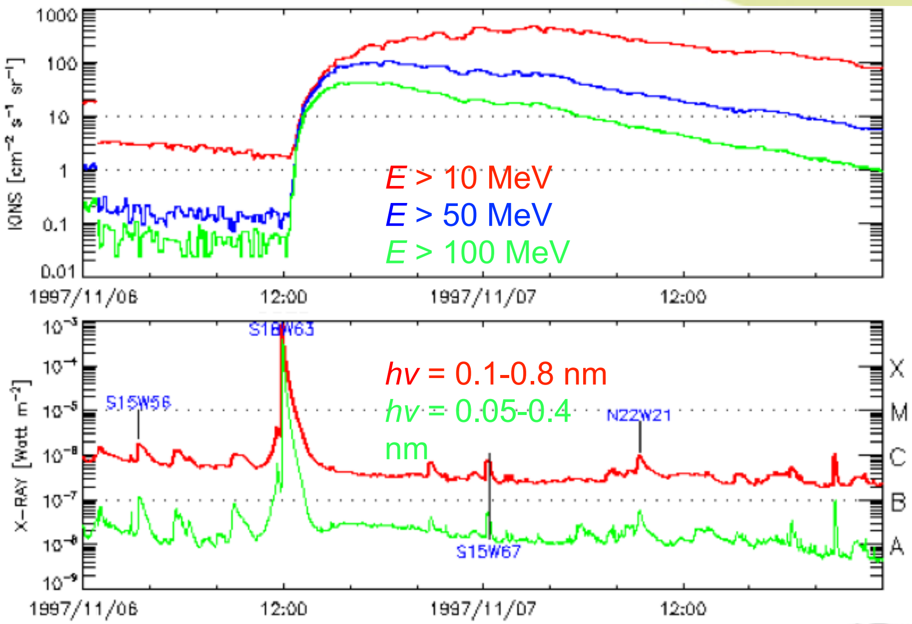
Relativistic Electron Alert System for Exploration (REleASE) and the UMASEP forecasting schemes

HESPERIA SUMMER SCHOOL

r. Bernd Heber, Christian-
echts-Universität zu Kiel,
Deutschland.

The Physics behind …



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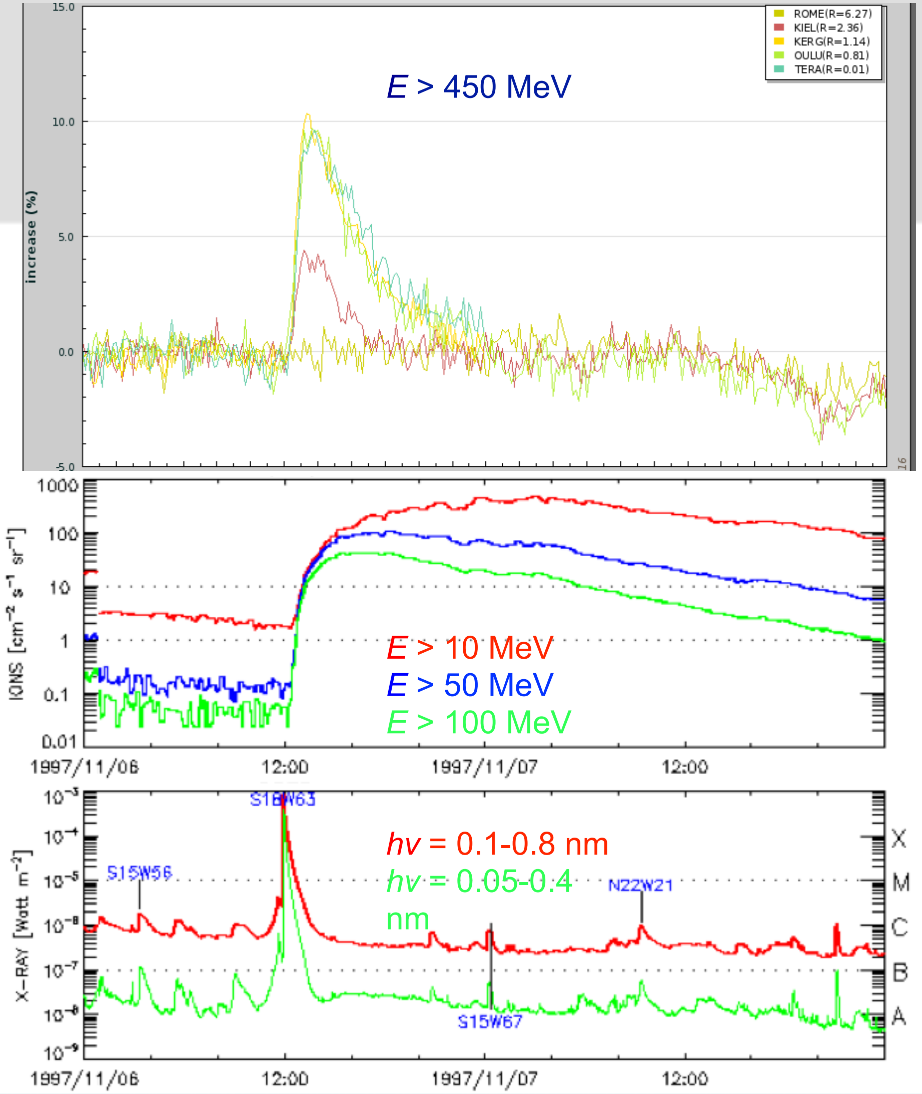
http://cafehayek.com/2014/03/then-a-miracle-occurs.html

Overview

- Repetition from previous lecture:
  - Solar flares (Lecture Ludwig Klein)
- UMASEP: the basic idea
- Repetition from previous lecture:
  - Particle transport (Neus Agueda)
- RELEASE: the basic idea

The Sun as a Particle Accelerator: Energetic photons, neutrons and particles

- Detection of energetic protons from the Sun with ground based neutron monitors (~1942) in association with solar flares.



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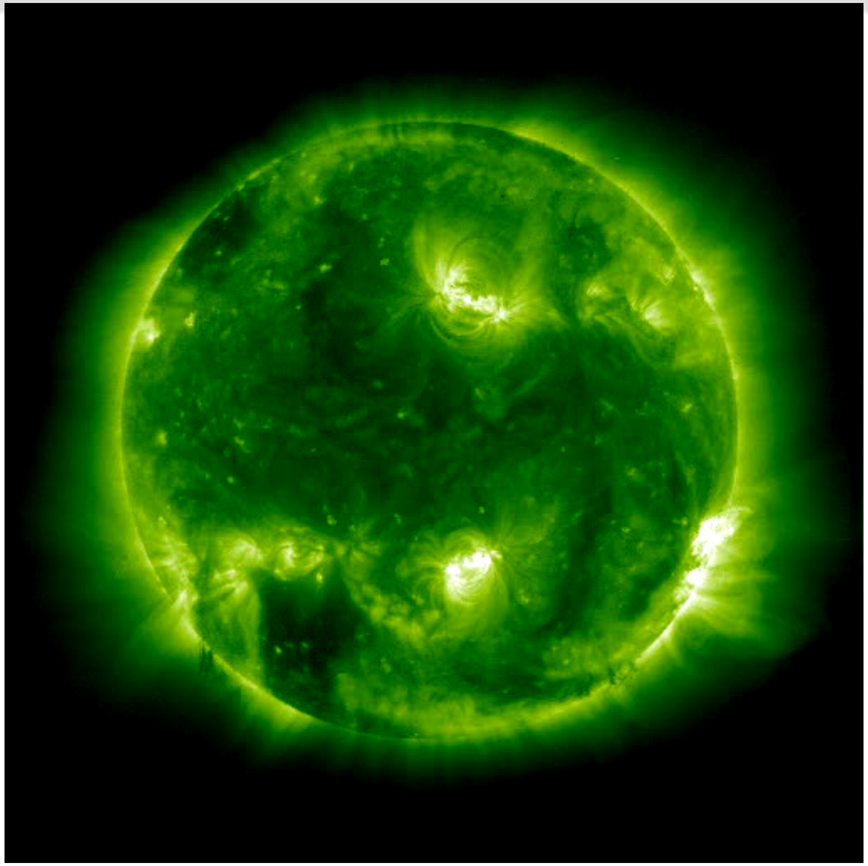
Solar flares

What is a solar flare ?

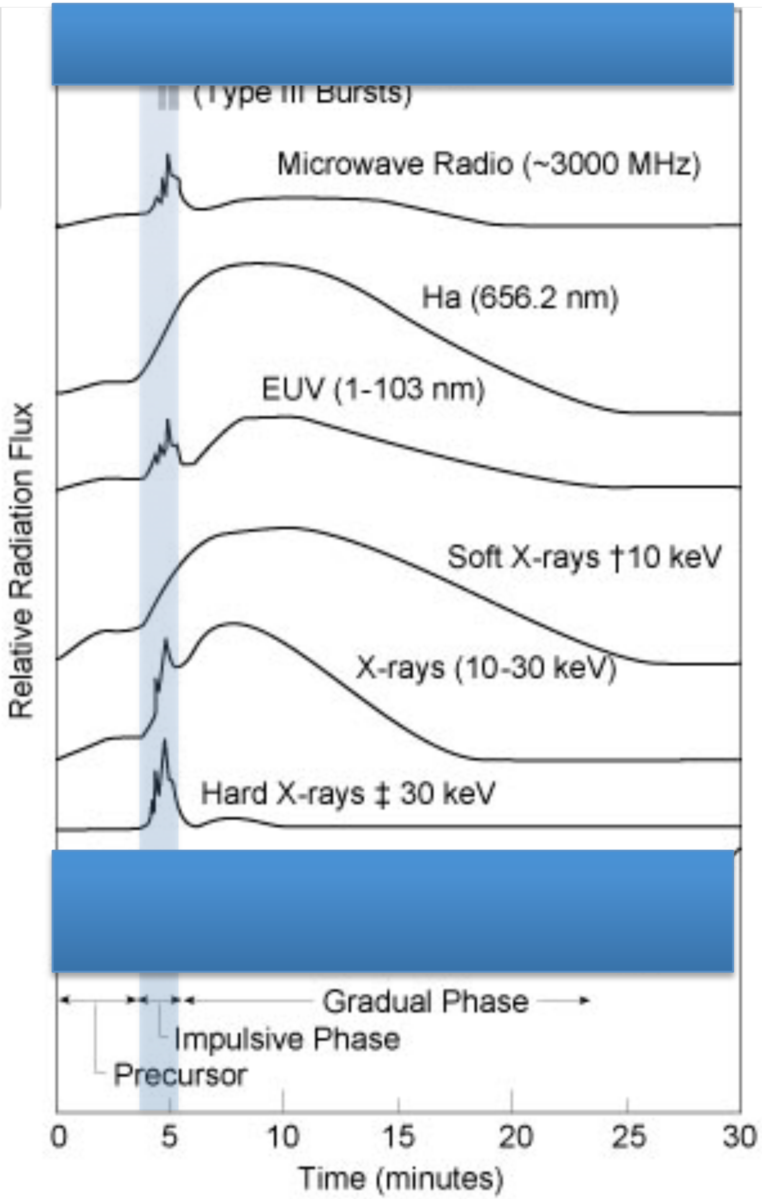


© SoHO/EIT (ESA/NASA)

- What is a solar flare ?
  - temporary brightening across the EM spectrum
  - limited volume of the corona and the underlying atmosphere
- What are the physical processes behind this phenomenology?
  - plasma heating to $T > 10^7$ K
  - acceleration of charged particles (electrons, protons, ions), sometimes to relativistic energies

Solar flares
Electromagnetic (EM) emissions

- Gross distinction:
  - short & spiky (microwaves[1], HXR)
  - long-lasting, smoothly evolving (Hα, SXR)
- Phases of a flare:
  - impulsive phase
  - main phase/gradual phase

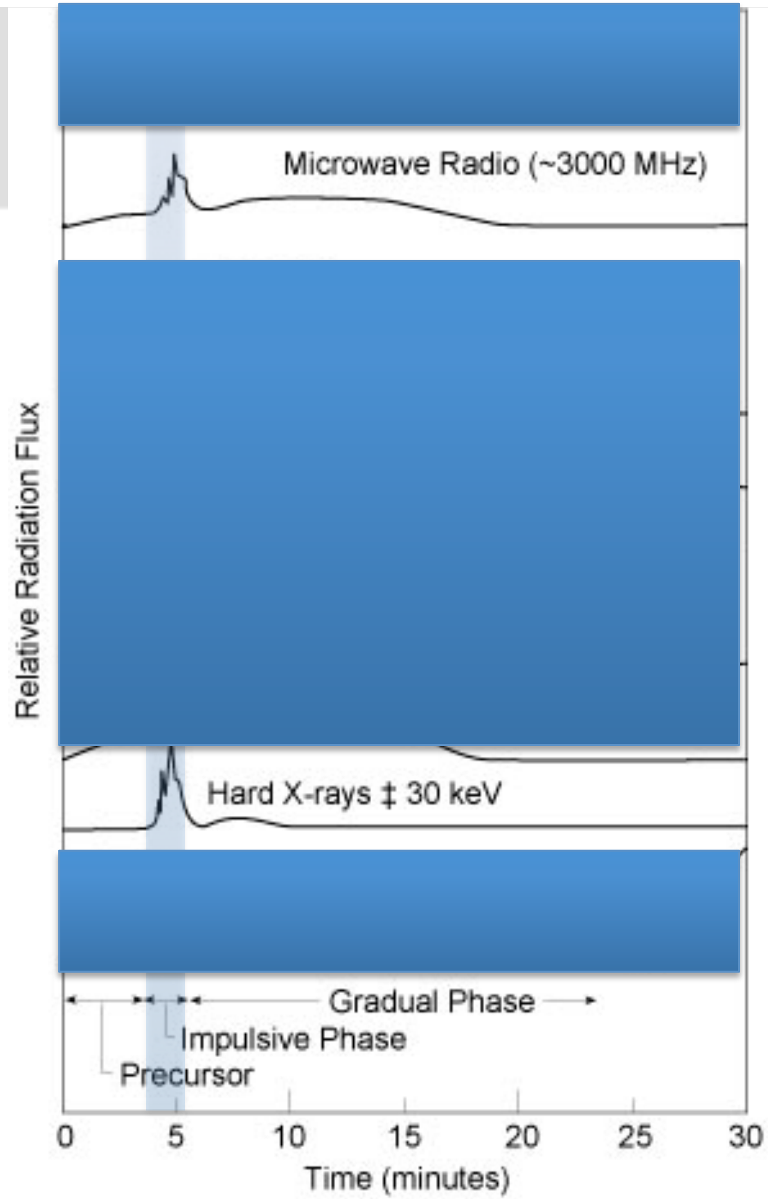


https://ase.tufts.edu/cosmos/print_images.asp?id=27

(1) ν ≥ 1 GHz

Solar flares
Electromagnetic (EM) emissions

- What is causing these time profile?
  - Suprathermal electrons



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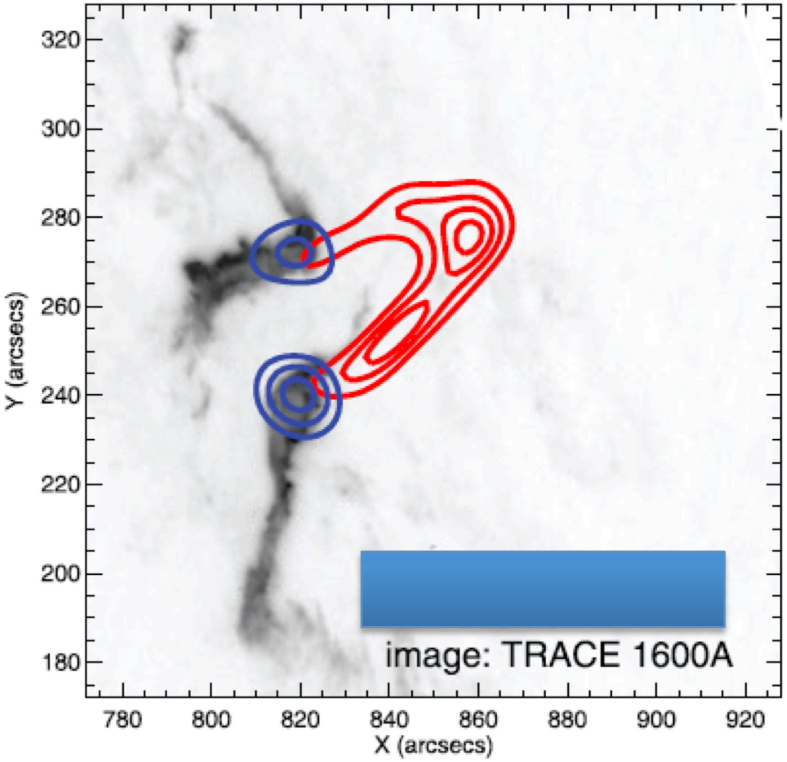
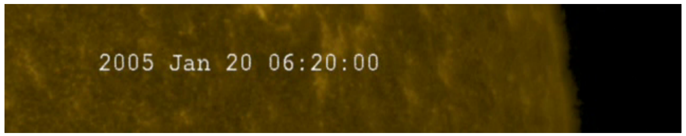
(1) $\nu \geq 1$ GHz

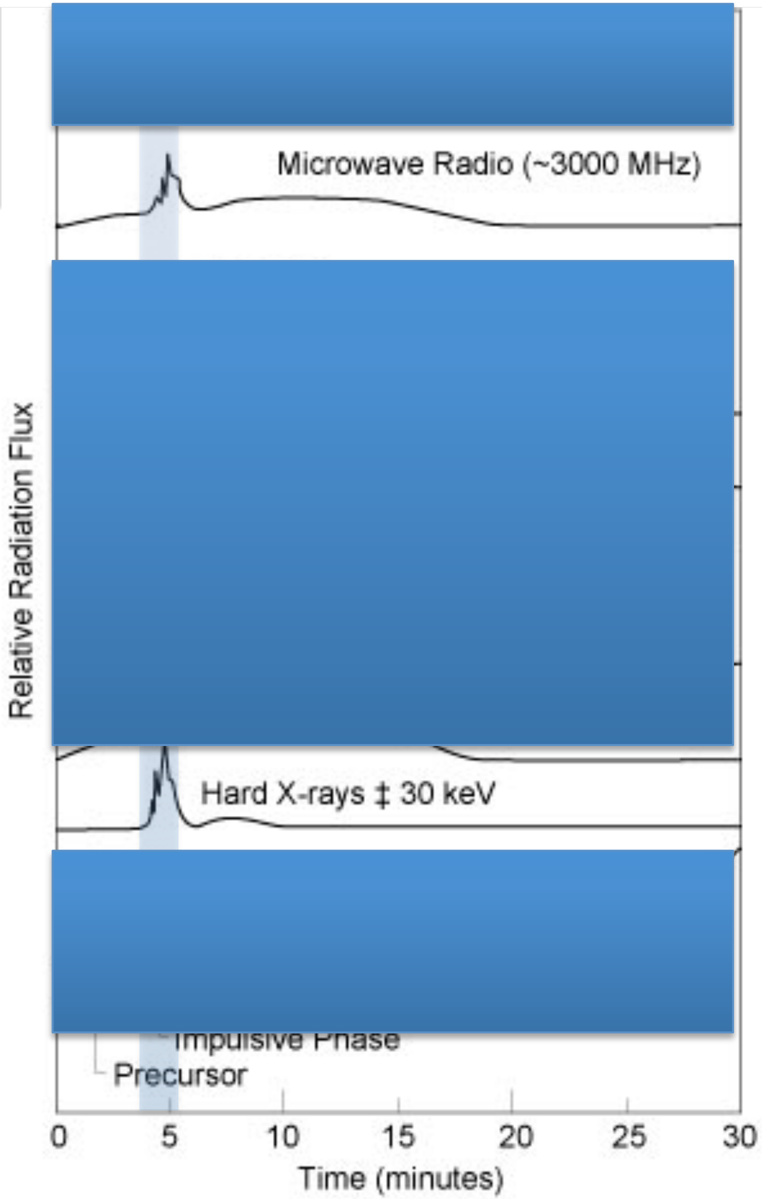
Solar flares
Electromagnetic (EM) emissions

- Where does the radiation comes from?





