Modeling the SEP/ESP Event of December 13, 2006

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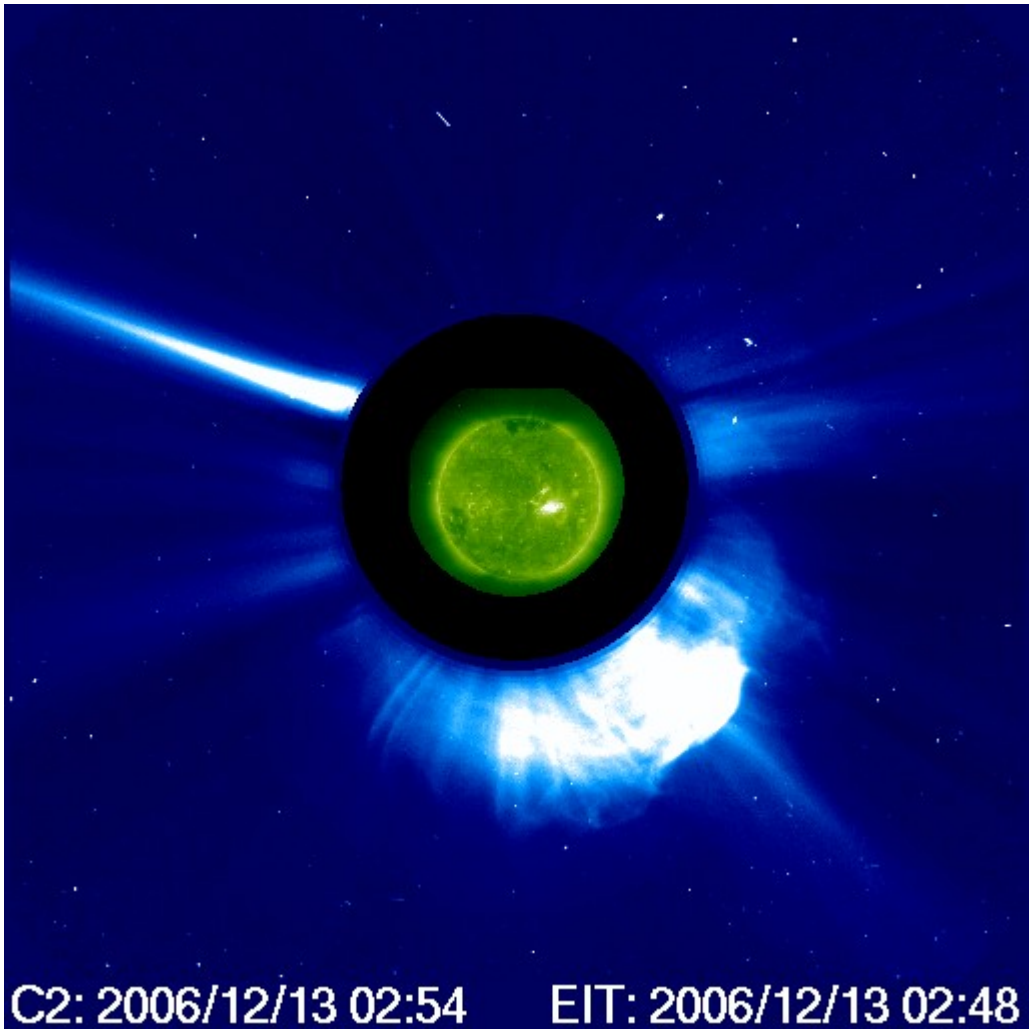
Outline:

- SEP event of December 13, 2006
- The PATH code (MHD, acceleration and transport blocks)
- Modeling of a mixed SEP event (flare particles + shock-accelerated particles)
- Results: spectra and intensities for protons and Fe ions
- Further studies/collaboration