(1) ν ≥ 1 GHz



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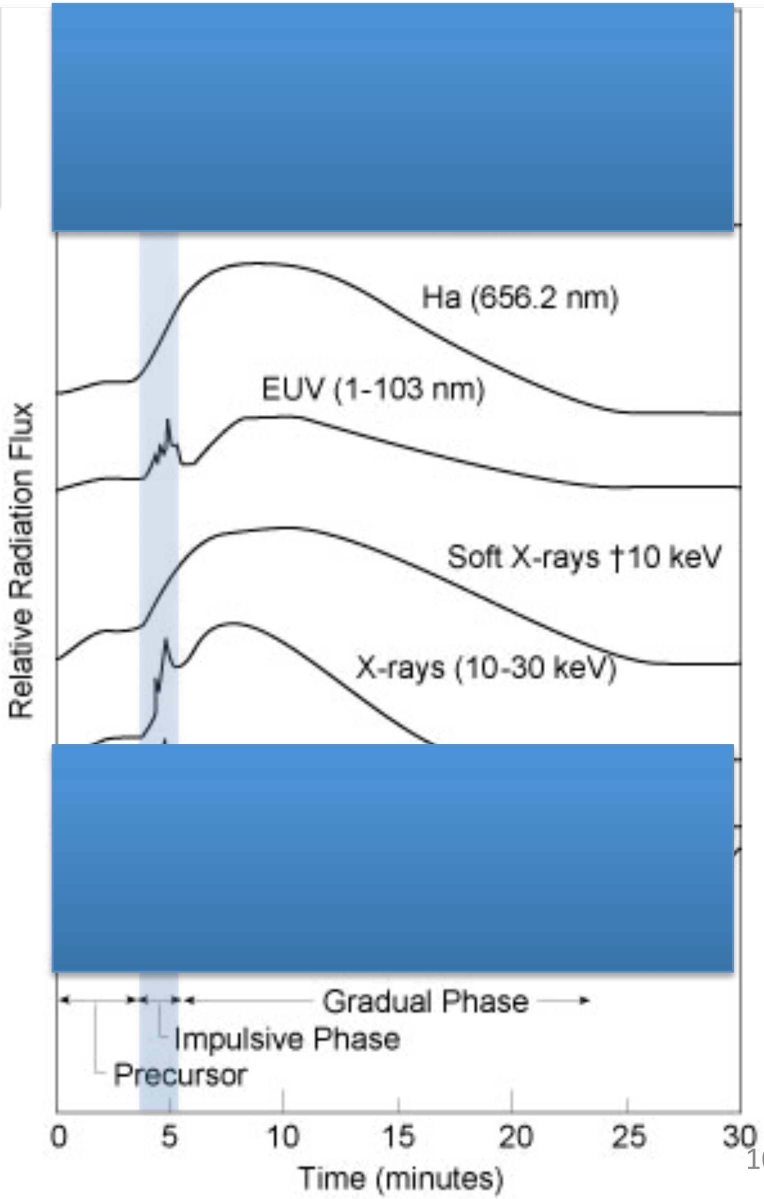
Solar flares
Electromagnetic (EM) emissions

- What is causing these time profile?
  – Heated plasma

- What about ions?



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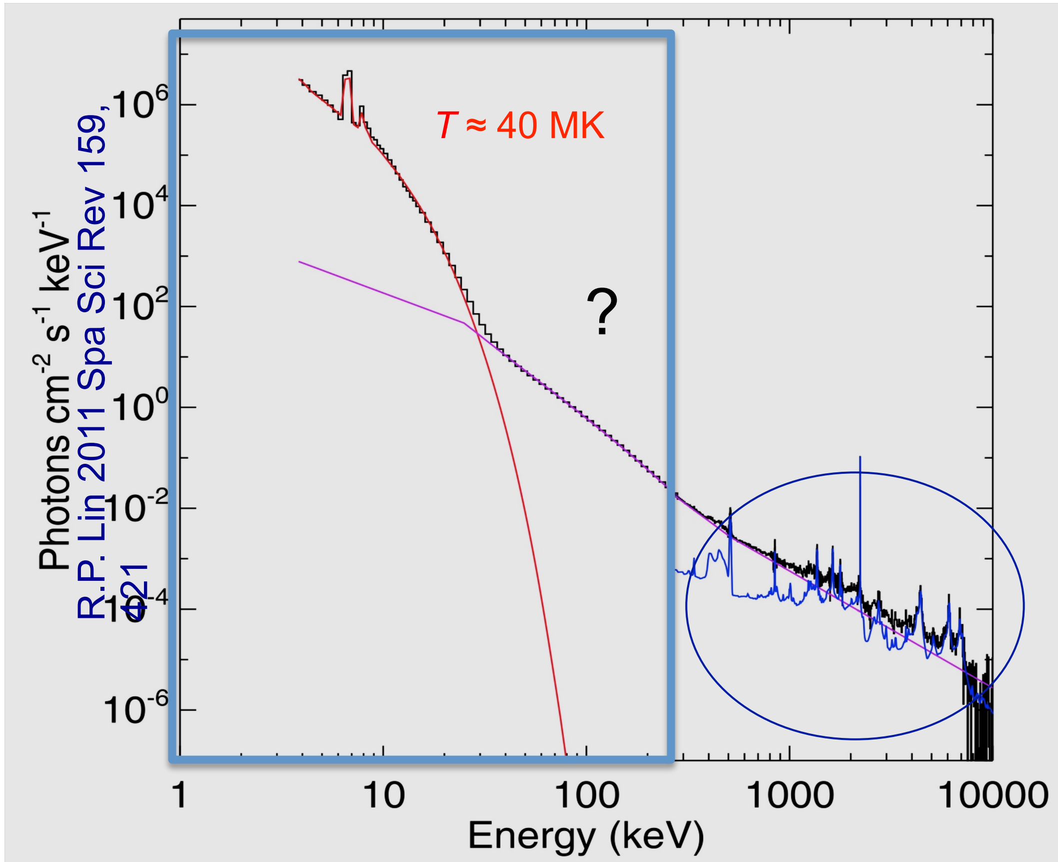
Solar flares – proton acceleration
Nuclear gamma-ray lines

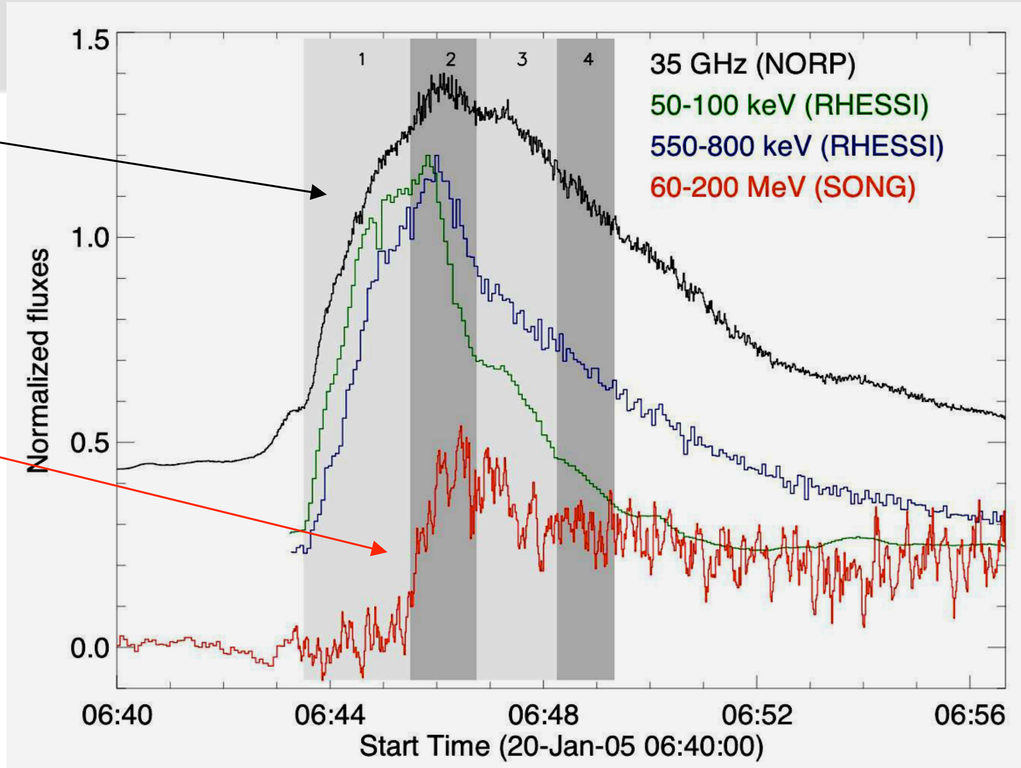
What does the spectrum tells us?



- Accelerated ions impinging on atmospheric ions: (narrow) de-excitation lines
- Accelerated ions impinging on atmospheric protons: broad de-excitation lines
- Neutron capture line:
  - *p(> 30 MeV)+X -> X'+n*
  - *n (thermalised) + p ->* $^{2}H^{*}$ *->* $^{2}H + \gamma$ (2.223 MeV)

Solar flares – proton acceleration
Pion-decay gamma rays

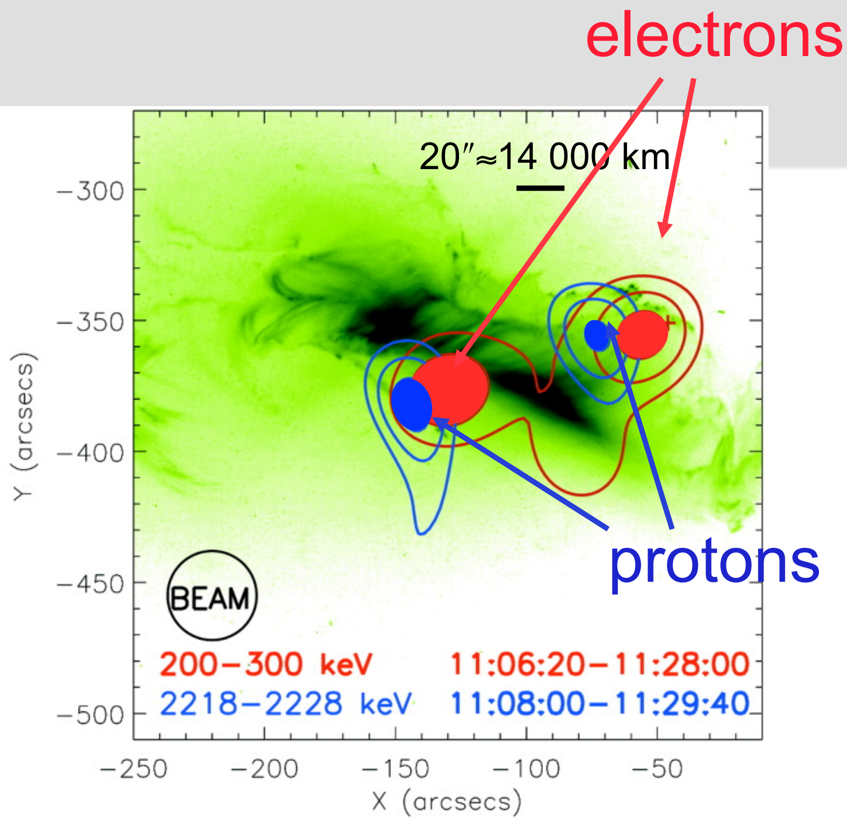
- At even higher ion energies: Gamma rays $h\nu > 60$ MeV: π^0 decay from p>300 MeV
- Protons (ions) > 300 MeV/nuc ->
  - $\pi^{+/-}$ -> $\mu^{+/-}$ -> $e^{+/-}$
  - π^0 -> 2γ (67 MeV)



5 min

Masson et al. 2009 Solar Phys. 257, 305

Solar flares – proton acceleration
Imaging observations



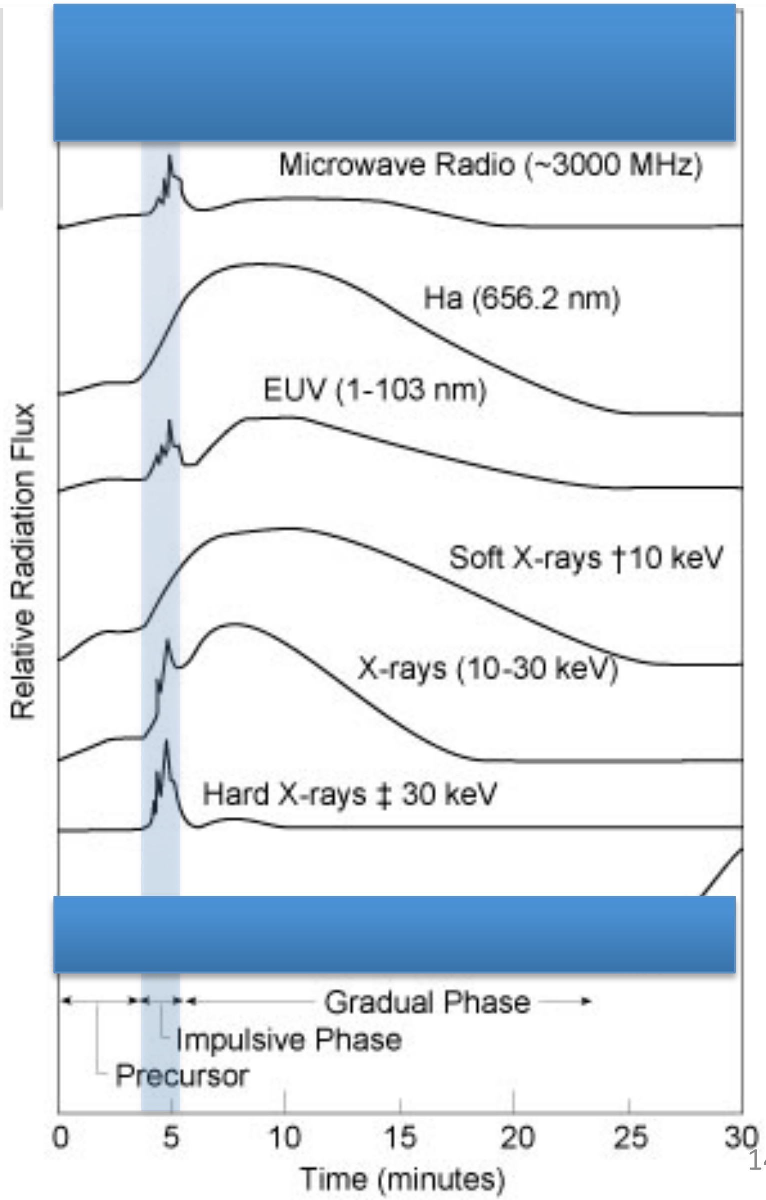
Hurford et al., 2006 ApJ 644, L93

- Imaging of the 2.223 MeV line (p≥30 MeV) and of HXR bremsstrahlung (e^{-}≥200 keV): consistently (4/5 cases) different sources (see Vilmer et al. 2011, Spa Sci Rev).

- Different acceleration regions ?

Solar flares
Electromagnetic (EM) emissions

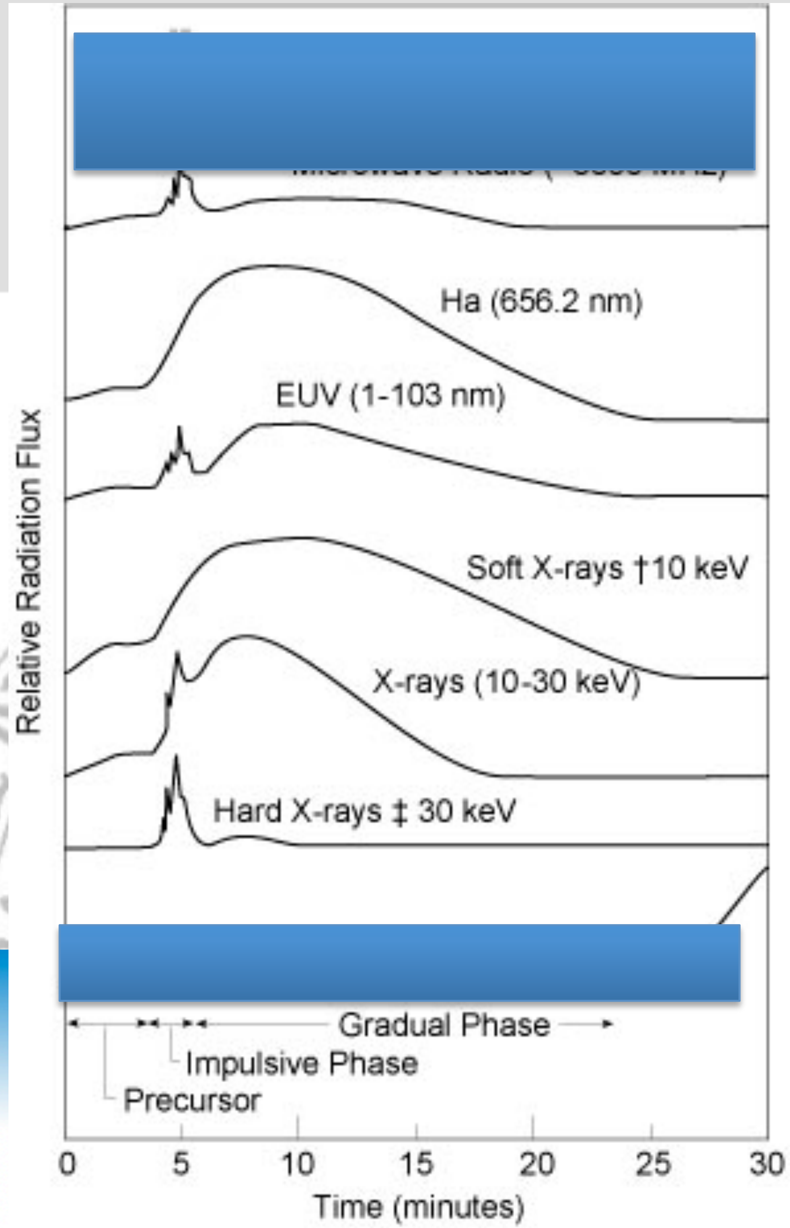
- Remember:
- Free magnetic energy is partially converted into acceleration of particles.
- Electrons and ions interact in the chromosphere /lower corona => Hard X-rays
- Ions need a minimum energy to be visible in gamma rays!
- One possibility: Ohmic heating by electrons of the coronal plasma



https://ase.tufts.edu/cosmos/print_images.asp?id=27

Solar flares (first aspects)

- All radiation investigated so far comes from closed magnetic regions in the chromosphere and corona



Overview

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- UMASEP: the basic idea
- Repetition from previous lecture:
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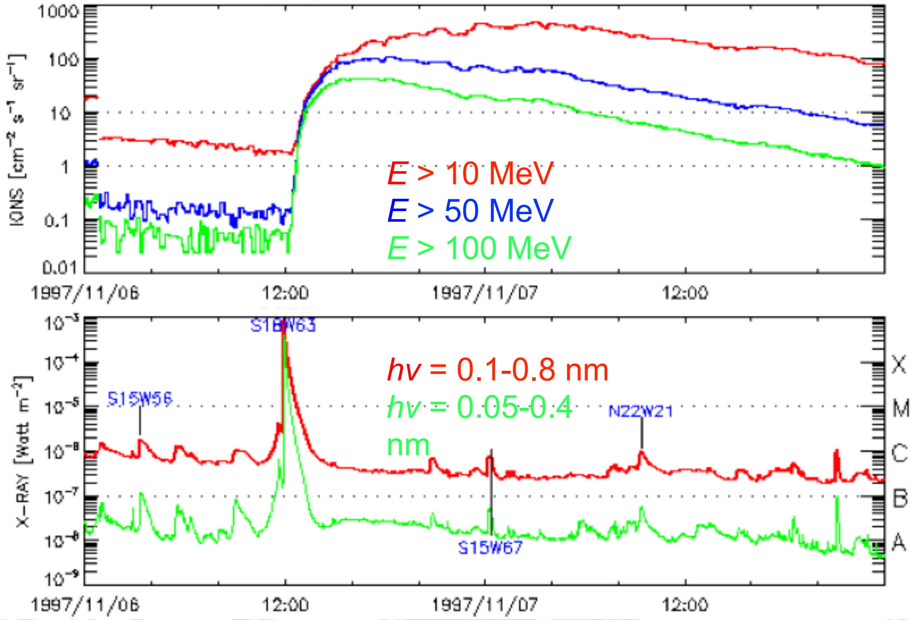
- RELEASE: the basic idea

Solar flares (first aspects)

- What about interplanetary space?
- How to get from X-rays to Protons?