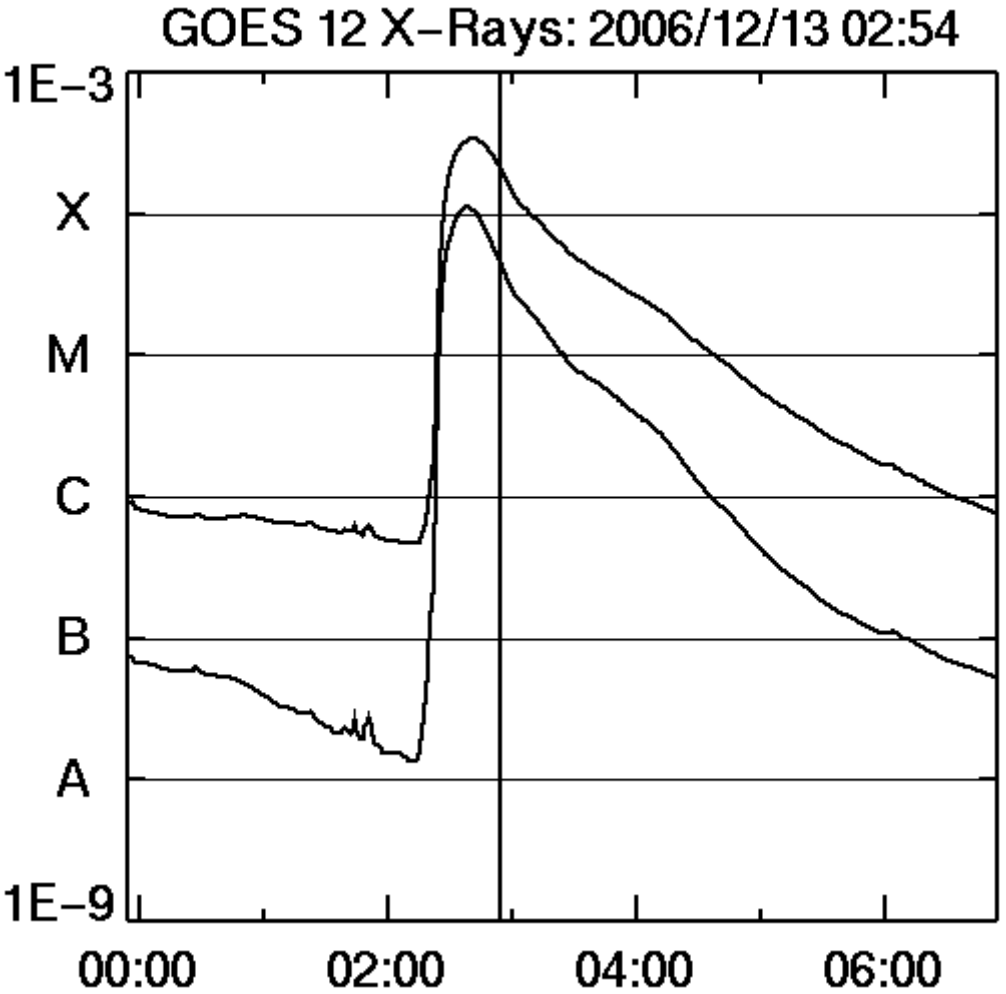
SEP event of December 13, 2006



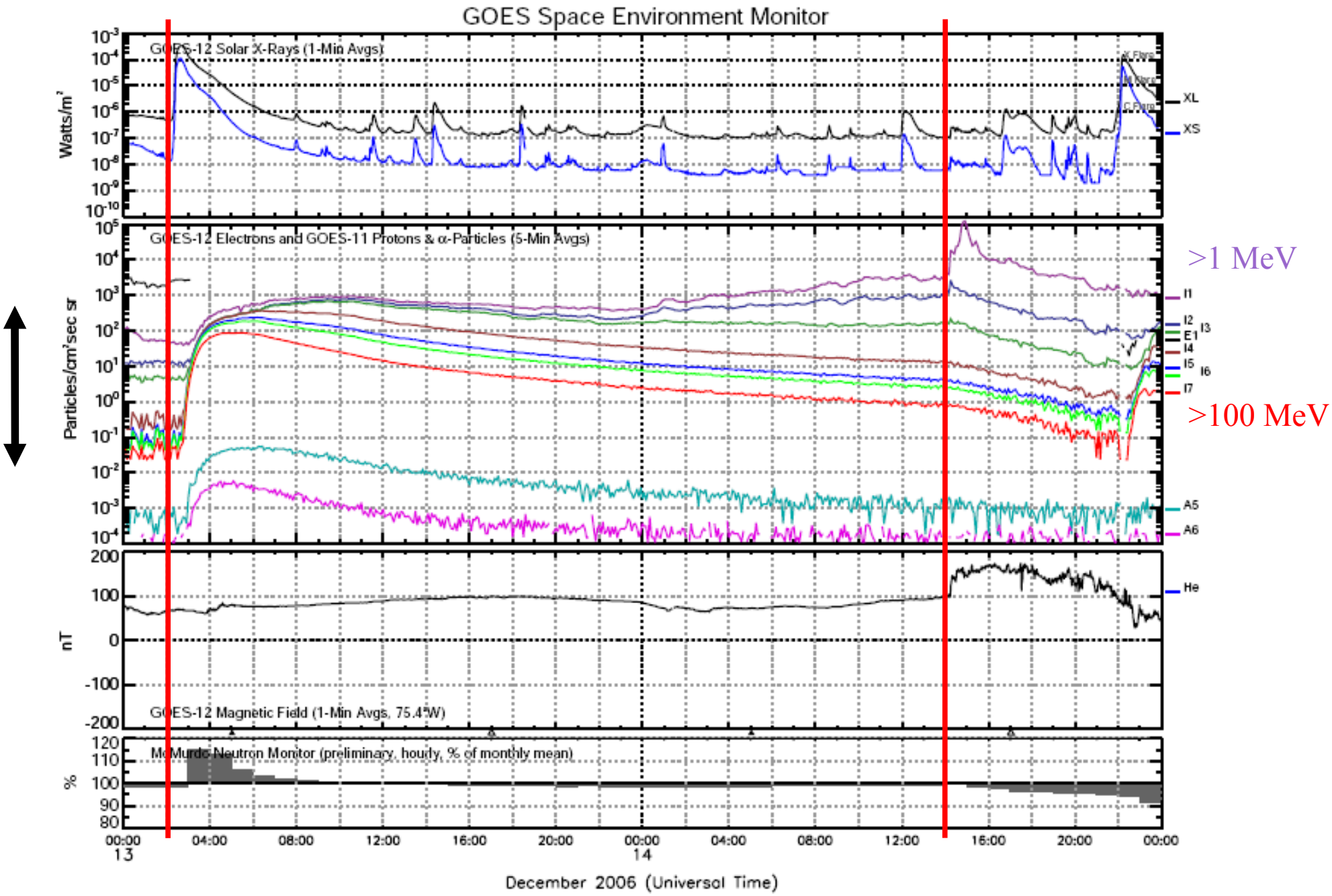
Halo CME: Dec. 13, 2006: 02:54:04

linear speed: 1774 km/sec;
speed at 20 R: 1573 km/sec;

(from the SOHO/LASCO CME Catalog, courtesy of the CDAW Data Center, GSFC).



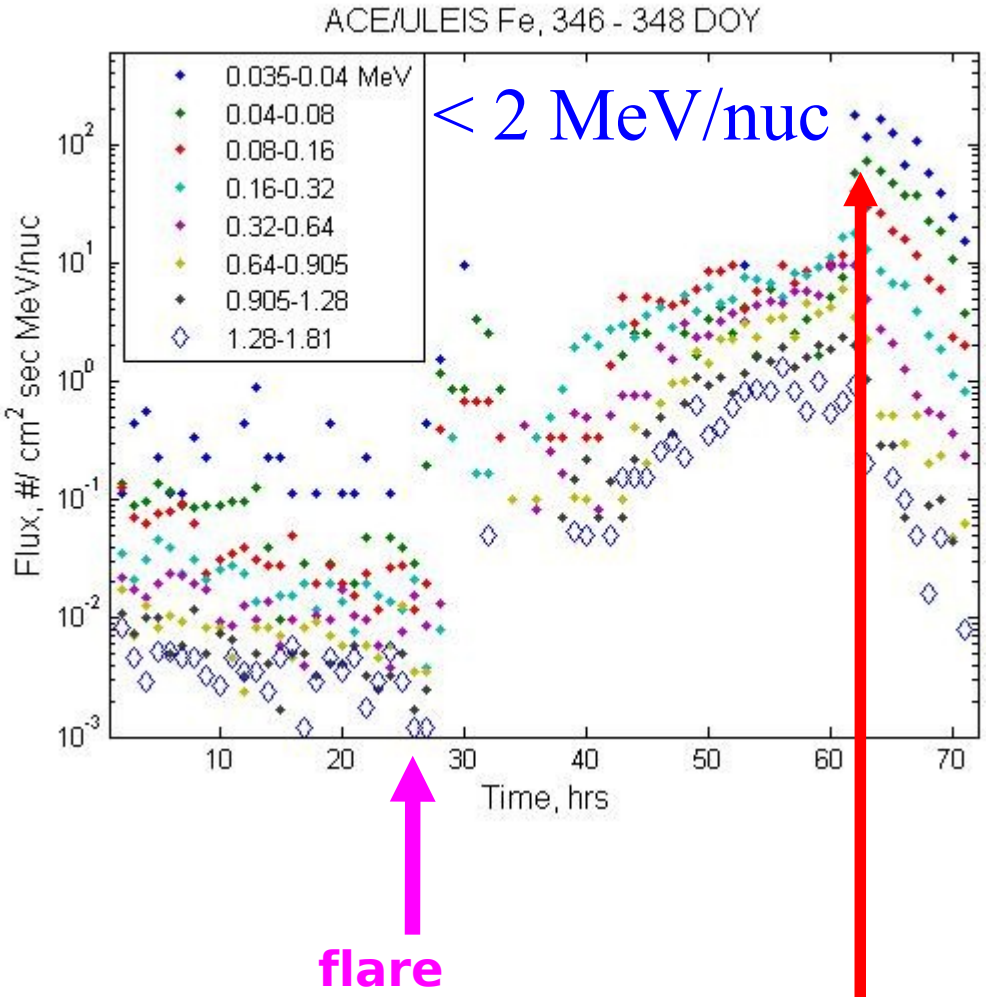
ESP Event (shock arrival at ACE: Dec. 14, ~1400 UT)

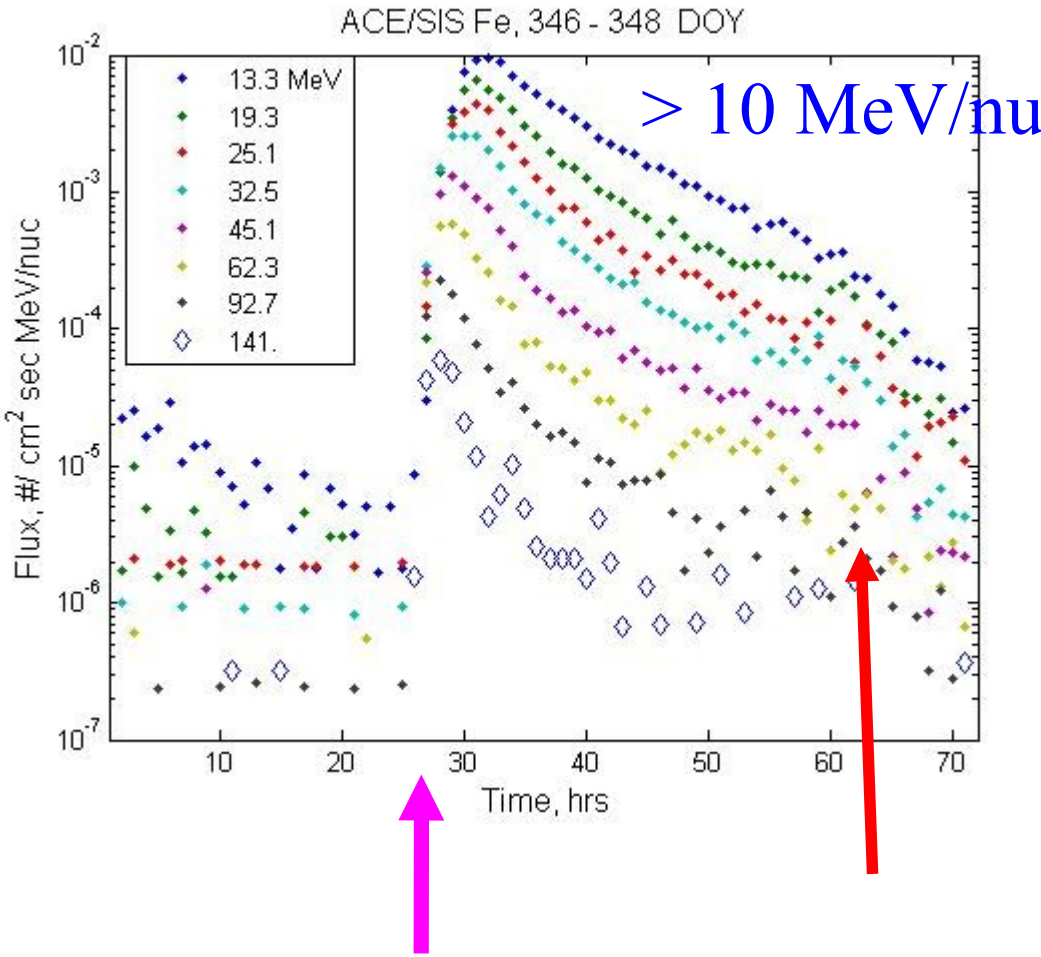

GOES Space Environment Monitor
GOES-12 Solar X-Rays (1-Min Avgs)
Watts/m²
XL
XS
GOES-12 Electrons and GOES-11 Protons & α-Particles (5-Min Avgs)
Particles/cm²sec sr
>1 MeV
I1
I2
E1
I3
I4
I5
I6
I7
>100 MeV
A5
A6
He
nT
GOES-12 Magnetic Field (1-Min Avgs, 75.4°W)
McMurdo Neutron Monitor (preliminary, hourly, % of monthly mean)
%
00:00
13
04:00
08:00
12:00
16:00
20:00
00:00
14
04:00
08:00
12:00
16:00
20:00
00:00
December 2006 (Universal Time)

GOES SEM Data Key

- XL 1 - 8 Å X-rays (Watts/m^2)
- XS 0.5 - 3 Å X-rays, or 0.5 – 4 Å prior to GOES-8 (Watts/m^2)
- E1 > 2 MeV (Electrons/cm^2 sec sr)
- I1 > 1 MeV (Protons/cm^2 sec sr)
- I2 > 5 MeV (Protons/cm^2 sec sr)
- I3 > 10 MeV (Protons/cm^2 sec sr)
- I4 > 30 MeV (Protons/cm^2 sec sr)
- I5 > 50 MeV (Protons/cm^2 sec sr)
- I6 > 60 MeV (Protons/cm^2 sec sr)
- I7 > 100 MeV (Protons/cm^2 sec sr)
- A5 150-250 MeV, 160-260 prior to GOES-8 (α-particles/cm^2 sec sr MeV)
- A6 300-500 MeV, 330-500 prior to GOES-8 (α-particles/cm^2 sec sr MeV)
- H_P Perpendicular to orbital plane (nanotesla)
- H_E Earthward (nanotesla)
- H_N Normal to H_P and H_E.
- △ Satellite Local Noon
- ▲ Satellite Local Midnight

ACE observations: Fe ions





flare

Energy ranges are in MeV/nuc

Approximate shock arrival time.

Particle Acceleration and Transport in the Heliosphere Code (PATH)

PATH model:

- SW modeling: initialization of the code;
- MHD shock modeling: boundary conditions at 0.1 AU -> main features of a shock dynamics;
- Seed particles: flare + SW particles;
- DSA at a quasi-parallel shock (*Lee, 1983; Gordon et al., 1999)*;

$\kappa_{\wp}$

PATH model:

- **New:** DSA at an oblique shock:

$$\kappa = \kappa_{\parallel} \cos^2\theta + \kappa_{\perp} \sin^2\theta$$

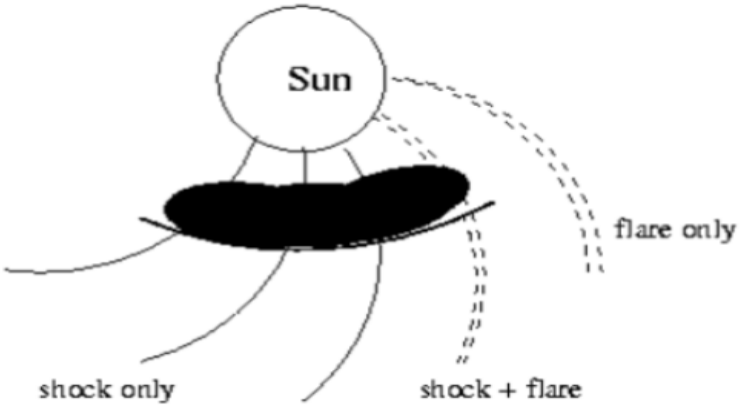
fixed shock angle

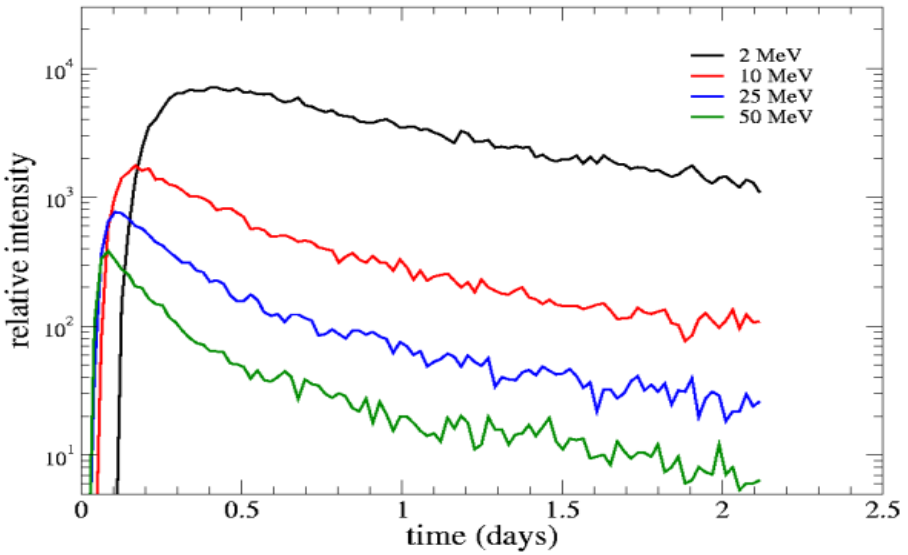
- Transport to 1 AU (mfp is function of p and r);

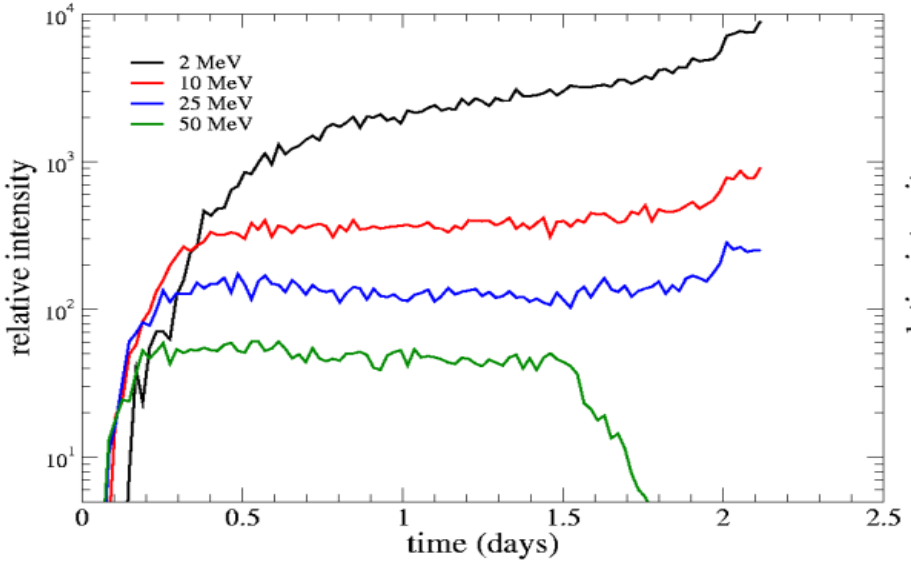
$$\lambda = \lambda_0 \left(\frac{pc}{1\mathrm{GeV}}\right)^{1/3} \left(\frac{r}{1\mathrm{AU}}\right)^{2/3}$$

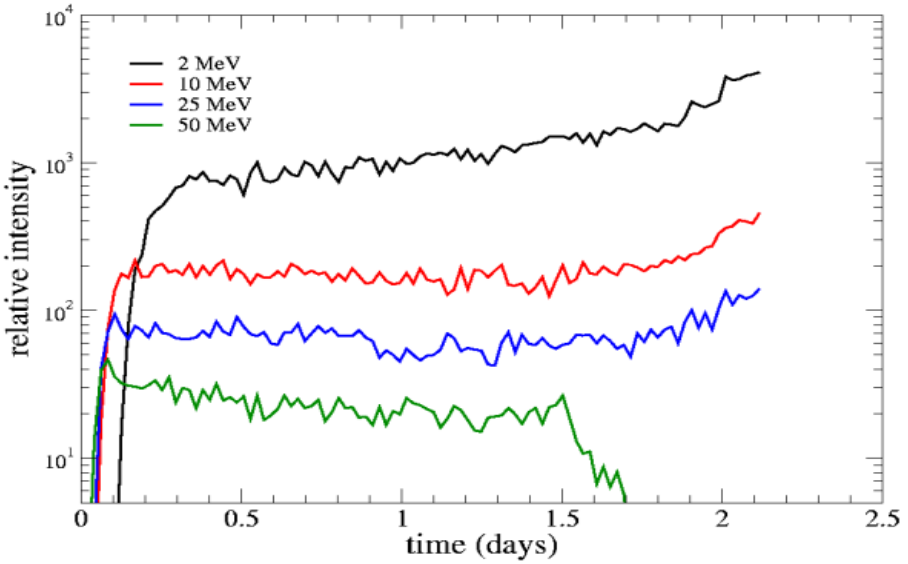
(Zank et al., 2000; Li et al., 2003; 2005; Matthaeus et al., 2004; Zank et al., 2004; 2007)