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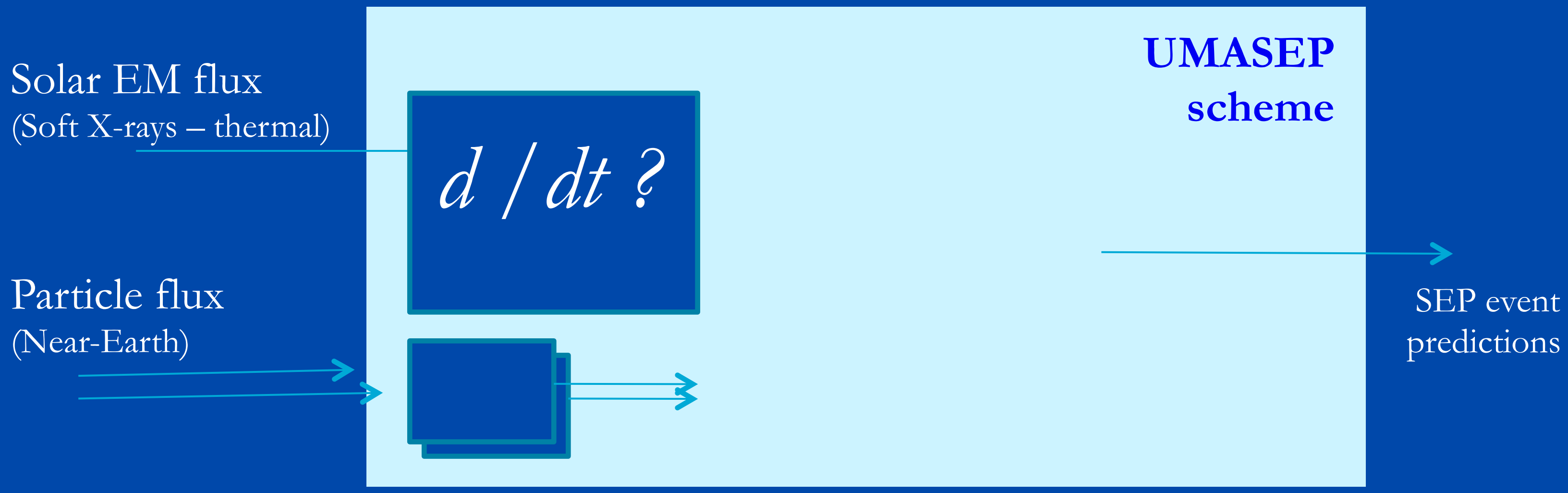
Parker (1963)

The UMASEP scheme (Núñez 2011, 2015)

- The UMASEP scheme infer a magnetic connection along which energetic protons are arriving near Earth, by investigating the solar electromagnetic (EM) flux and the particle flux at near-earth.

- .

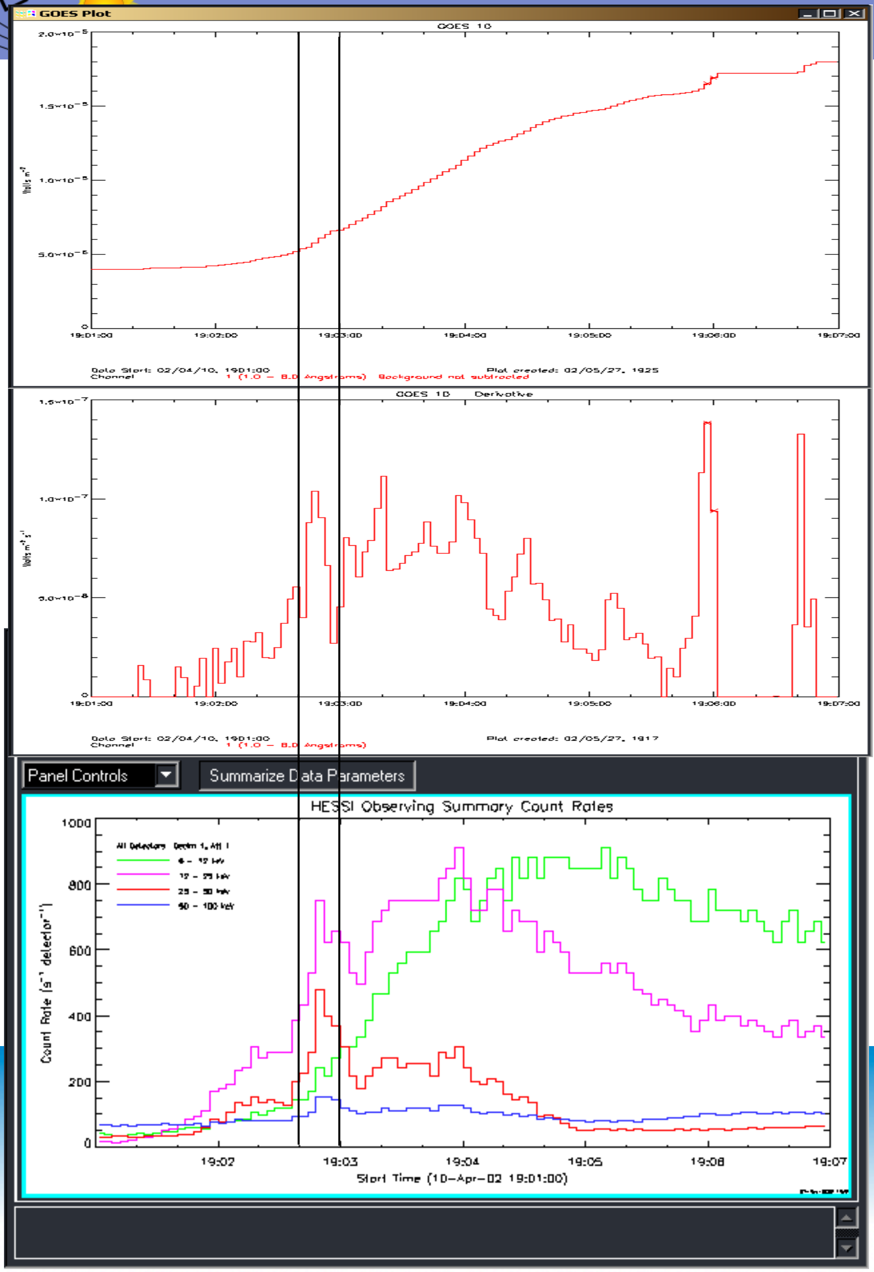


Refs. Núñez, M. 2011, *Space Weather*, 9

Núñez, M., 2015, *Space Weather*, 13

The Neupert Effect

- The time integral of the hard X-ray emission closely matches the temporal variation of the soft X-ray emission.
- Implies that accelerated electrons that produce the hard X-rays also heat the plasma that produces the soft X-rays.



10 April 2002

GOES 10 1 - 8 Å

Time derivative GOES 1 - 8 Å

RHESSI Light Curves

- 6 – 12 keV
- 12 – 25 keV
- 25 – 50 keV
- 50 – 100 keV

SXR:HXR Ratio vs. Flare Size

A. Veronig et al. A&A, in press (2002)

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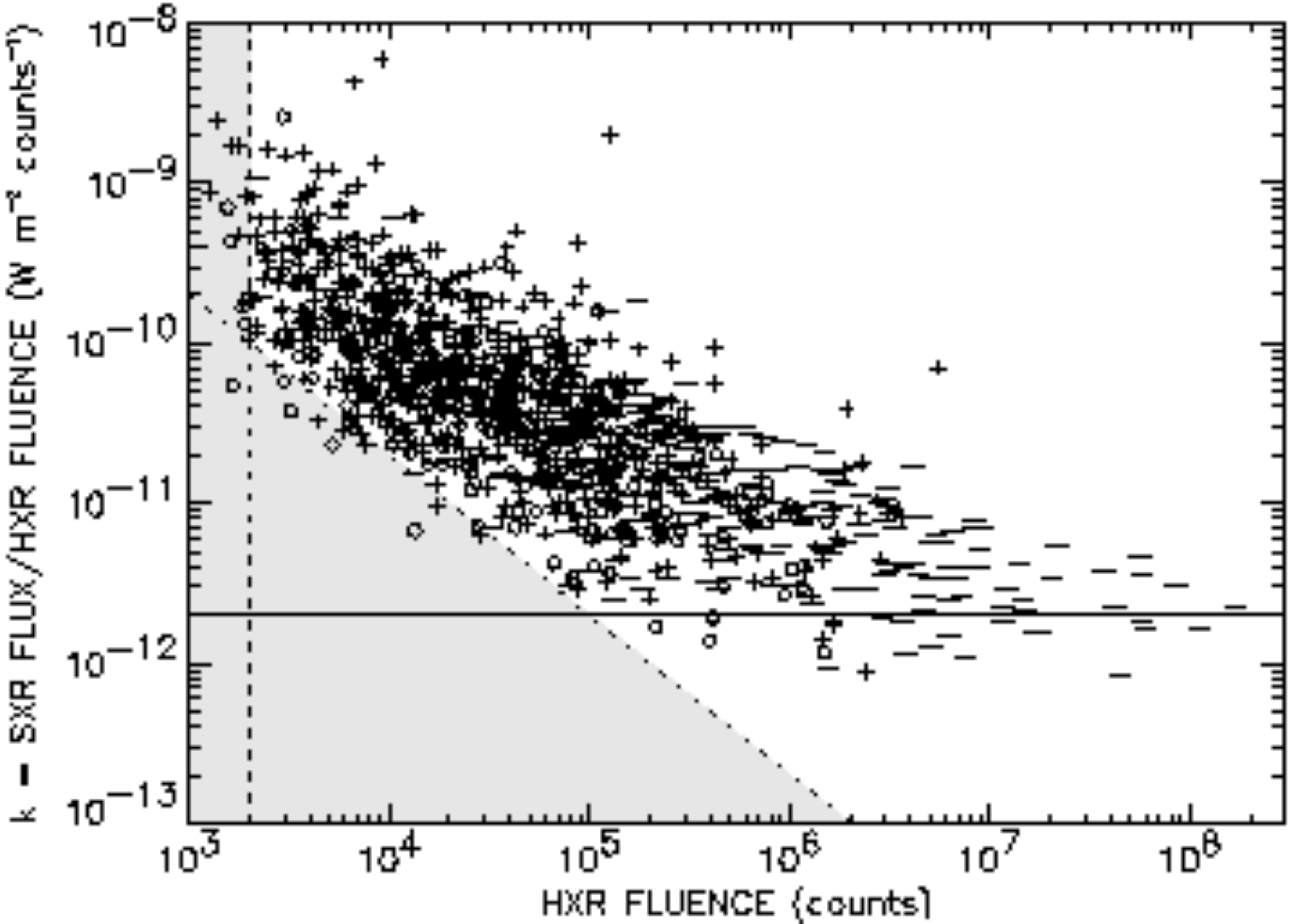

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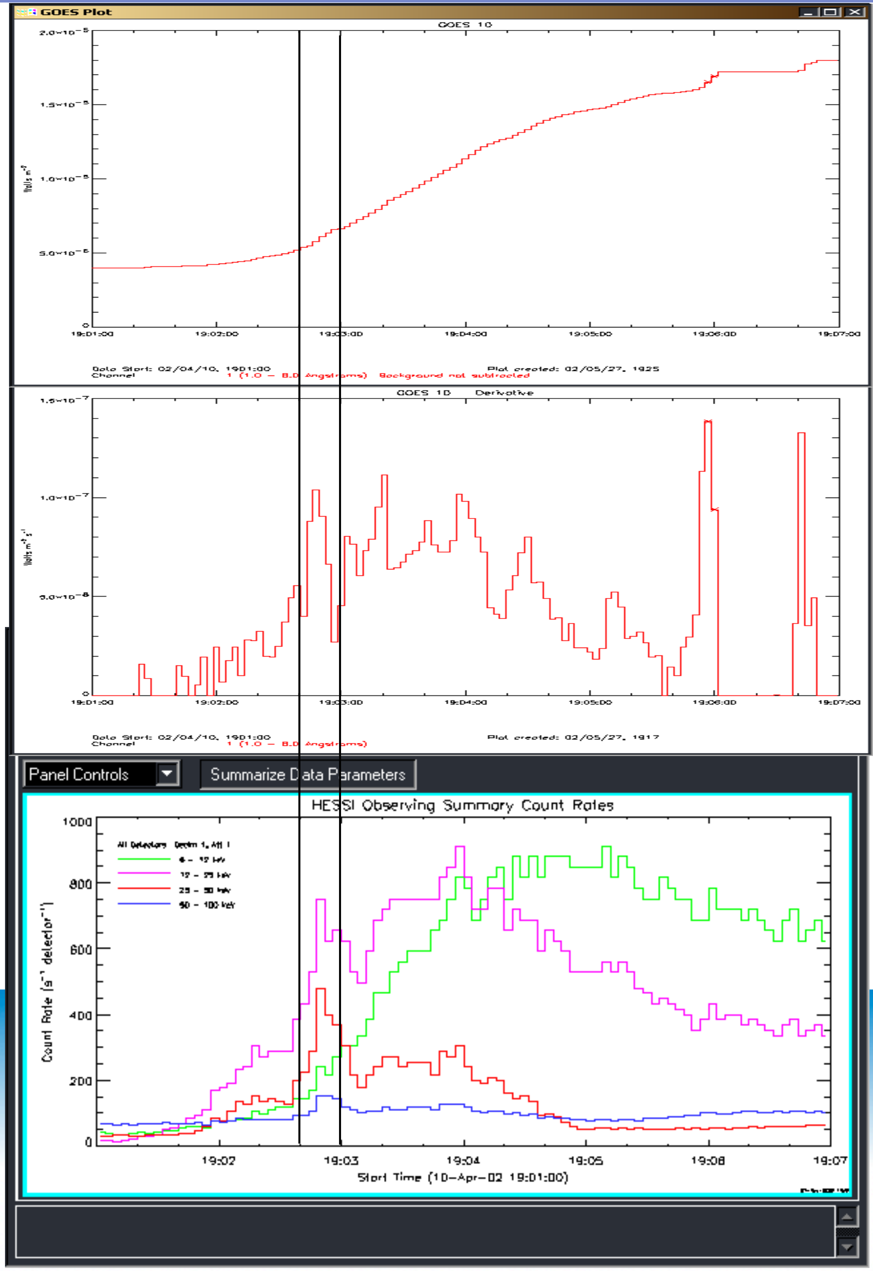

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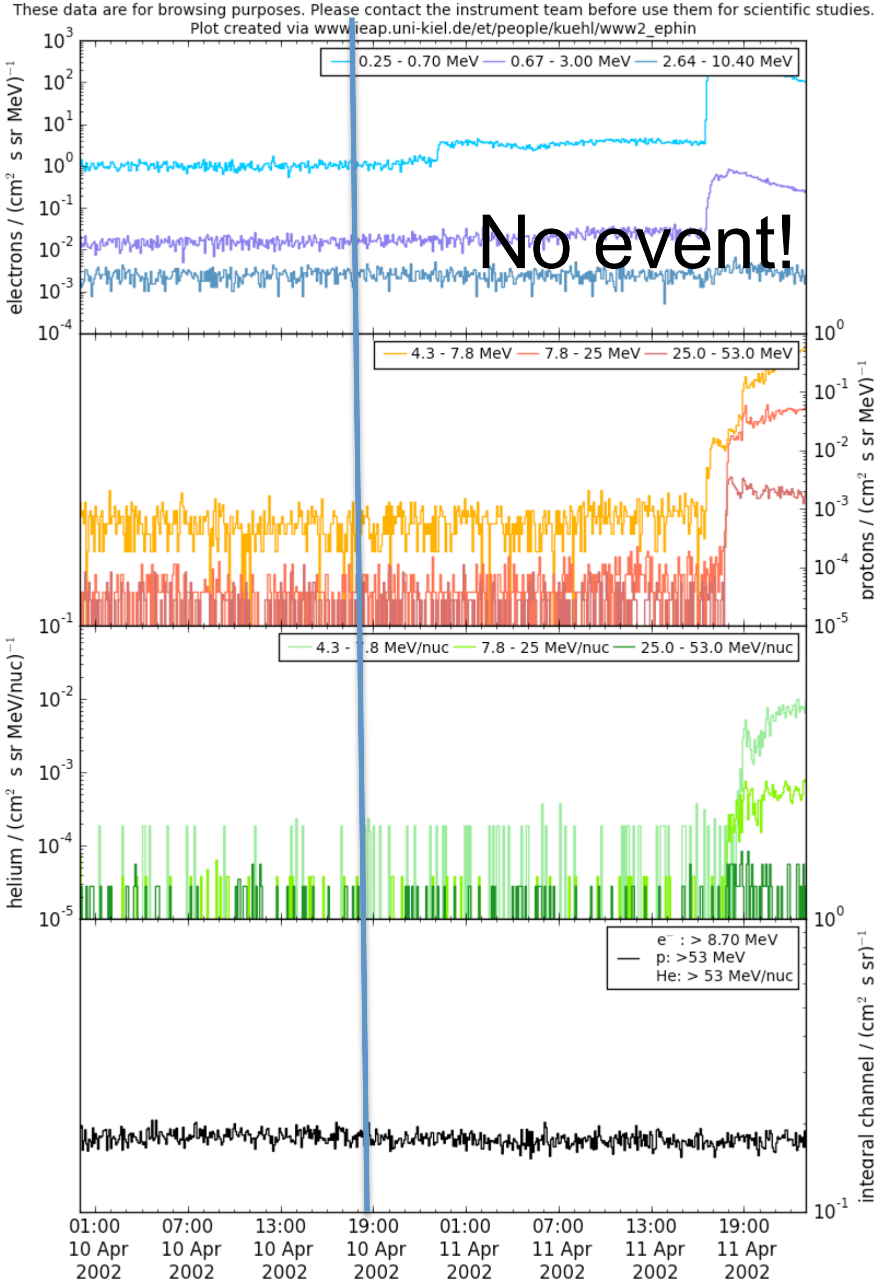
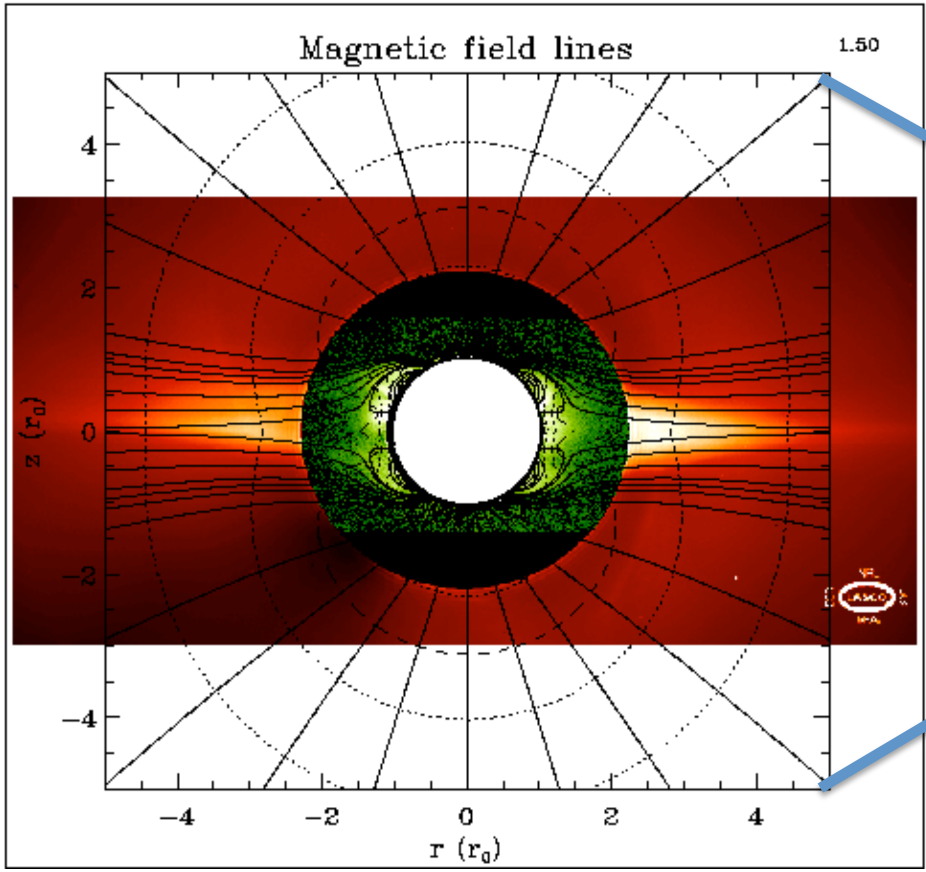
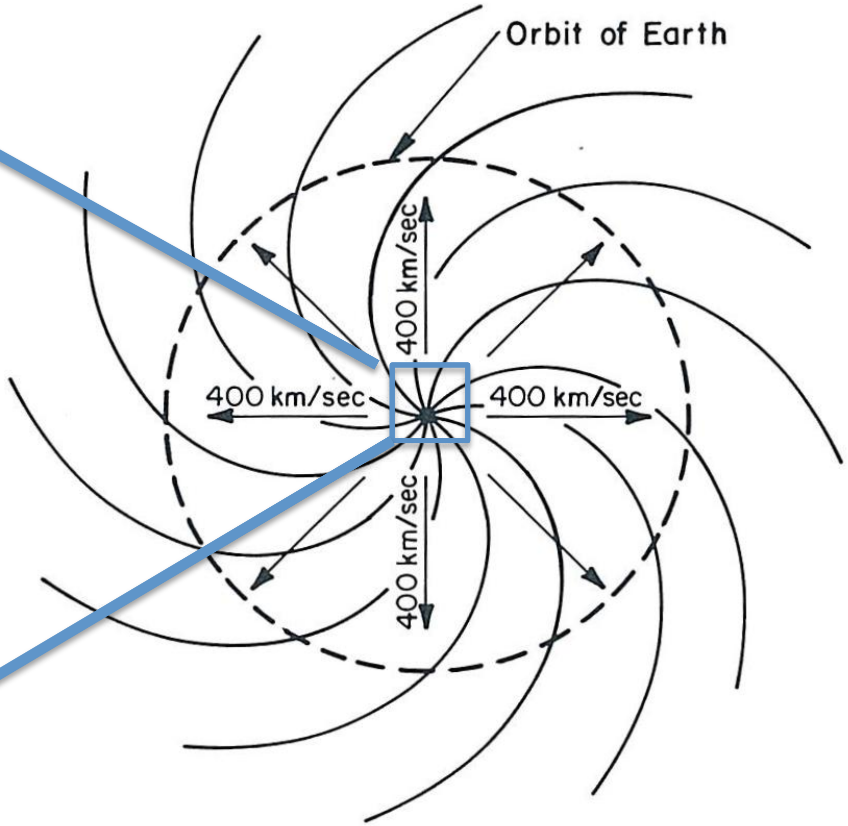


No event!

What is the problem?





The Physics behind …

How do we know that particles leave the corona?

http://cafehayek.com/2014/03/then-a-miracle-occurs.html

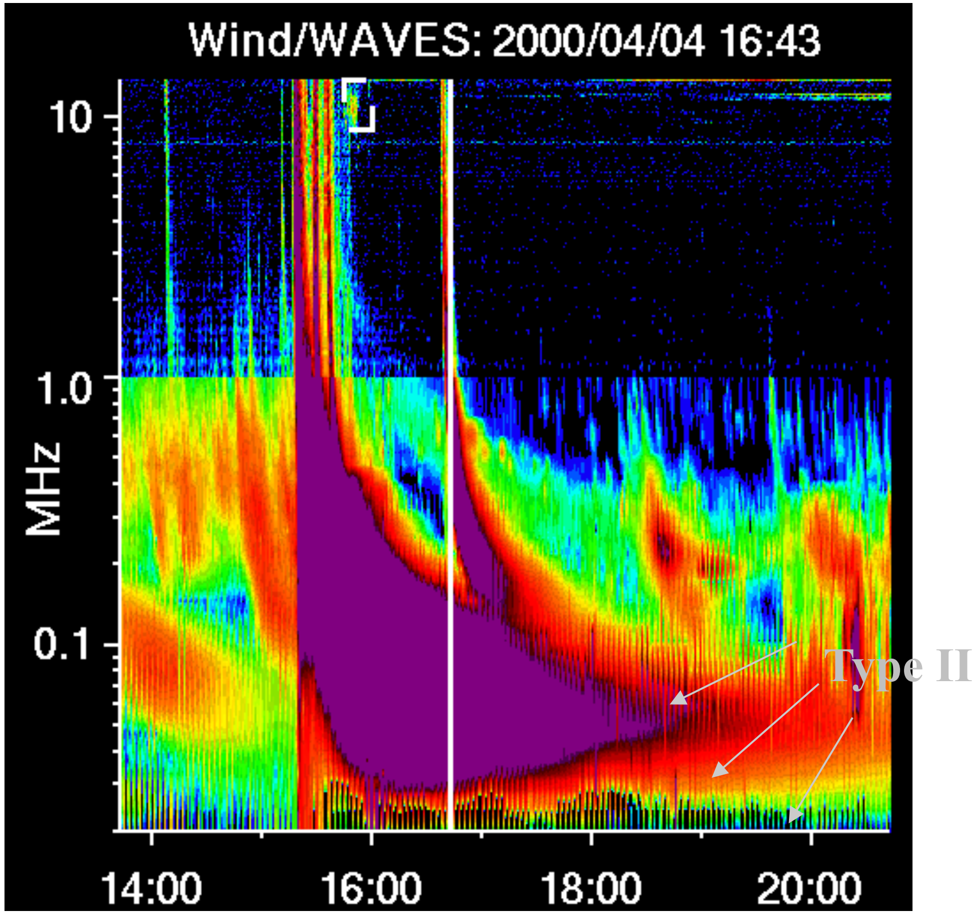
Parker (1963)

Injection into the IPM

This is a radio spectogram.

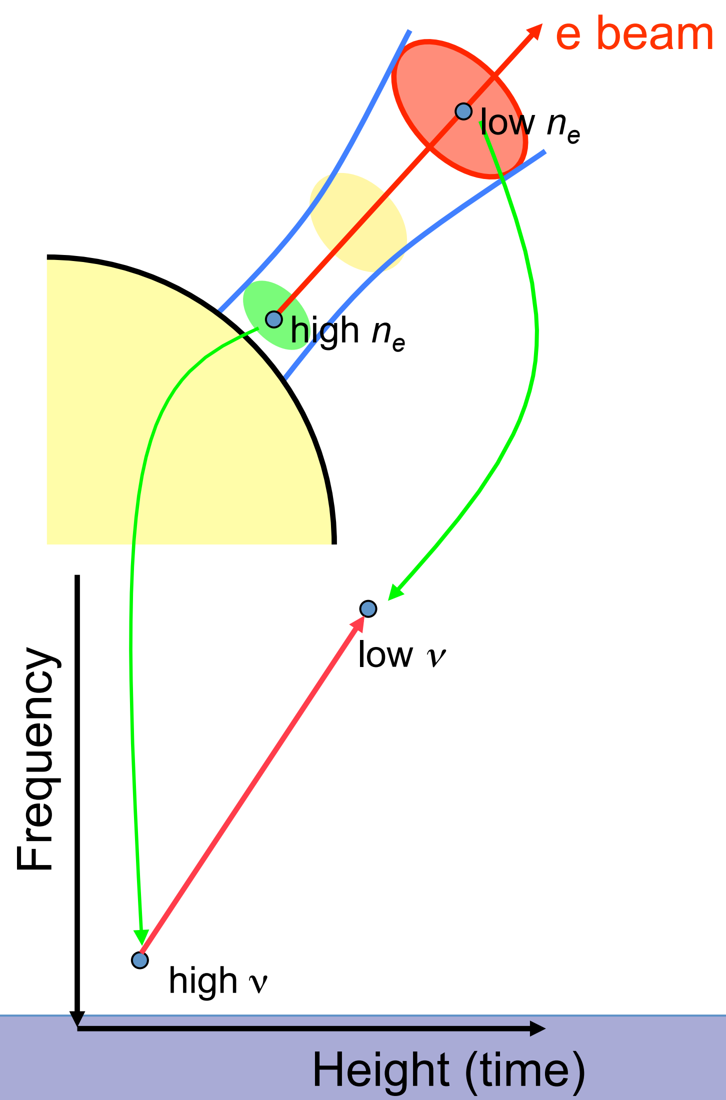
What does it show?

What is causing this features?



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

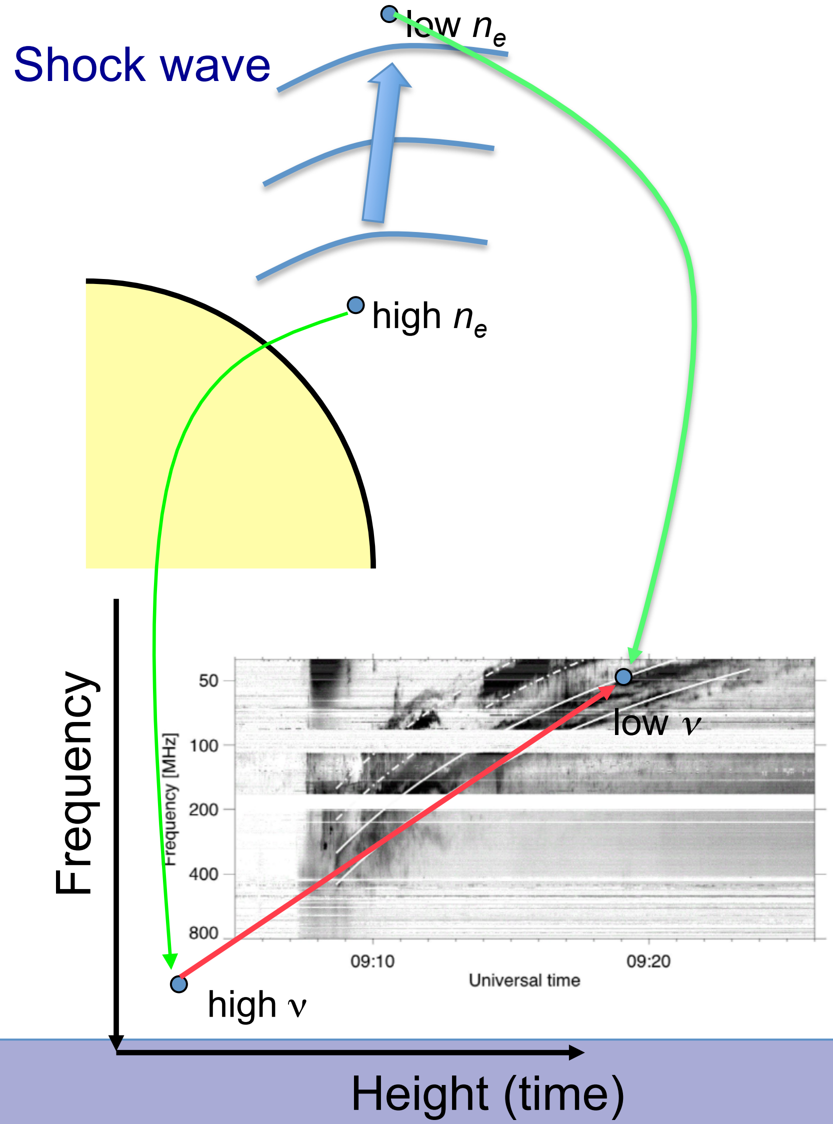
Solar flares – energy release and particle acceleration
Why not using radio emission from electron beams



- e beam rising through corona → Langmuir waves at decreasing ν
- Coupling with ion sound waves ($\nu_S \ll \nu_L$) or Langmuir waves → EM waves (T=transverse) at
  - $\nu_T = \nu_L + \nu_S \approx \nu_L \approx \nu_{pe} \sim \sqrt{n_e}$ "fundamental"
  - $\nu_T = \nu_L + \nu_L = 2\nu_L \approx 2\nu_{pe}$ "harmonic"
- Short burst that drifts from high to low ν ("type III" burst); lower ν → greater height
- Radio image: ν-dependent height

Coronal mass ejections

Why not using radio emission from a shock wave



- Shock wave rising through corona → e-reflection → Langmuir waves at decreasing ν
- Coupling with ion sound waves ($\nu_S << \nu_L$) or Langmuir waves → EM waves (T=transverse) at
  - $\nu_T = \nu_L + \nu_S \approx \nu_L \approx \nu_{pe} \sim \sqrt{n_e}$ "fundamental"
  - $\nu_T = \nu_L + \nu_L = 2\nu_L \approx 2\nu_{pe}$ "harmonic"
- Burst that drifts from high to low ν more slowly than type III ("type II" burst); lower ν → greater height

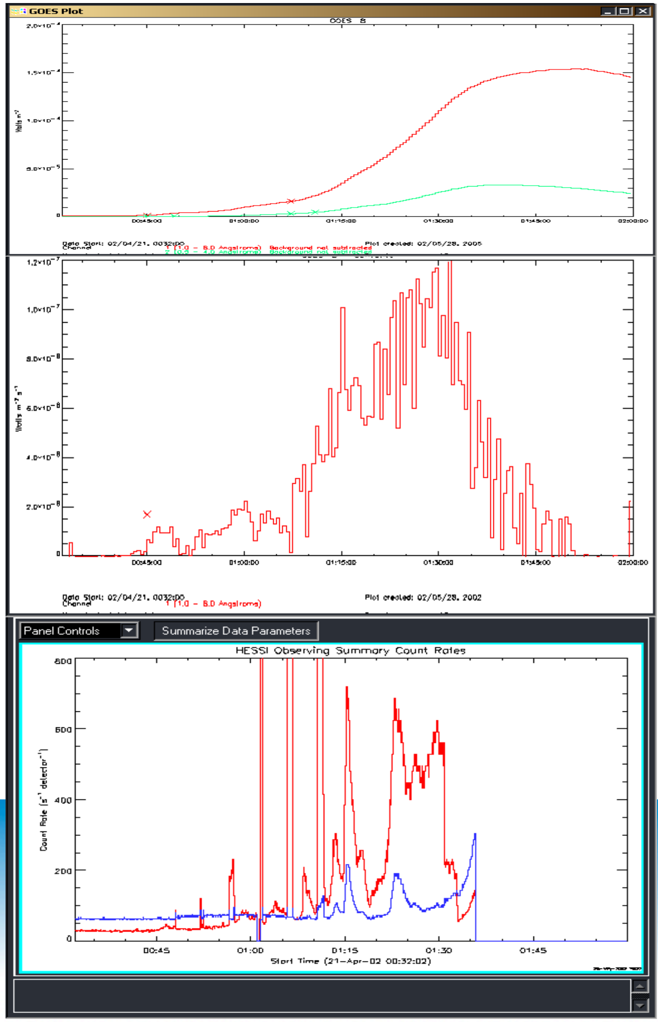
The Physics behind …

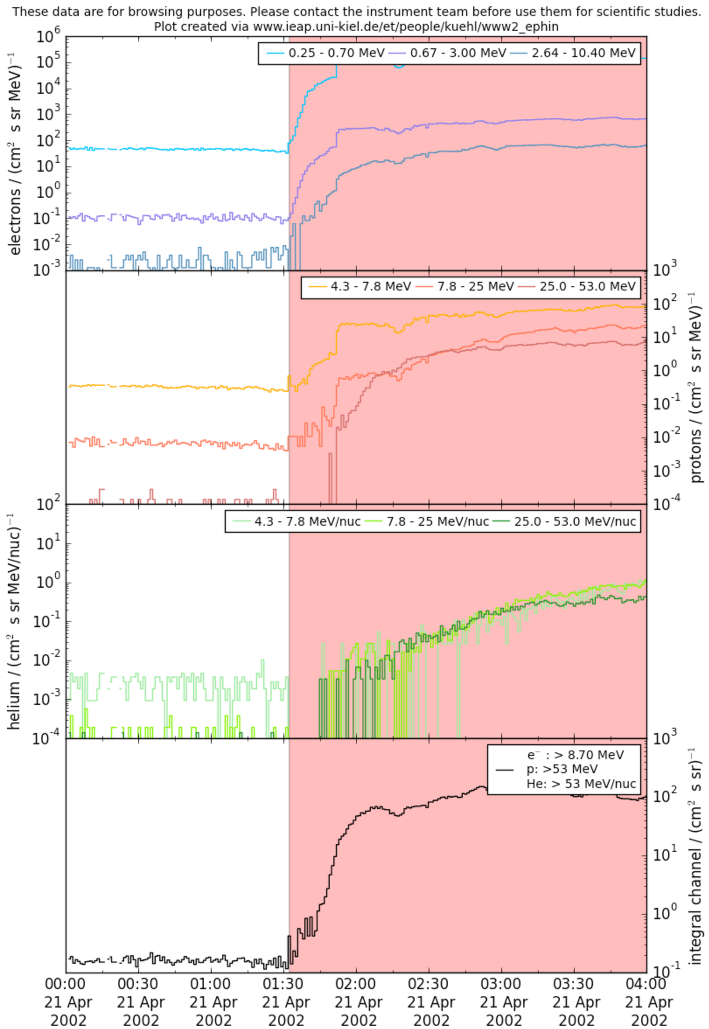
But radio data are not available in real time

http://cafehayek.com/2014/03/then-a-miracle-occurs.html

Parker (1963)

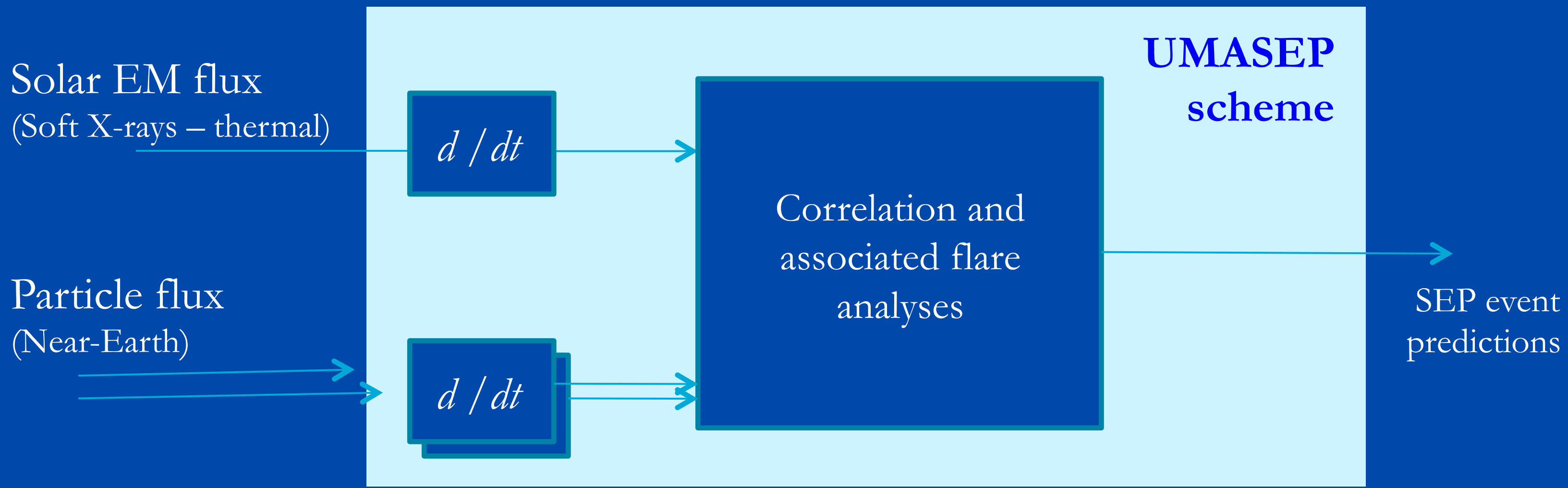
- From remote sensing to in-situ observations?