Modeling the 3 possibile cases:









From Li and Zank, GRL, 2005

Input of the PATH model

- SW model/background
- MHD shock
- Shock obliquity
- Injection with energy (10 keV) and efficiency (1% flux density)
- Ratio of Q/M for seed particles
- Flare parameters

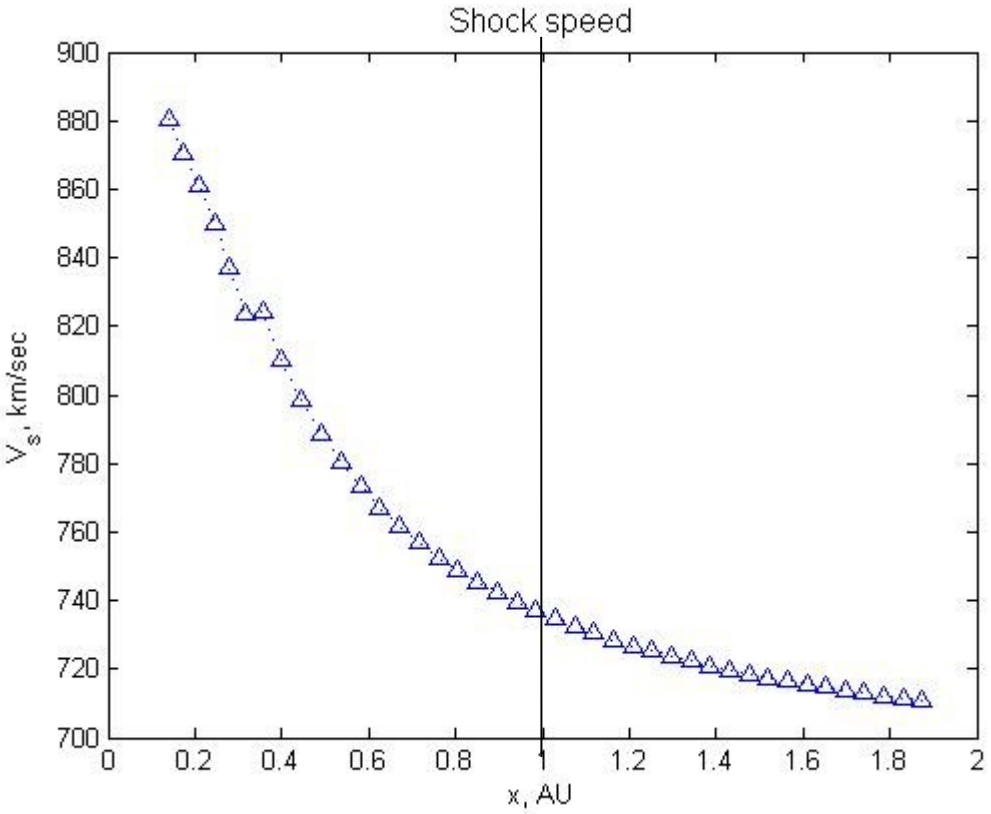
(Zank et al., 2000; Li et al., 2003; 2005; Zank et al., 2007)

Shock parameters at 1 AU (derived from ACE observations):

Compressional ratio: 3.0 +/- 0.3
Upstream SW speed: 650 +/- 30 km/sec;
Shock speed: 800 +/- 50 km/sec;
Arrival time ~ 35 hrs
Theta_Bn ~ 30;

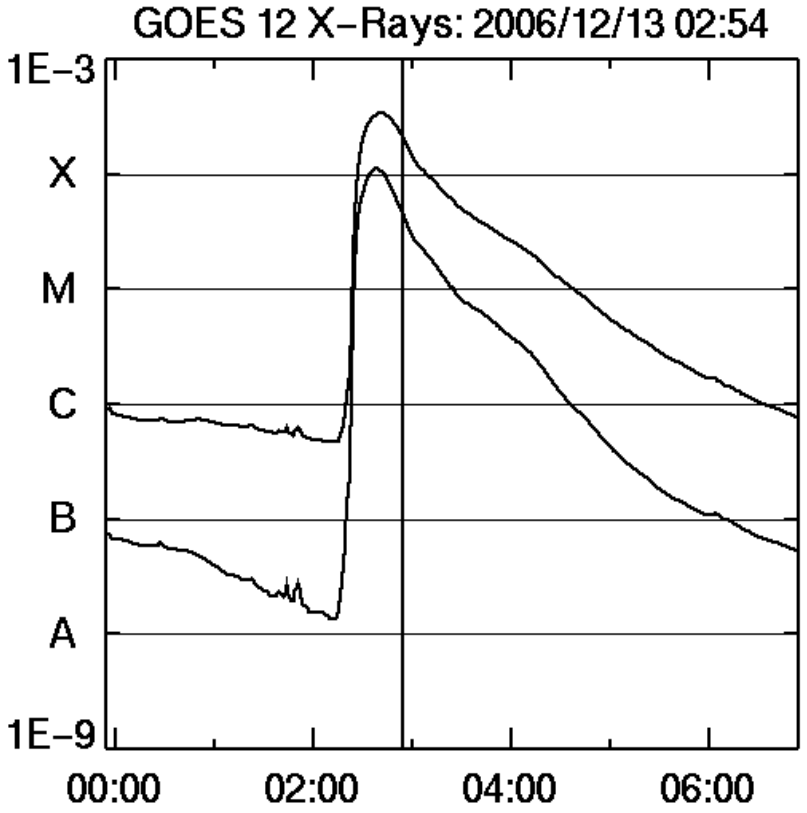
Model (at 1 AU):

Compressional ratio: 2.8
Upstream SW speed: 650 km/sec;
Shock speed: 730 km/sec;
Arrival time ~ 49 hrs



Flare parameters:

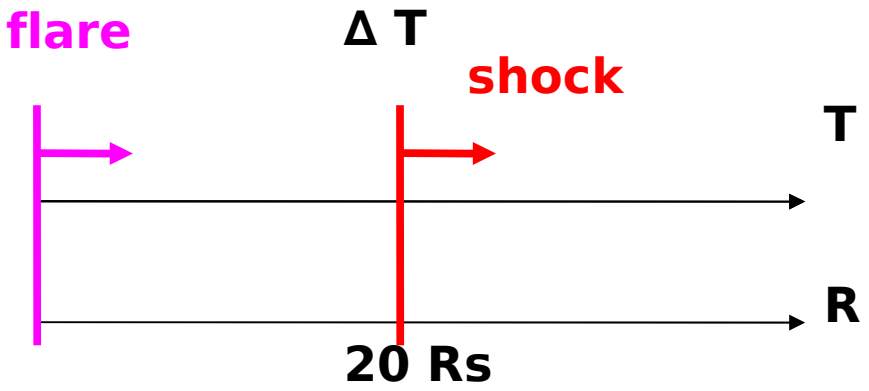
The flare starts at 02:14:00 UT on Dec. 13 and ends at 02:57:00 UT.
The duration is ~43 min. Peak intensity (X3.4) is at ~02:40:00 UT.