The UMASEP scheme (Núñez 2011, 2015)

- The UMASEP scheme infer a magnetic connection along which energetic protons are arriving near Earth, by correlating solar electromagnetic (EM) flux with the particle flux at near-earth.
- If the correlation is high and the associated solar flare is also strong, then the UMASEP scheme issues a SEP prediction.



Refs. Núñez, M. 2011, *Space Weather*, 9

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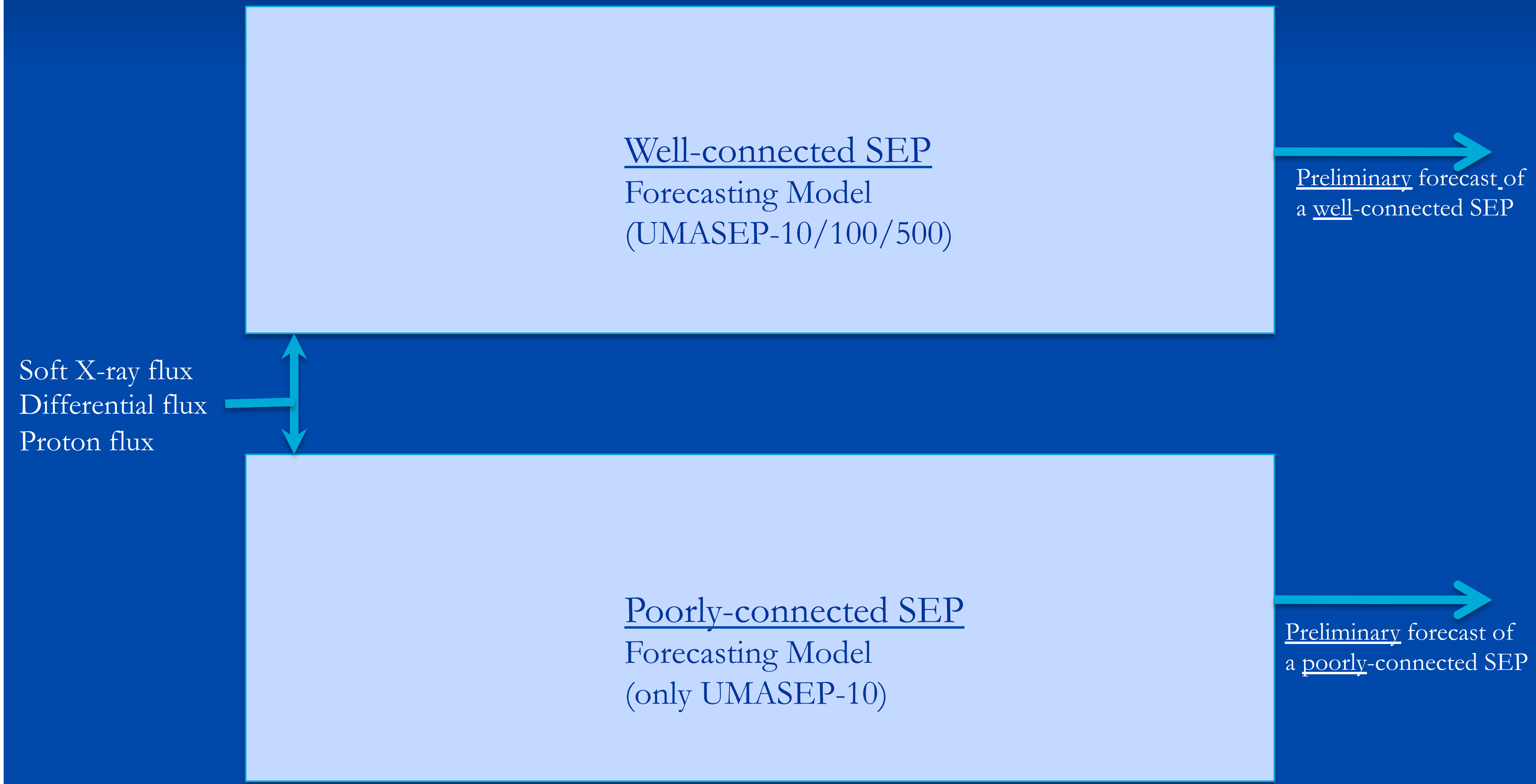
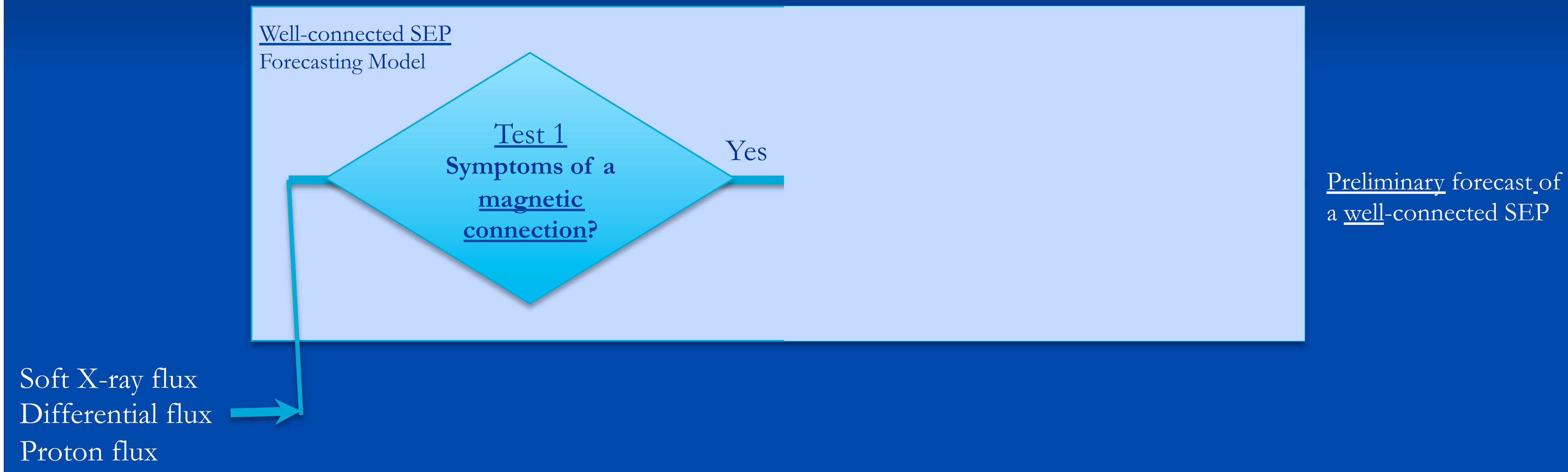
UMASEP Models



For the case of UMASEP-10, this dual-model was calibrated by using 27 years of SXR/proton data (updated every year)

UMASEP Models



Poorly-connected SEP
Forecasting Model

UMASEP Models

Well-connected SEP
Forecasting Model

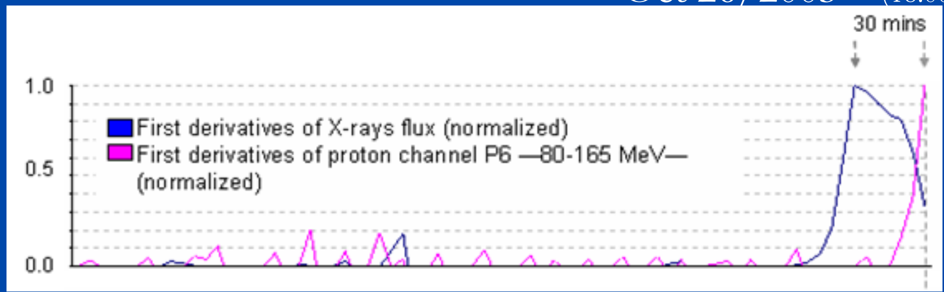
Test 1
Symptoms of a magnetic connection?

Yes

Preliminary forecast of a well-connected SEP

Soft X-ray flux
Differential flux
Proton flux

Oct 26/2003 (18:00)



OK

Poorly-connected SEP
Forecasting Model

UMASEP Models

Soft X-ray flux
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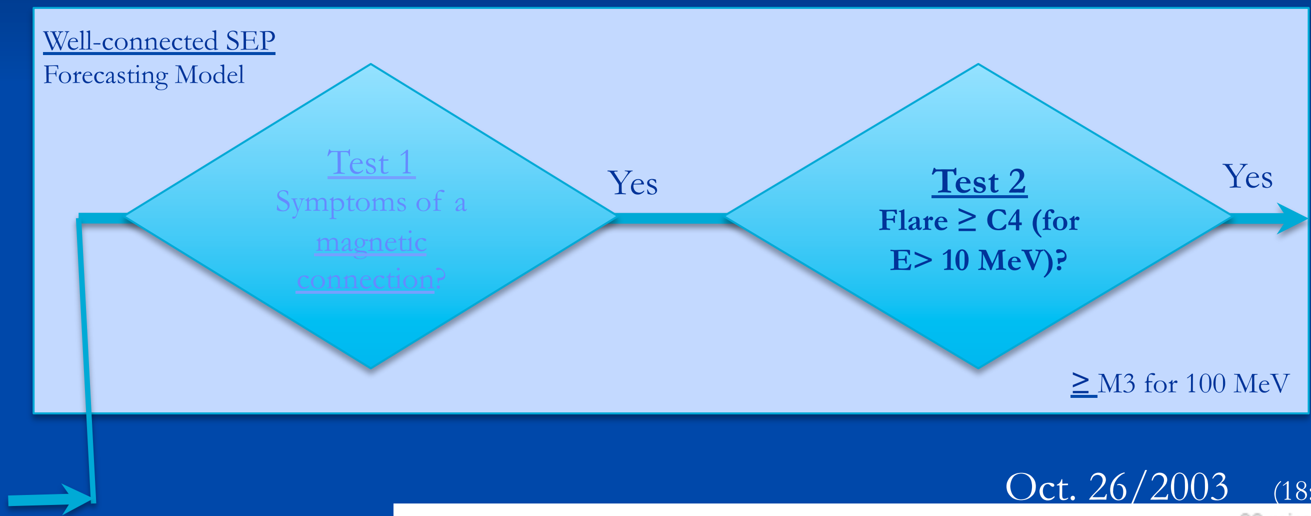

Preliminary forecast of a well-connected SEP

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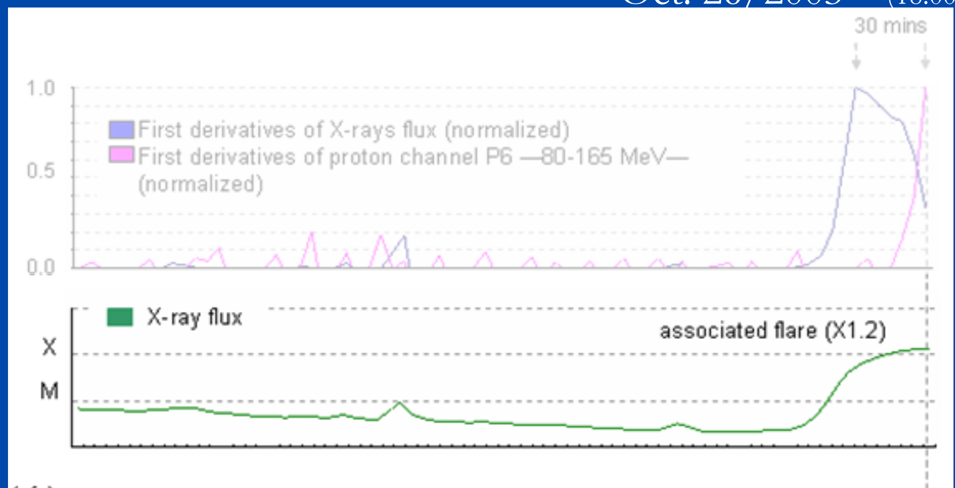
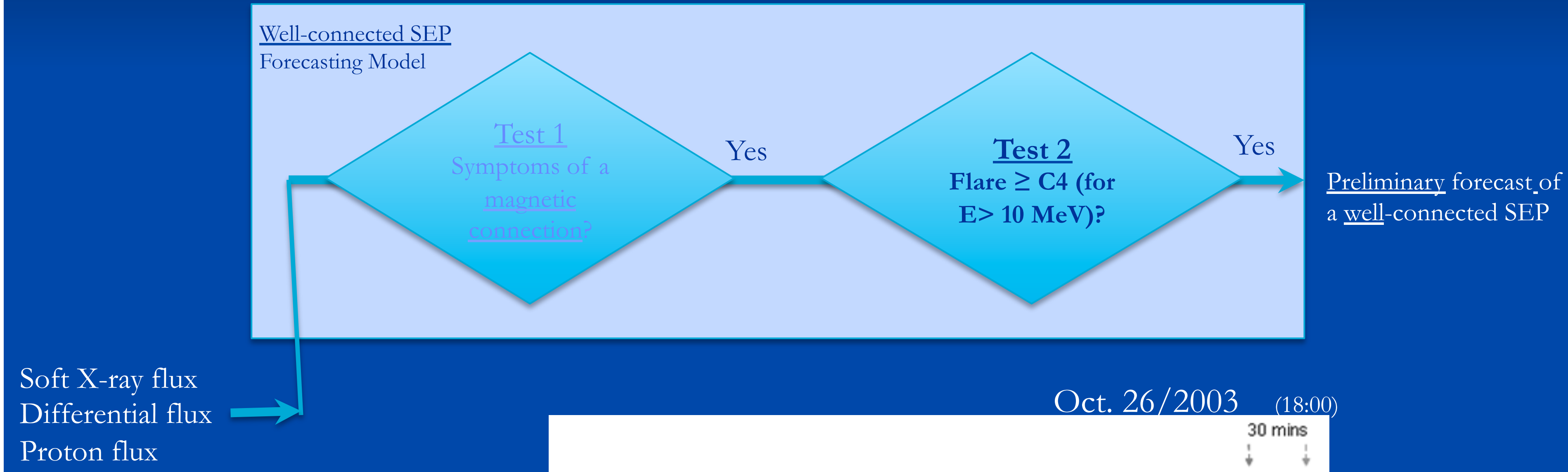


OK

← ?

Poorly-connected SEP
Forecasting Model

UMASEP Models



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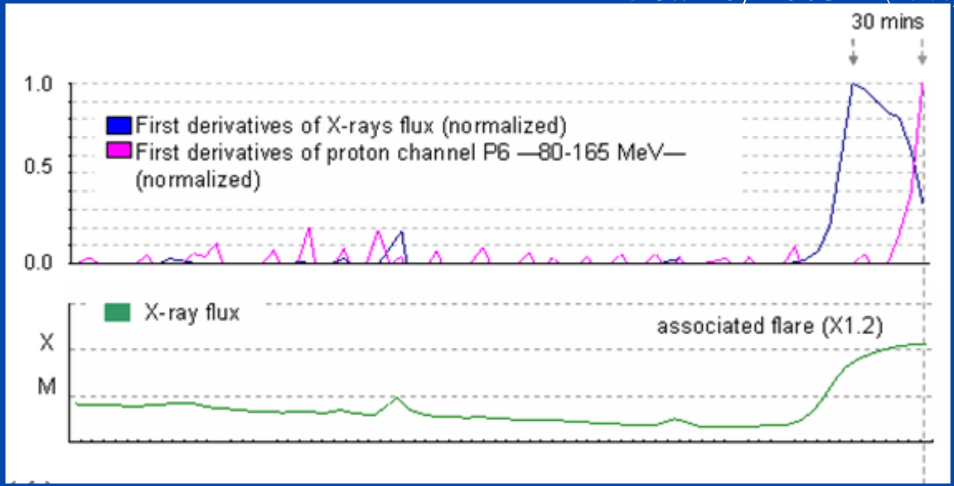
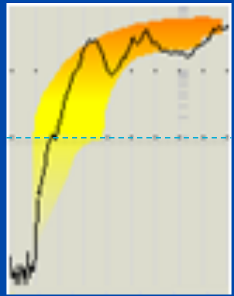


OK

OK



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Scatter free transport

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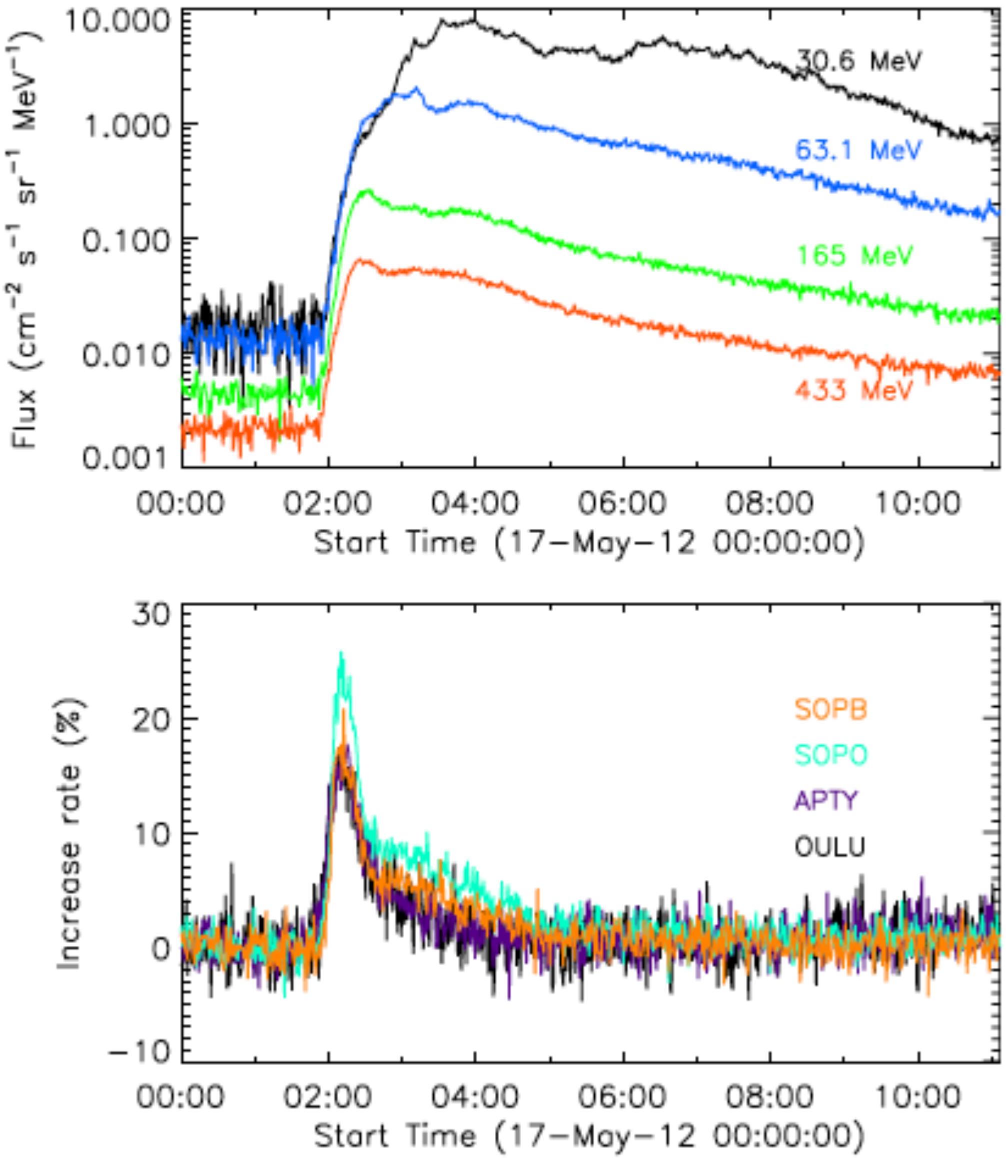

Protons

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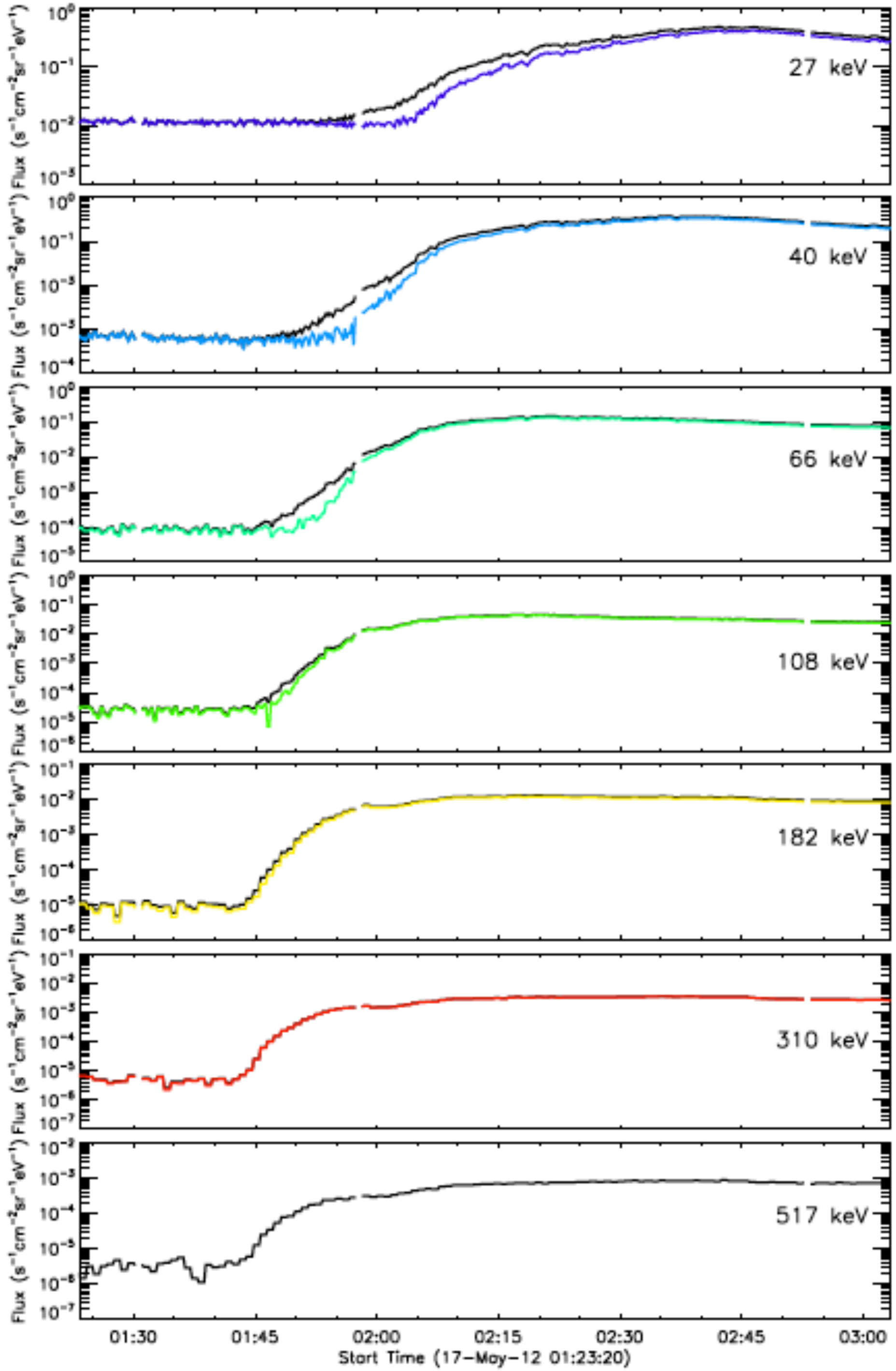

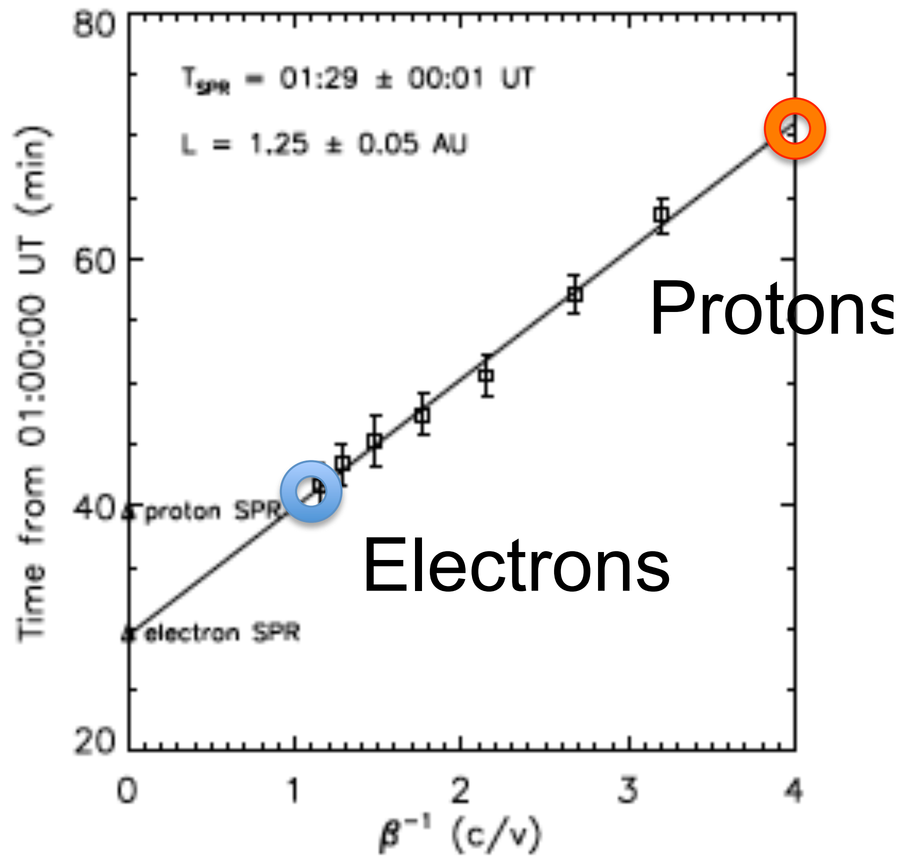

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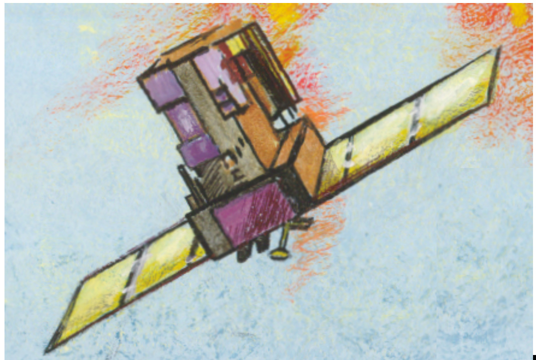
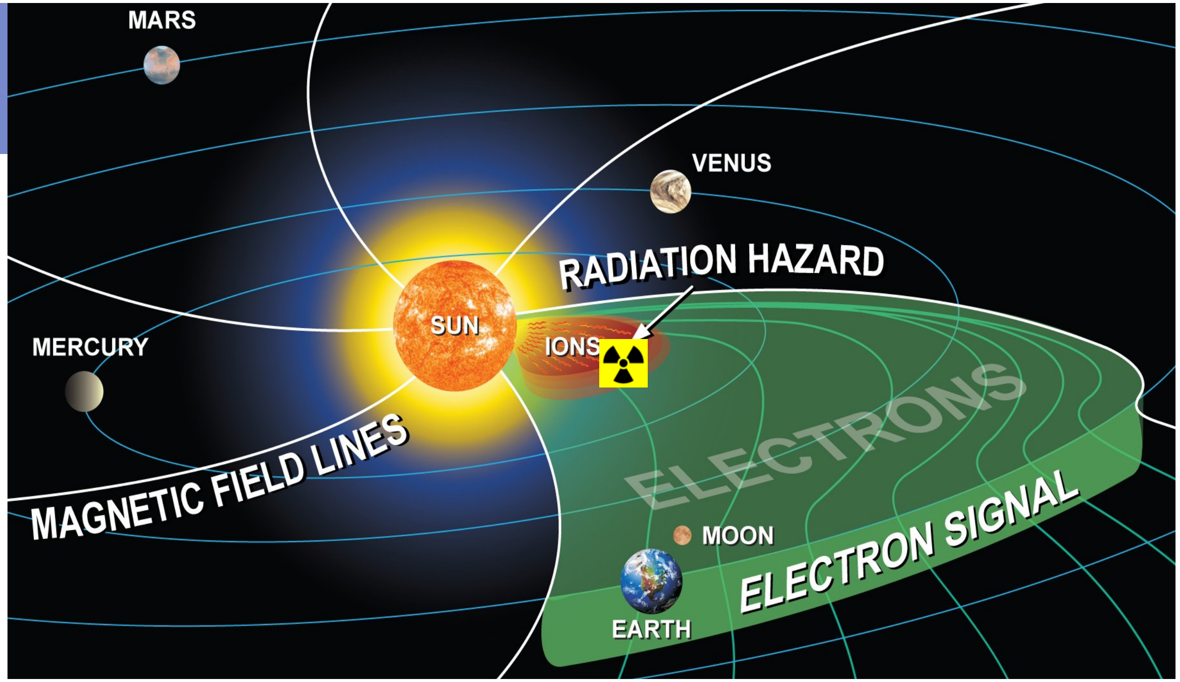
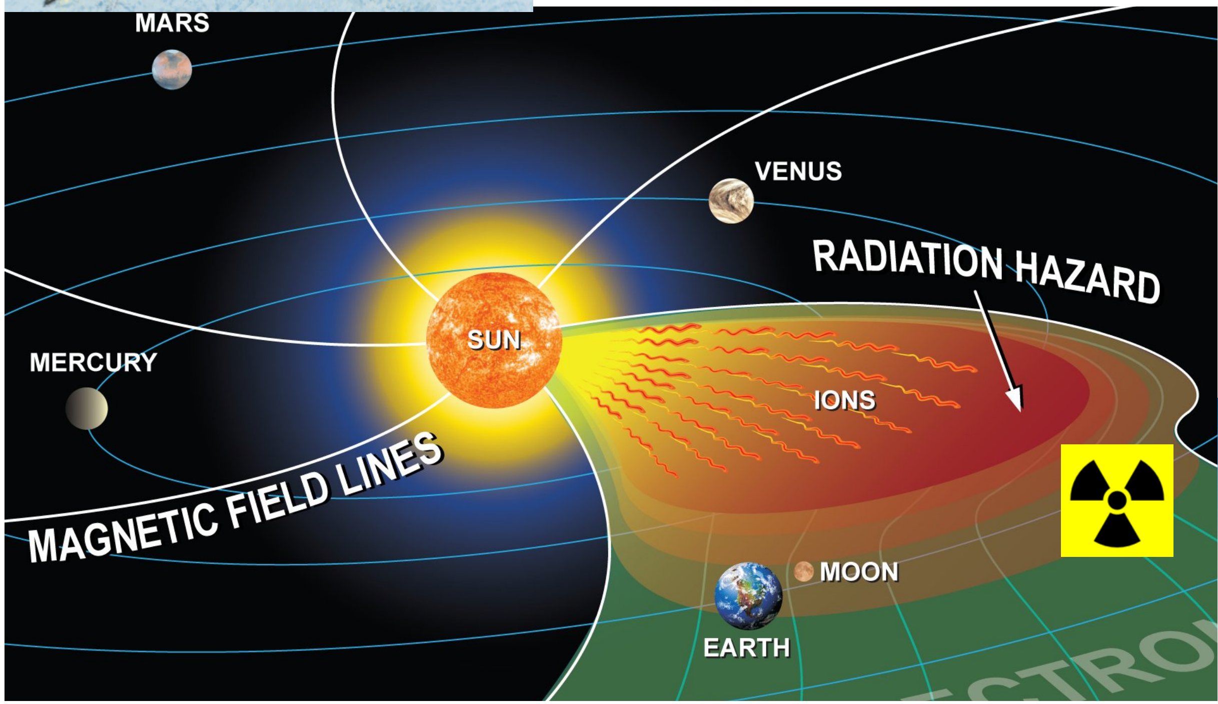