Input for the code:

- duration of 2580 sec.
- max particle energy: 1GeV
- particle spectra ~$p^{-4.5}$
- ratio of Q/M for seed particles: Q[Fe]=16;
- flare to SW particles ratio: variable
- new: delay between start of the flare and launch of the CME: 40 min;

Delay between start of the flare and launch of the CME at 0.1 AU



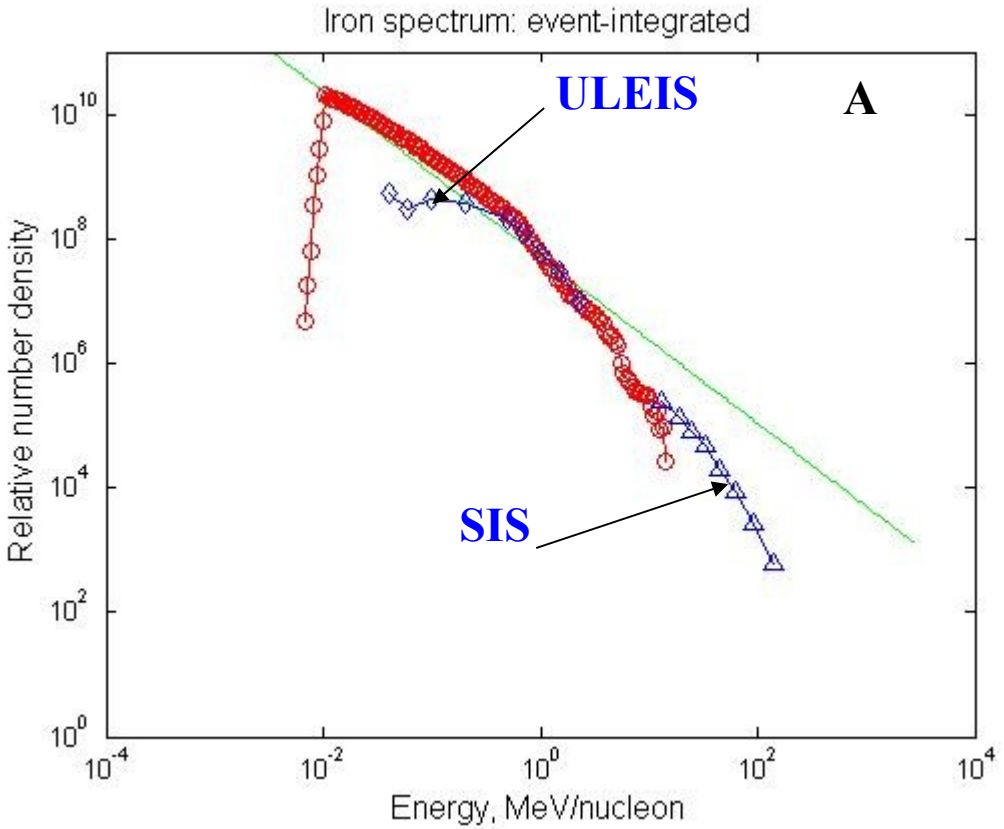
Output of the PATH model (at 1 AU)

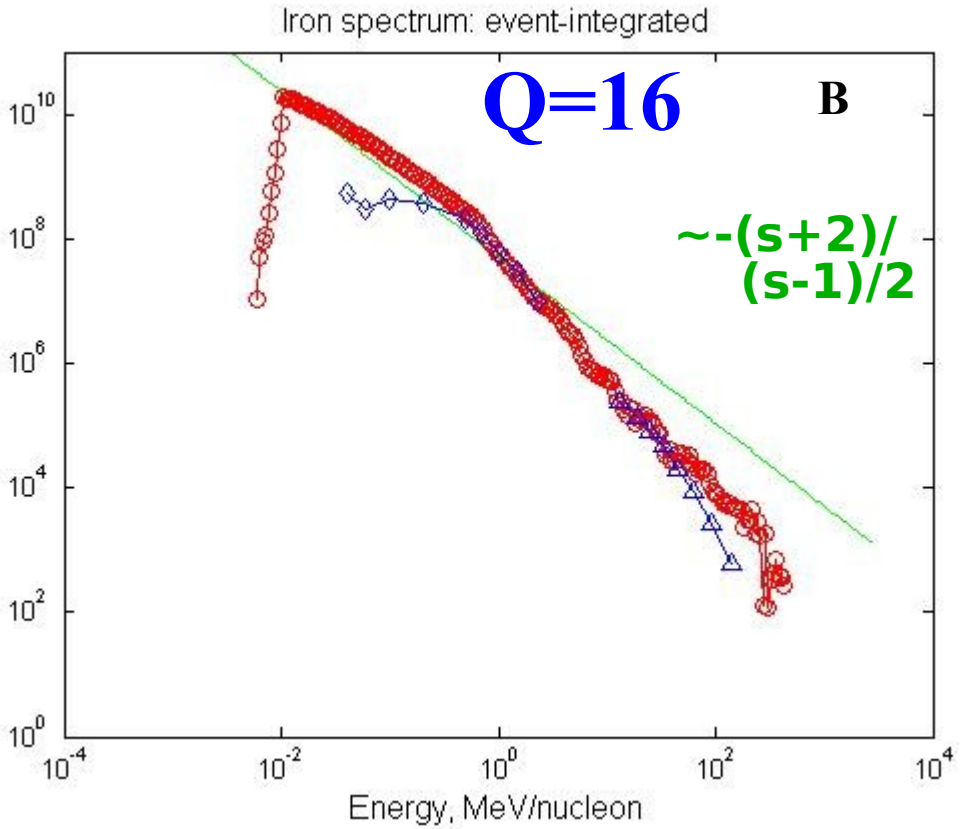
- Spectra of protons and heavy ions
- Time-intensity profiles of protons and heavy ions
- Comparison with satellite measurements at 1 AU
- Energy- and time-dependent abundance ratios: Fe/O, etc.

- **Can we model the main features of the mixed SEP event?**
- **Can we capture the main physics?**

Spectra: ratio of flare to SW particles

Event-integrated spectra of Fe ions (~ 50 hrs):





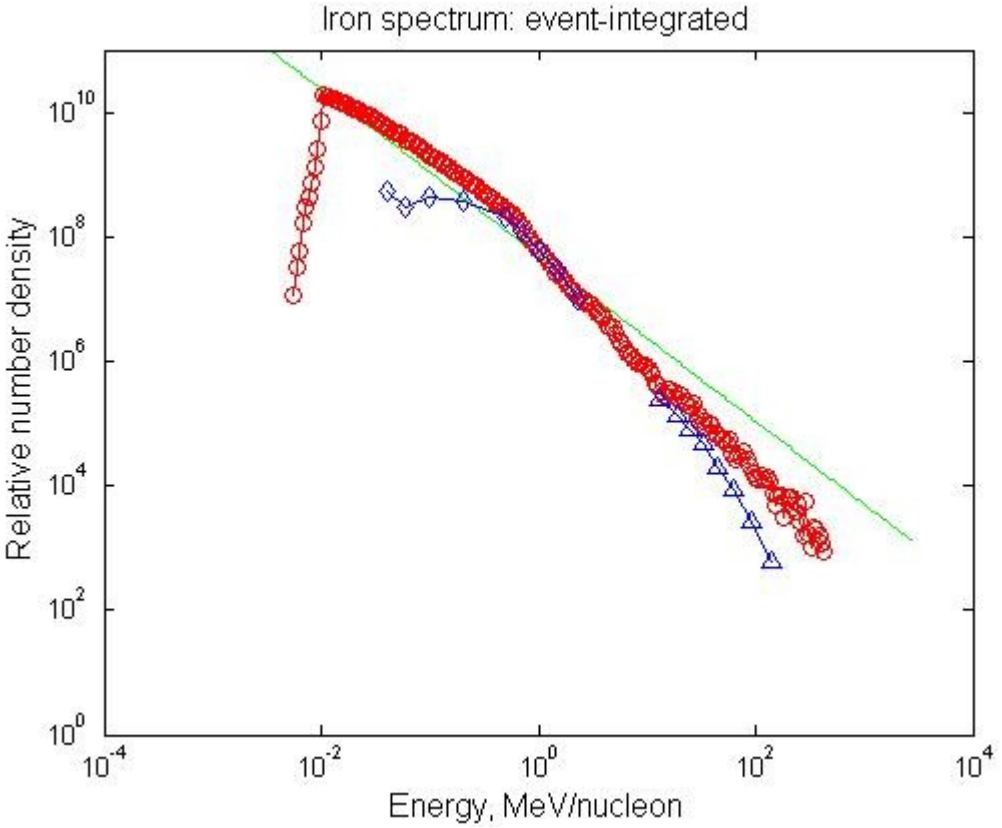
Seed population:

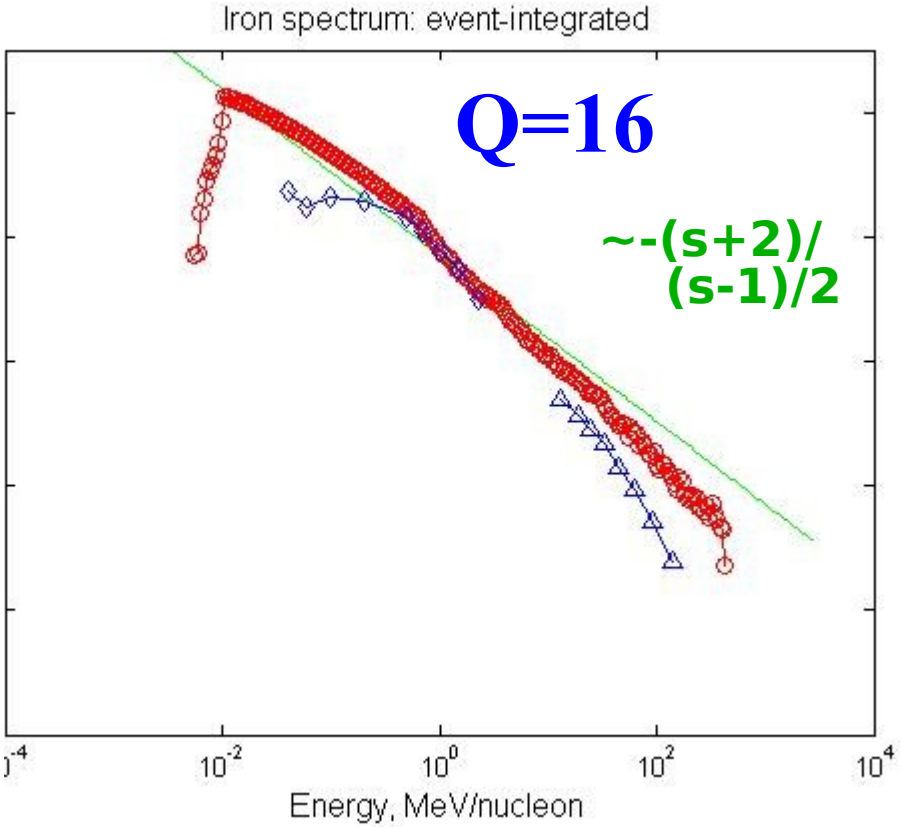
A – shock only

B – 25% flare particles

Role of flare particles: influence the high-energy part of the particle spectra

Event-integrated spectra of Fe ions (~ 50 hrs):





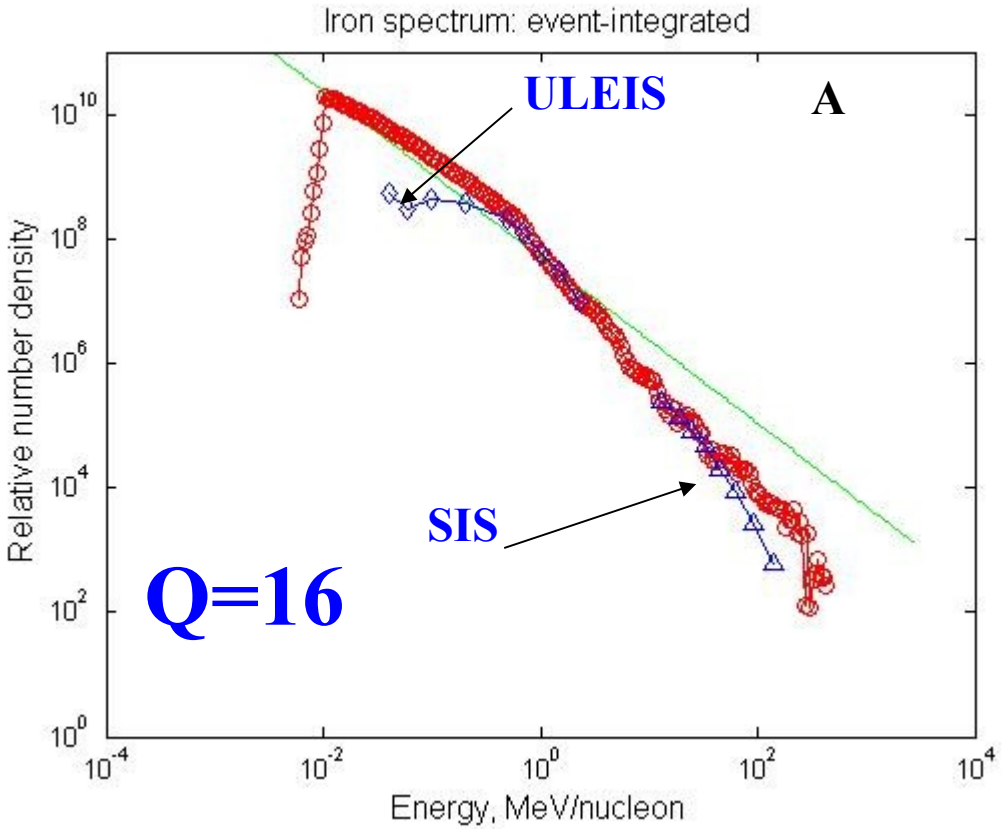
Seed population:

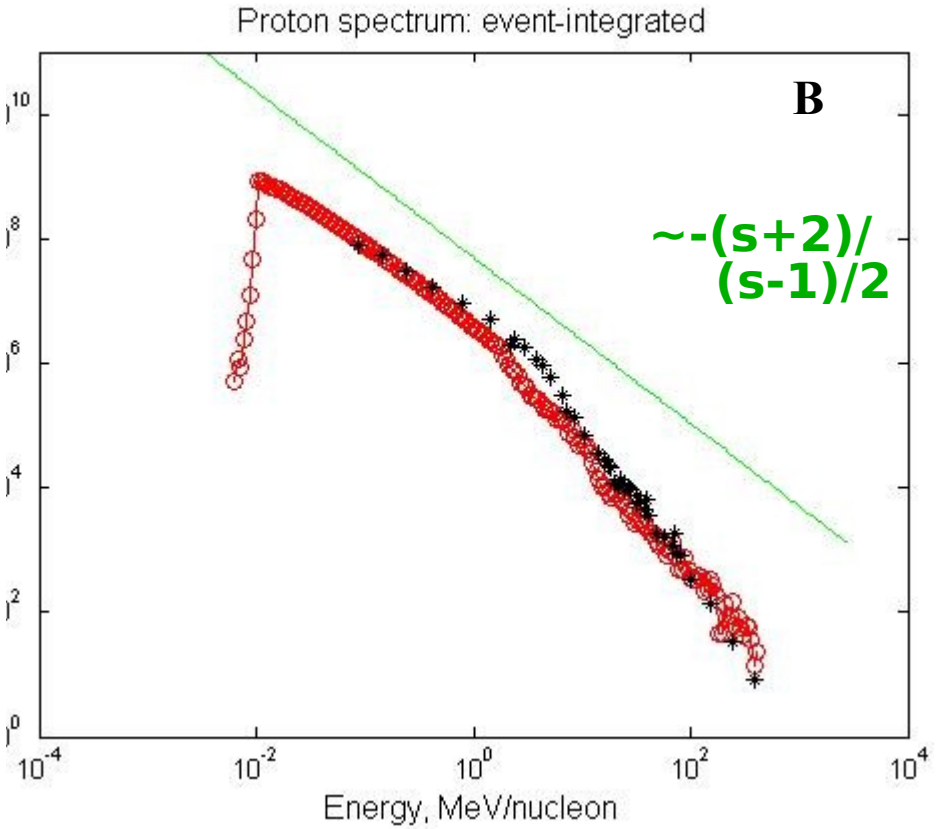
Emax ~$(Q/A)^2$

C – 45% flare particles

D – 75% flare particles

Event-integrated spectra (~ 50 hrs)**:**





IRON **PROTONS**

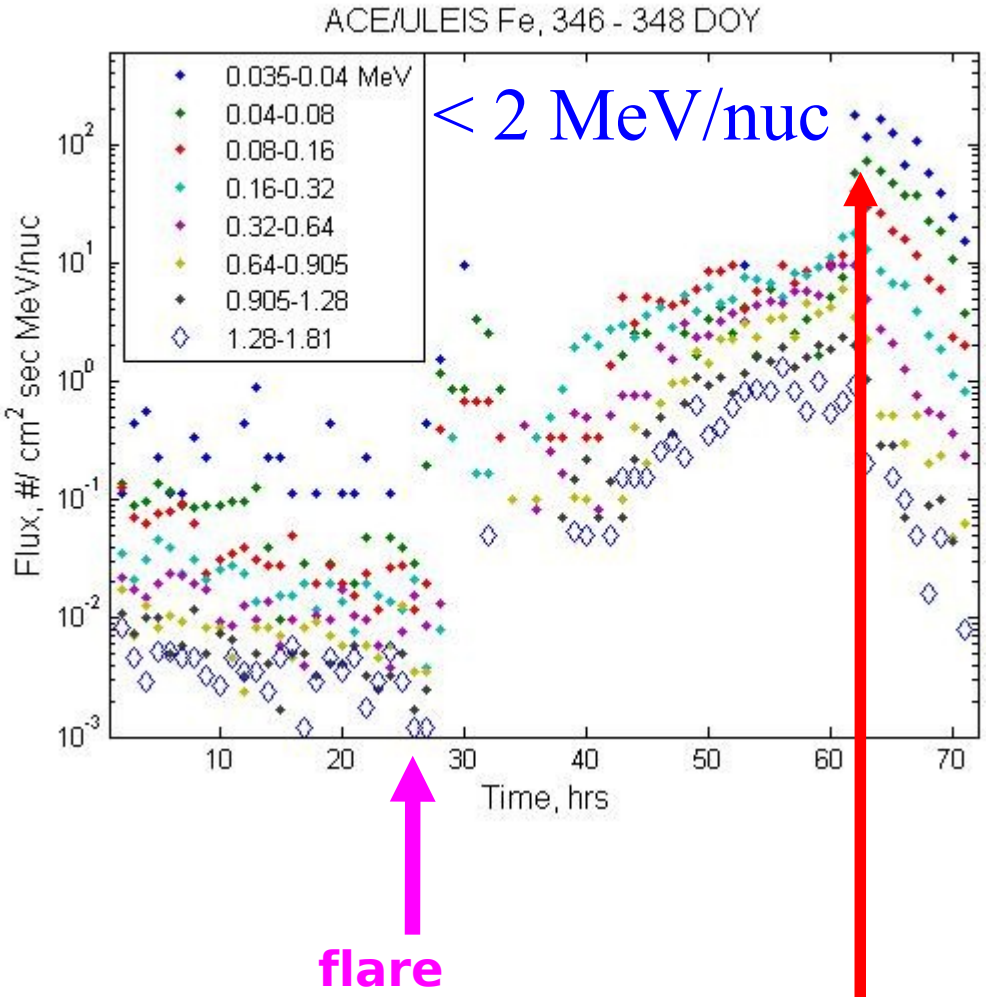
25% flare particles

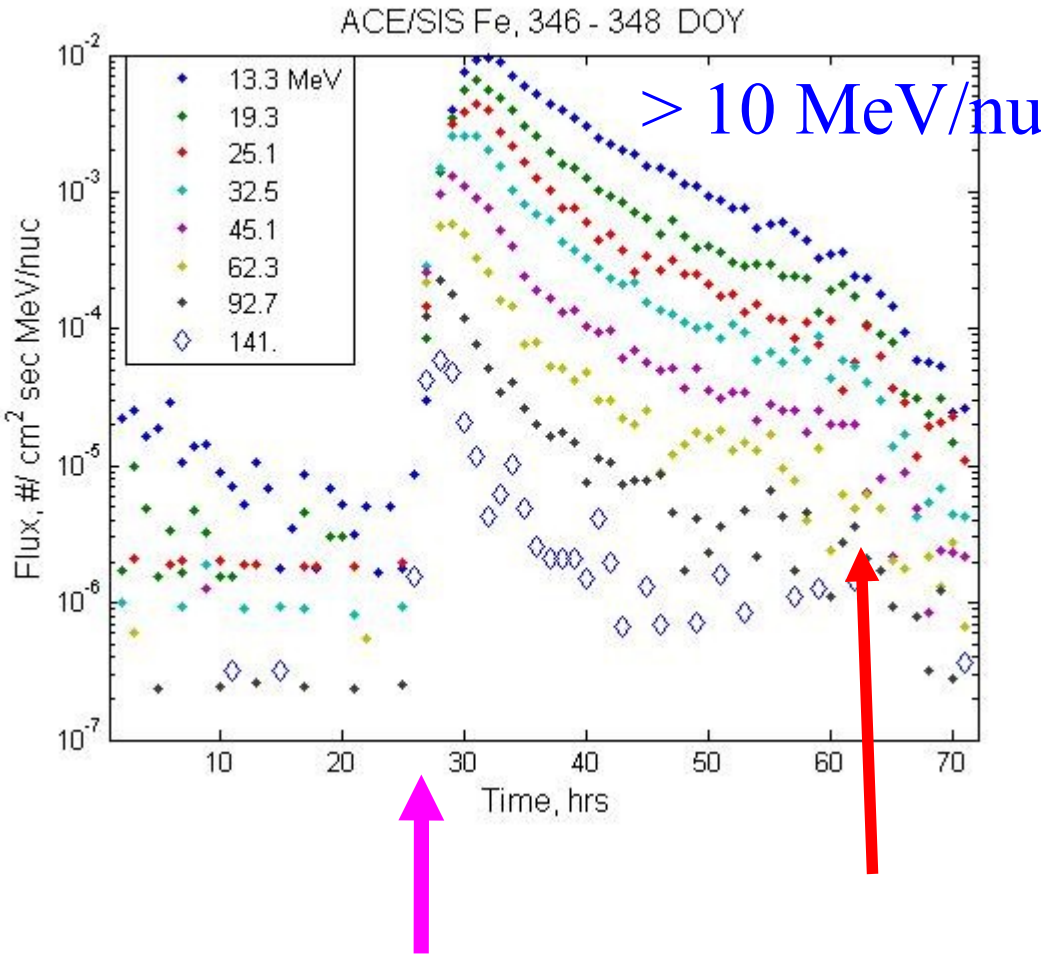
ACE, STEREO, GOES and

SAMPEX (by R. Mewaldt)