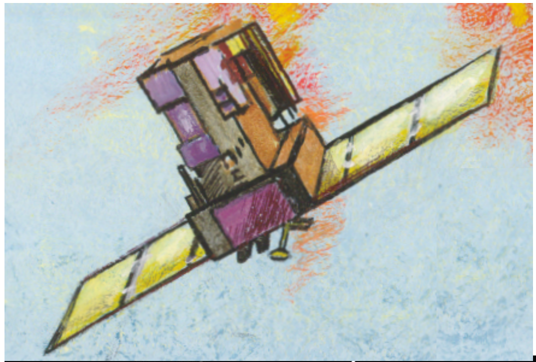
D ~ 1.2 AU

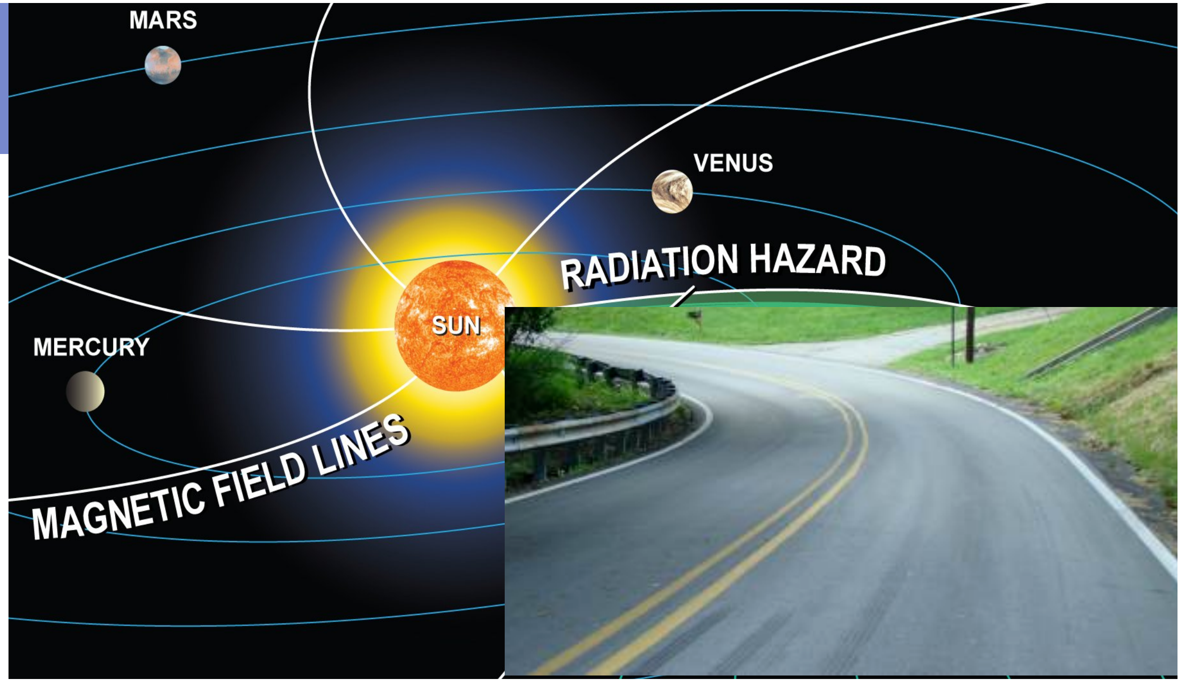
v_{el}(1 MeV) = 0.95 c

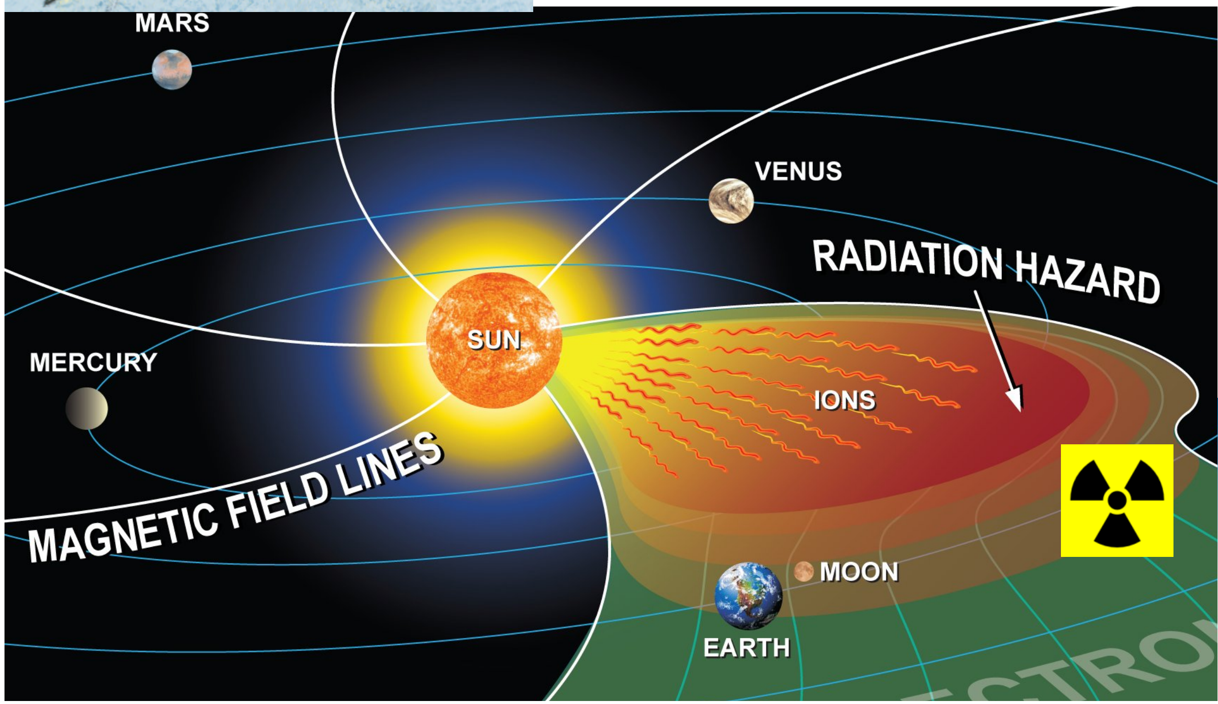
T_{el} (1 MeV) =10.5 min

REleASE

Relativistic Electron Alert System for Exploration







D ~ 1.2 AU

v_p(30 MeV) = 0.25 c

T_p(30 MeV) = 40 min

ΔT ~ 30 min

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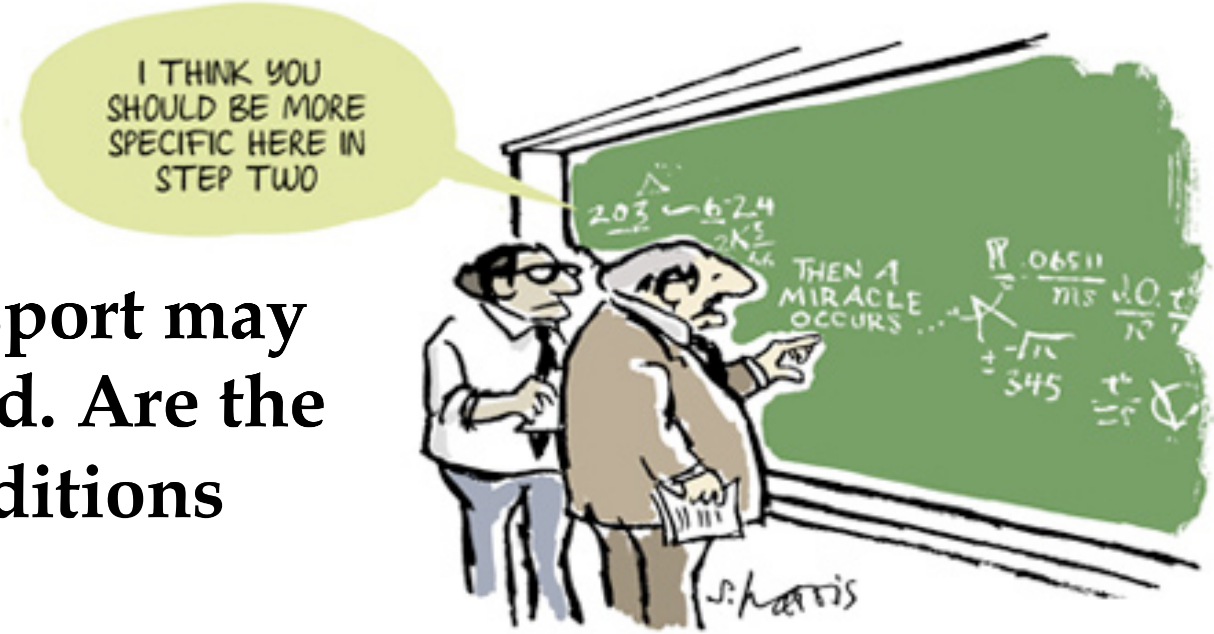
The Physics behind …



Scatter free transport may be oversimplified. Are the propagation conditions the same?

http://cafehayek.com/2014/03/then-a-miracle-occurs.html

Parker (1963)

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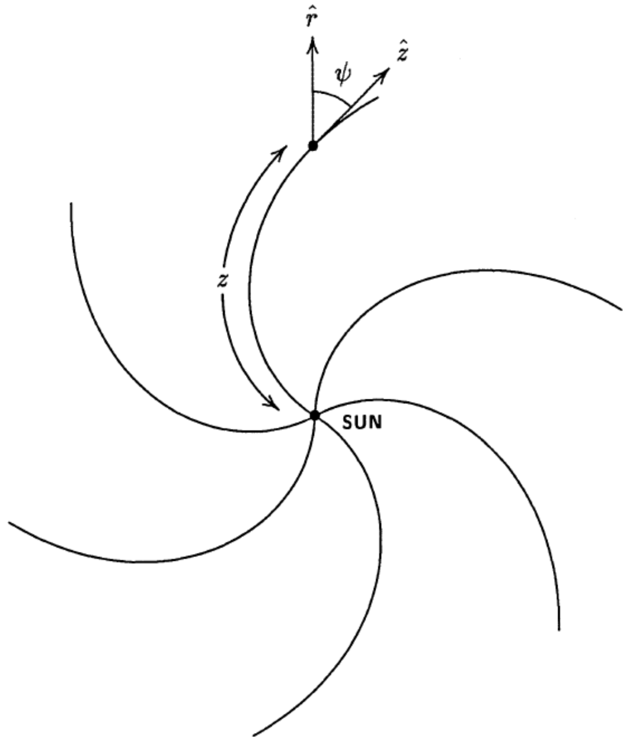
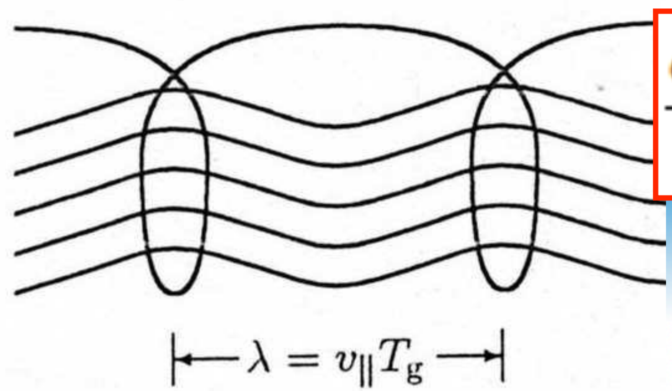
Transport in the IPM



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

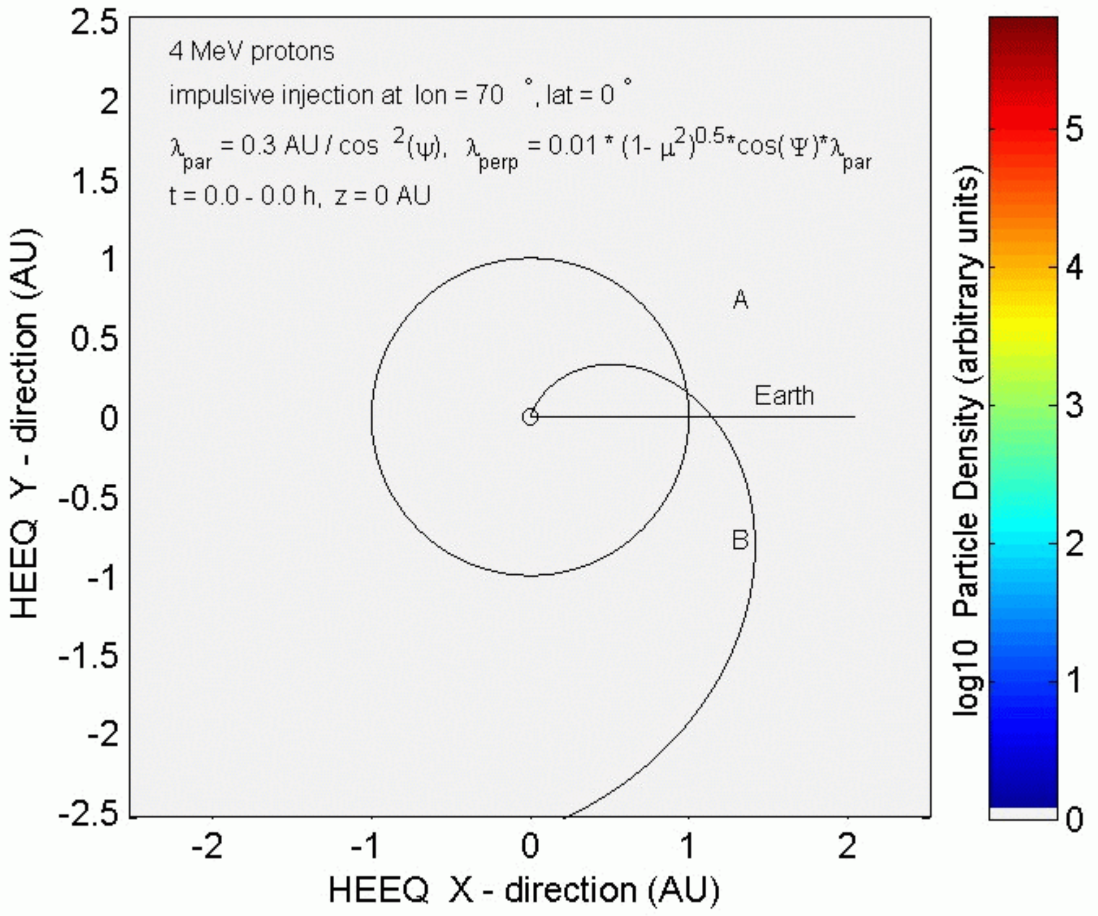
$$\dot{\mu} = \frac{1-\mu^2}{2L} v \qquad \frac{1}{L} = -\frac{\partial \ln B}{\partial Z}$$



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

Focused transport equation

Transport in the IPM



Diffusion coefficients

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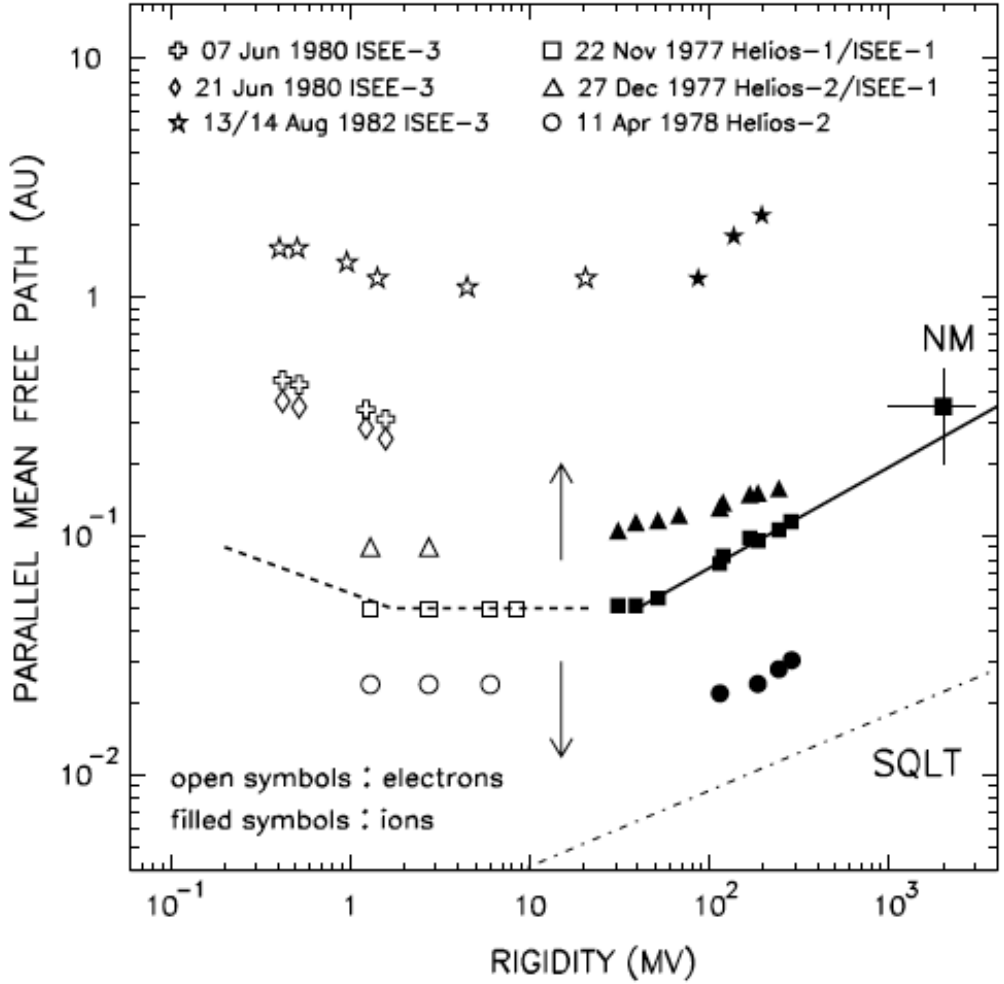
Does it work when taking into account a more complex particle transport?

Yes!



SUMMER SCHOOL

SEP events

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- CME driven shocks and flares accelerate particles

Impulsive events

- **related to impulsive X-ray flares**
- duration from hours to a day, low intensity
- **electron, heavy-ion and ^{3}He rich**
- narrow longitude range

- **Gradual events**

  - **related to CMEs and gradual X-ray flares**
  - duration from days to a week, high intensity → Space environment
  - **electron poor, normal ion abundances**
  - wide longitude range

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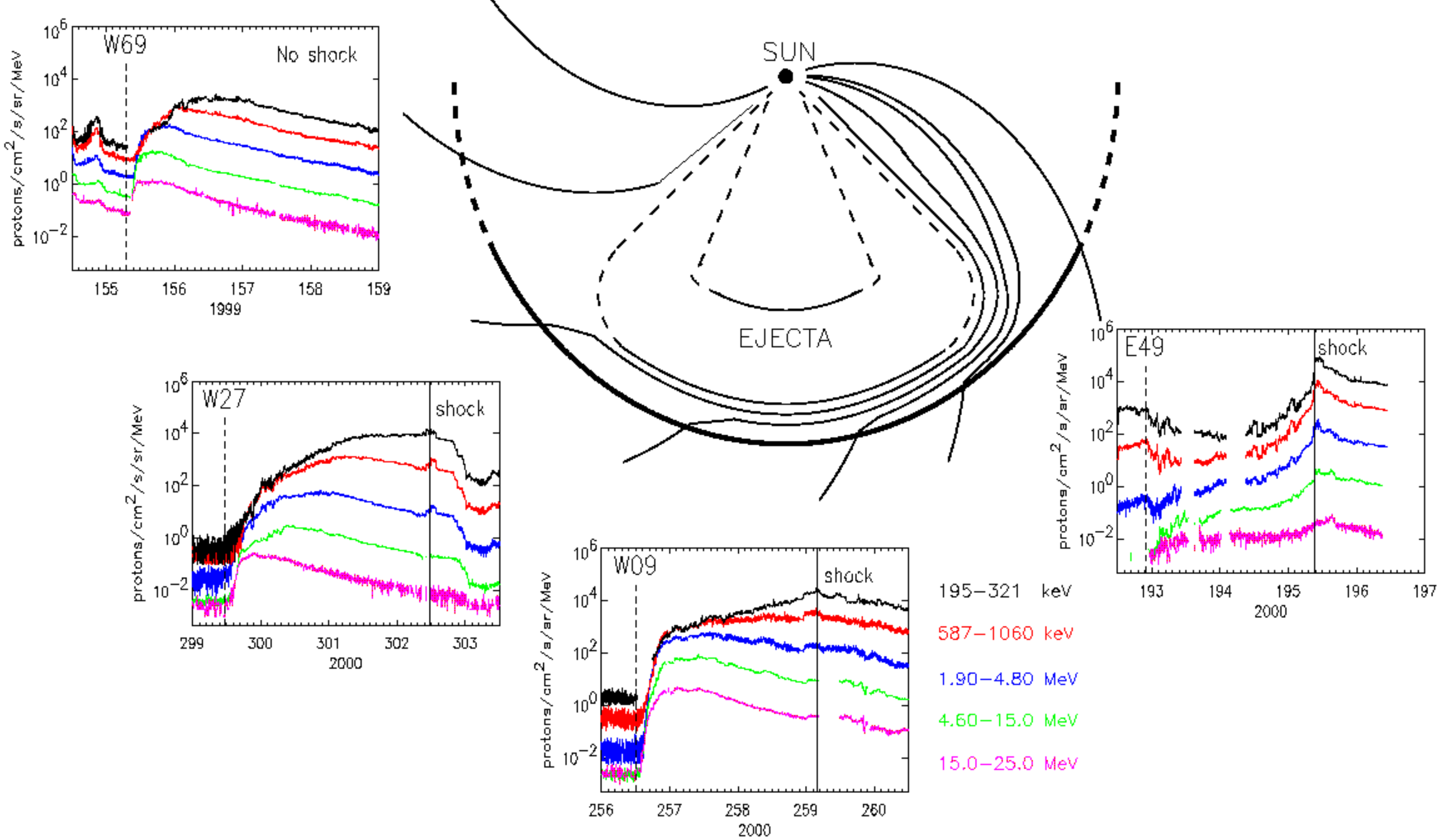
Longitude distribution: gradual events as a function of energy



Starting points

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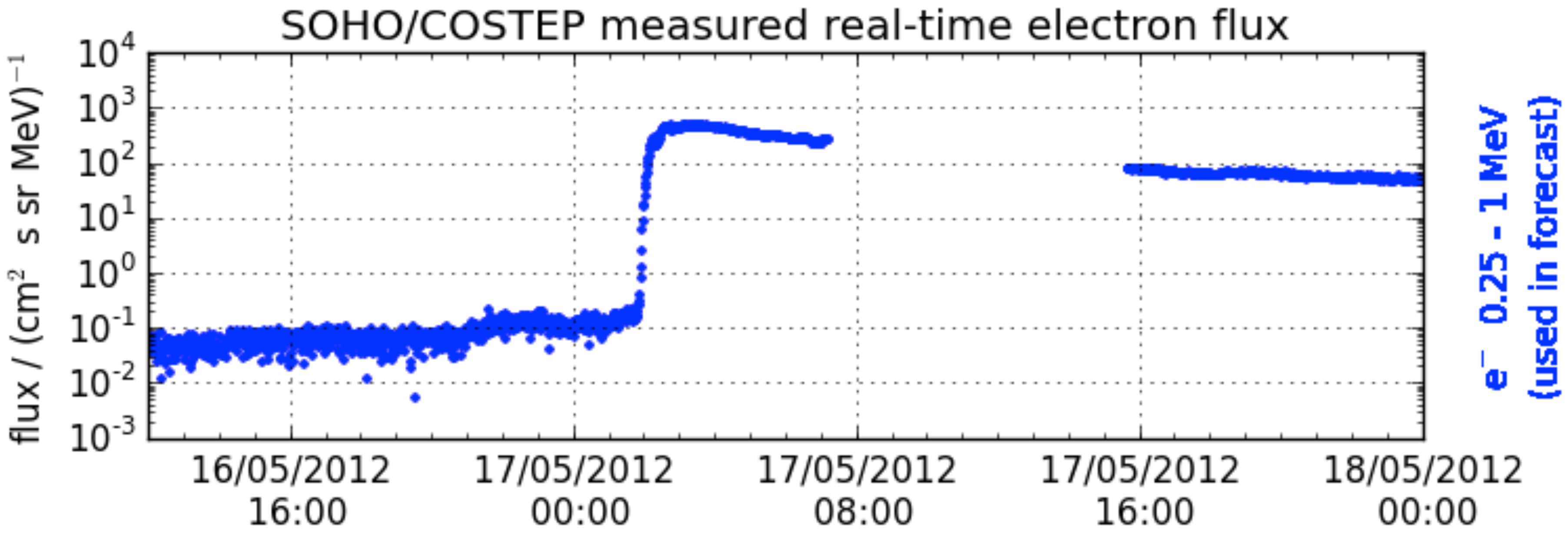

Measurement of MeV electrons by EPHIN

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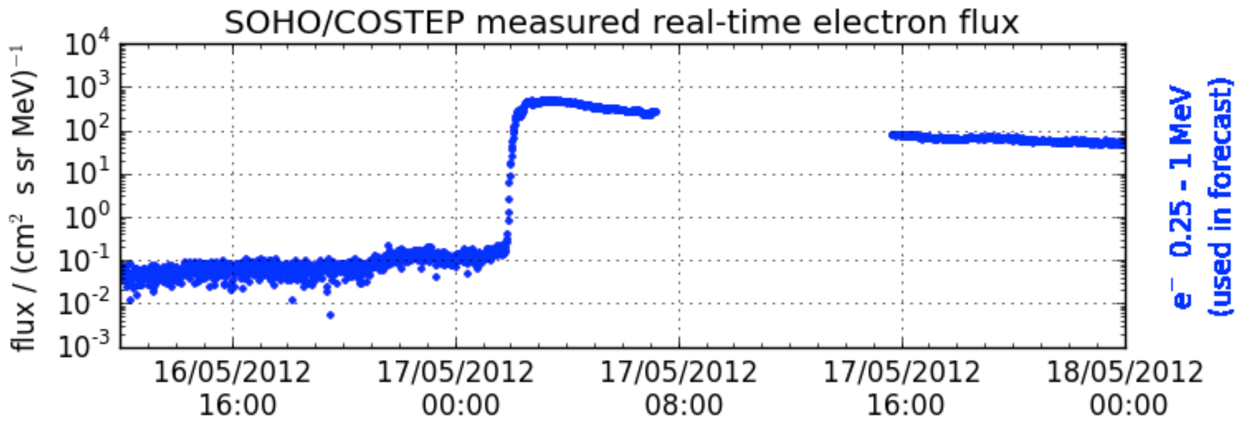
Relativistic electrons always arrive at 1 AU ahead of non-relativistic SPE ions allowing their forecasting.

Coming from one source with "identical" propagation conditions, significant correlations between electron and proton time-profiles exist.

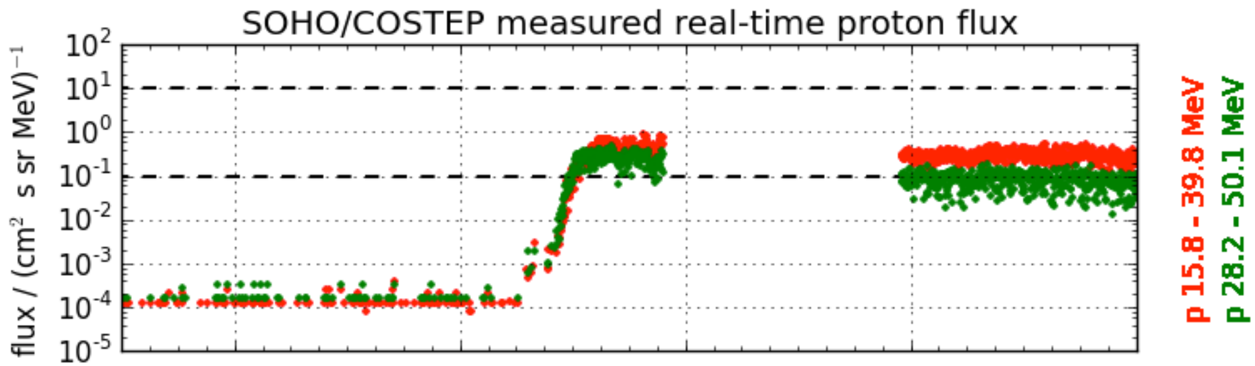
Therefore, a matrix to forecast proton intensities was developed.

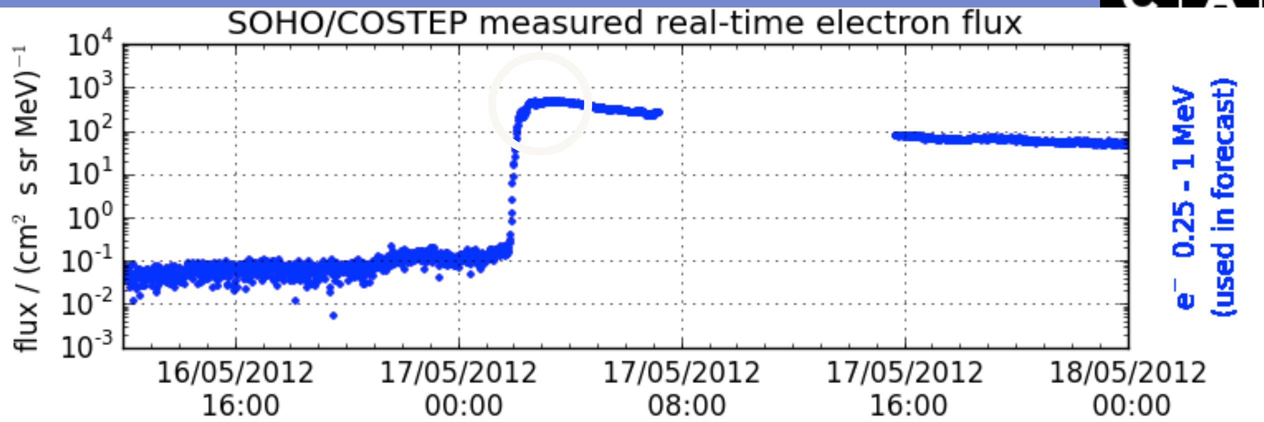
Posner, *Space Weather J.*, 2007

The task

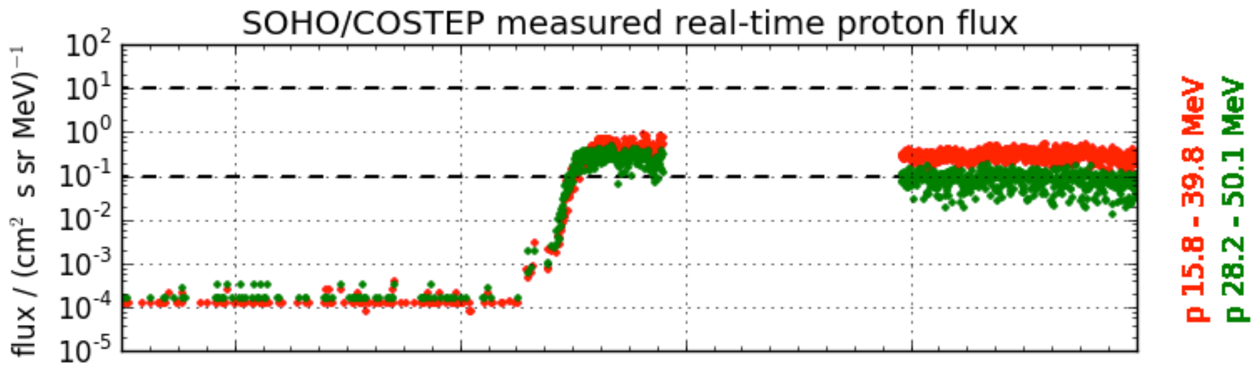


REleASE



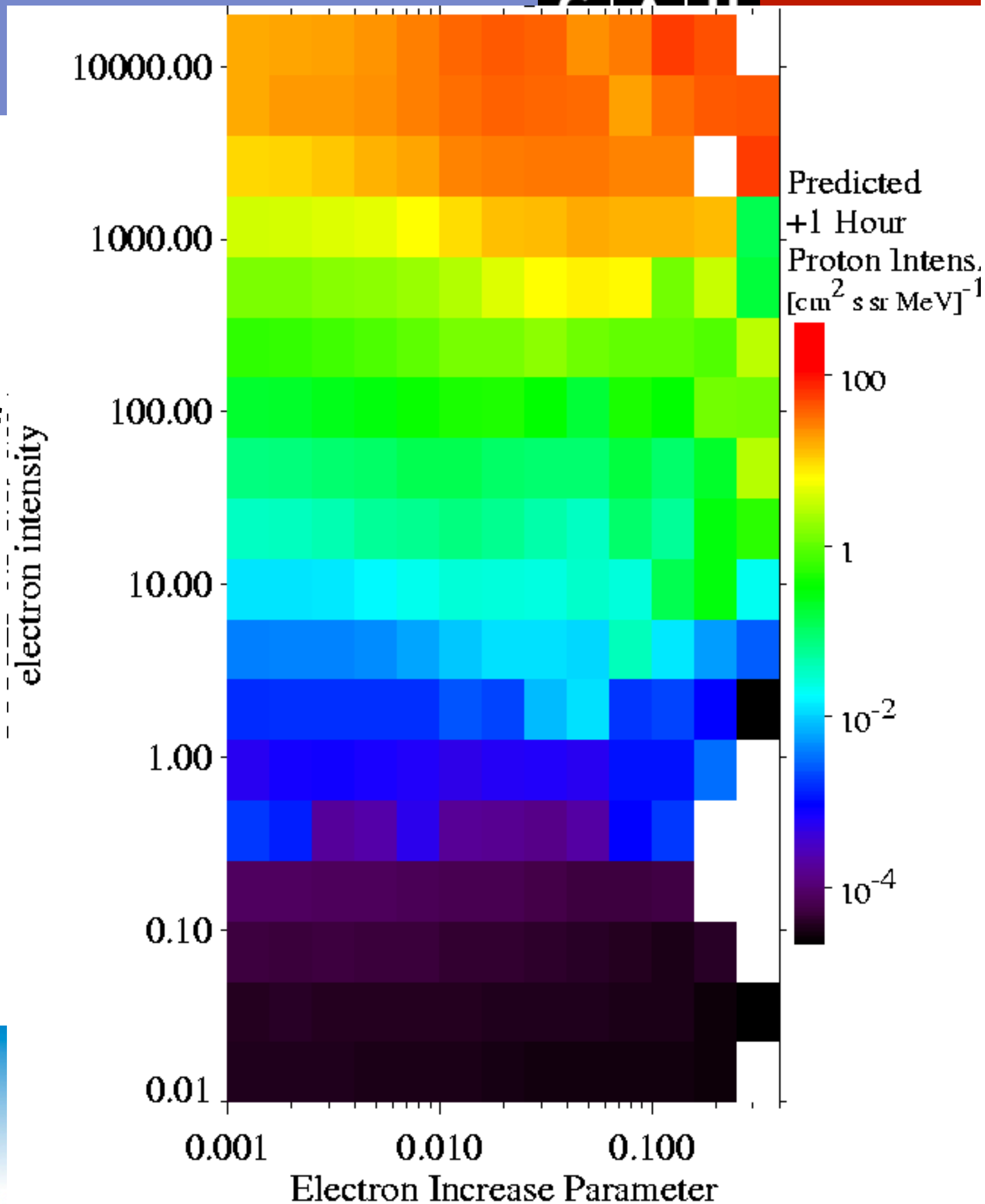


Use data from 1998 to 2005 and find correlation between the maximum intensities of electrons and protons:



A matrix is the foundation of this forecasting technique. It combines continuous minute-by-minute observations through the main phase of solar cycle 23 (“learning phase”, 1998-2002). The matrix spans across electron intensities and rise times and any time the electron intensity increases, a value is added at the locus given by the two parameters. The value that is filled in is the proton intensity observed one hour later.

At any one time, a forecast simply pulls the average matrix proton value for the given electron locus and turns it into a near-term proton intensity prediction.



Release

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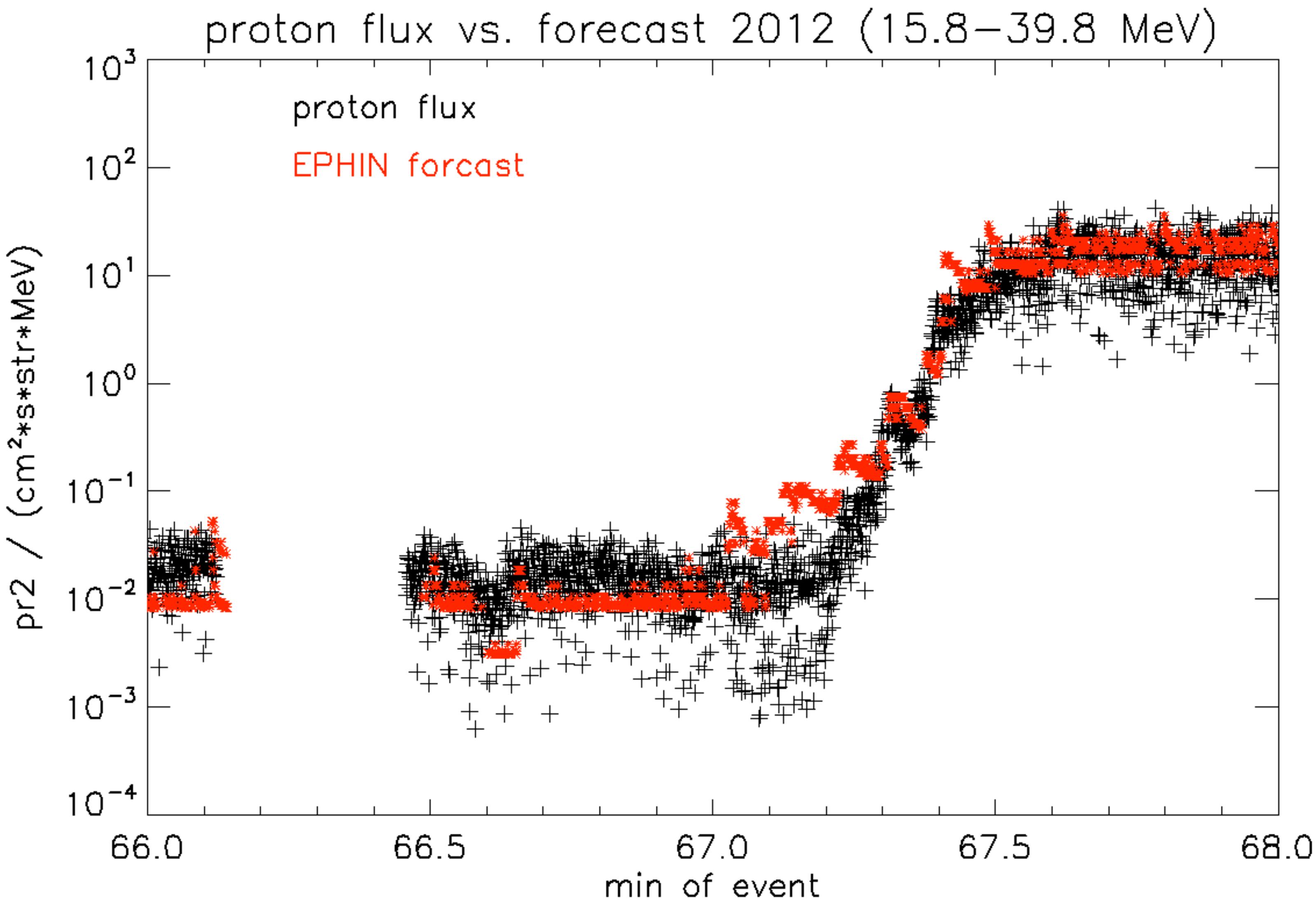


SUMMER SCHOOL

Summary

Acceleration of ions and electrons at the SUN

8 min

Remote sensing signals from the lower corona (x and γ-rays)

? min

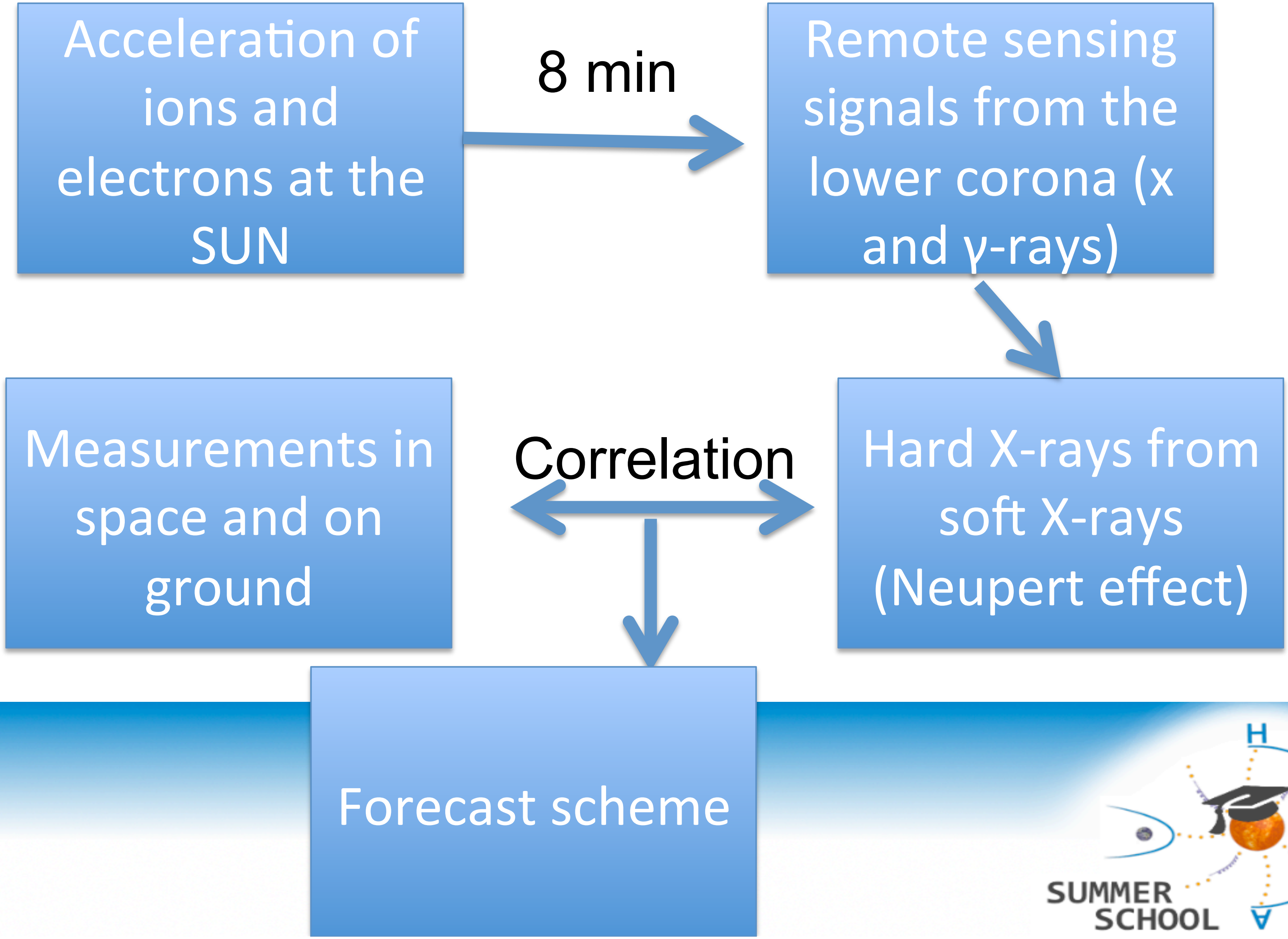
Injection into the interplanetary medium (radio signal)

Interplanetary transport

Measurements in space and on ground

Energy dependent

Summary (UMASEP)



Summary (RELEASE)

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Acceleration of ions and electrons at the SUN

8 min →

Remote sensing signals from the lower corona (x and γ-rays)

→

Electrons and Ions injected at same region and same transport

Correlation ↔

From Electrons ions are predicted

SUMMER SCHOOL

Project exercise

- Make yourself familiar with the temporal and physical difference and common things between electromagnetic radiation and particles.
- UMASEP forecast is based on the fact that particles are injected into the IPM in correlation with the hard X-ray.
- RELEASE relies on the fact that electrons and ions are injected at the same time and that the propagation as well as the e/p-ratio is constant.