Intensities

ACE observations: Fe ions





flare

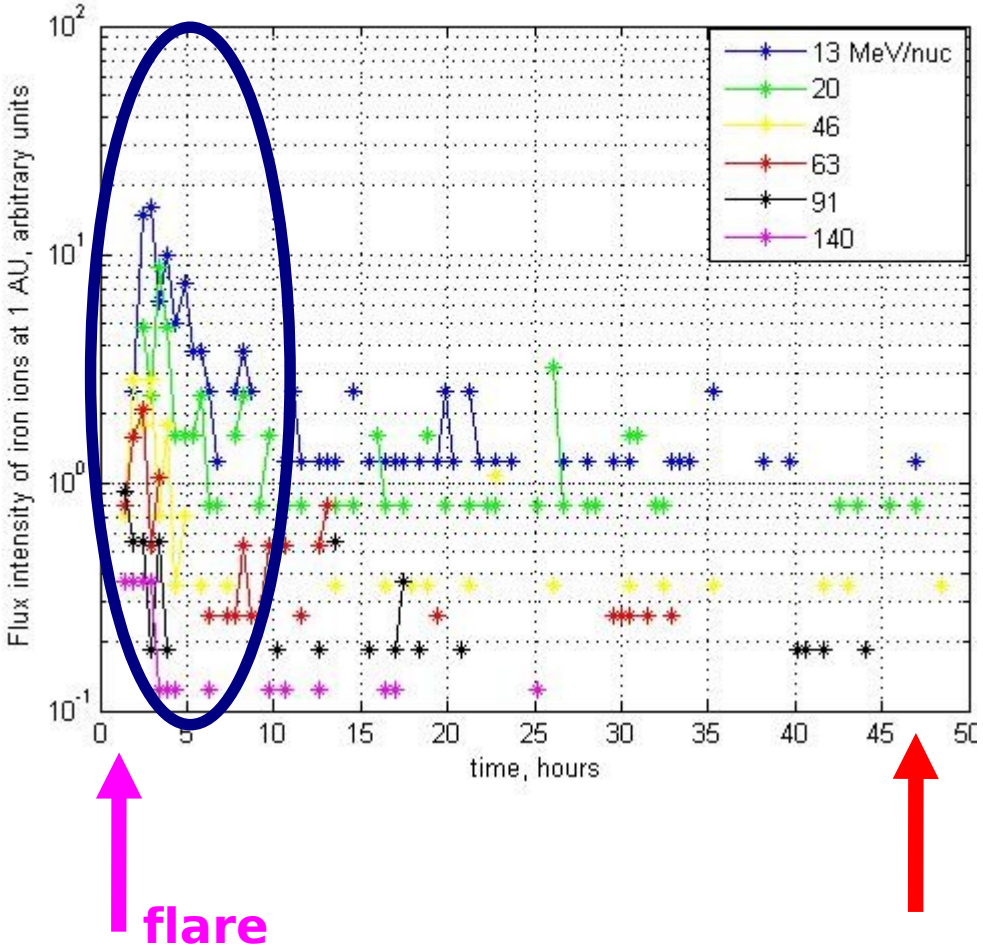
Energy ranges are in MeV/nuc

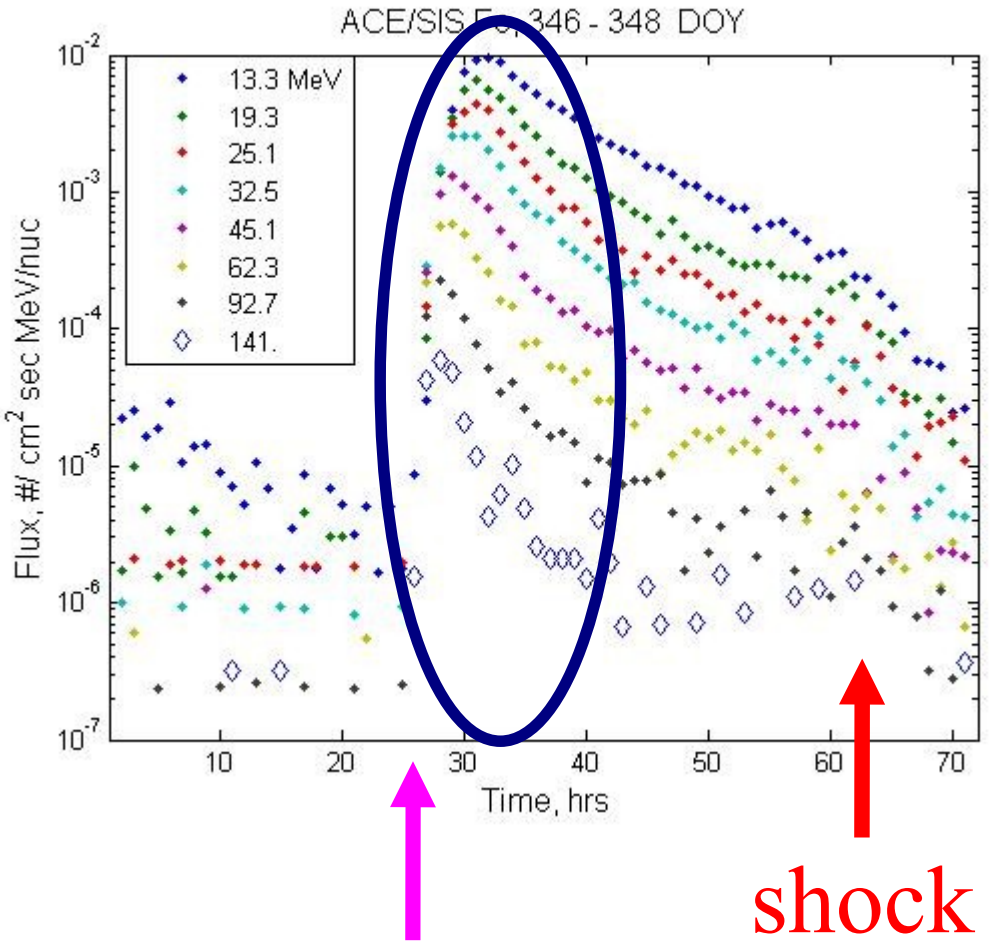
Approximate shock arrival time.

High-energy range
(E>20 MeV)

Fluxes of iron ions

delay ~ 40 min





flare

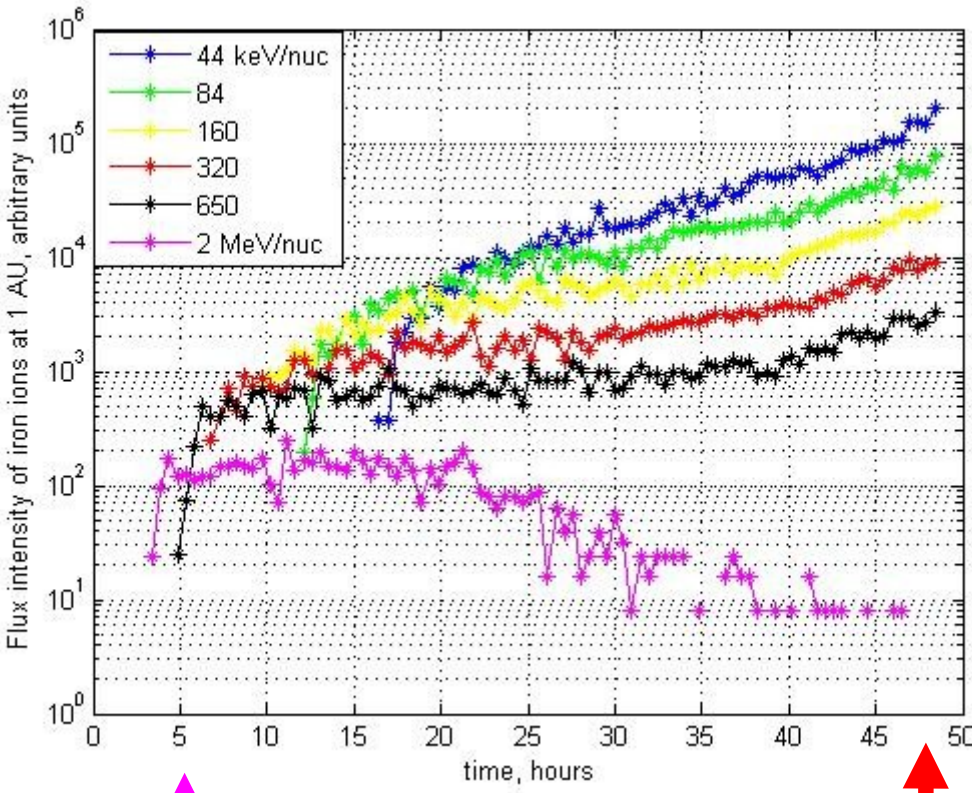
shock

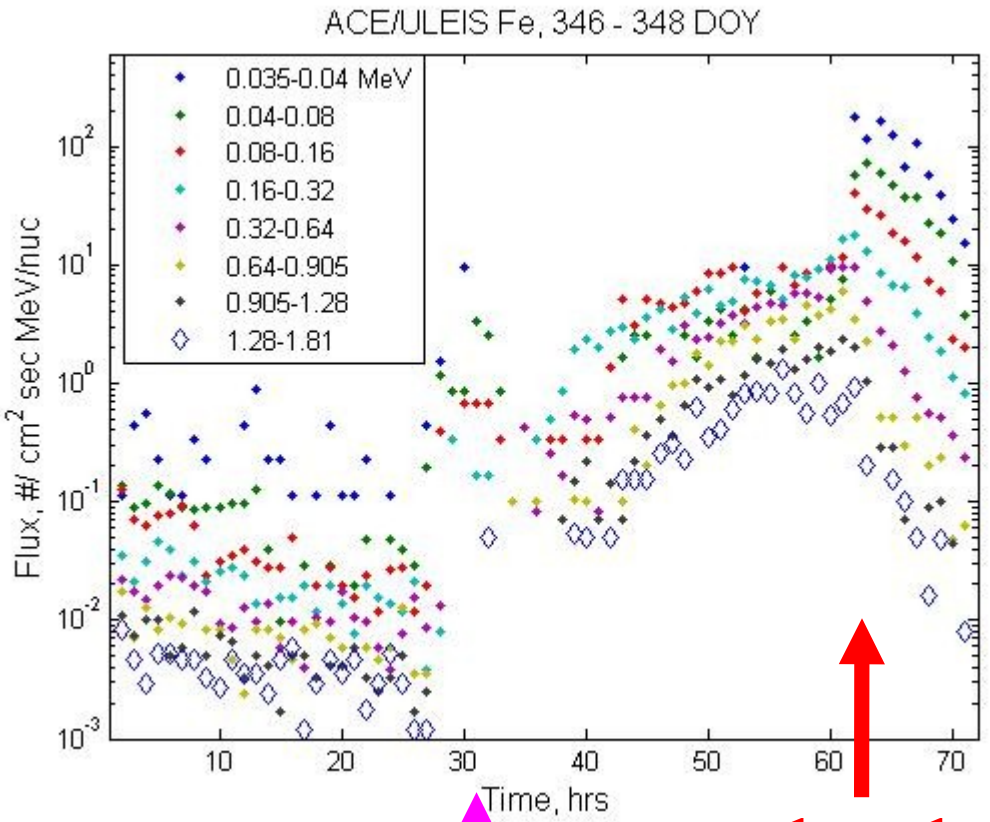
Model: 25% flare particles

Low-energy range
(E< 2 MeV)

Fluxes of iron ions
Q[Fe]=16

delay ~ 40 min





shock

Model: 25% flare particles

Conclusions:

- A time-dependent 1D model of an oblique shock propagation, local particle injection, DSA and non-diffusive transport in the IP medium is applied to explain observations of the large SEP event of Dec. 13, 2006.
- Modeling results describe contribution from both flare and shock-accelerated particles.
- Based on the PATH model we can describe/understand main features of ion spectra and intensity profiles.
- Currently our model is being extended to 2D/3D geometry (oblique shock configuration) with perpendicular diffusion included.

Further study & collaboration:

- Verify our model by using low- and high-energy proton and heavy ion measurements by ACE, STEREO, GOES and SAMPEX (*C. Cohen, R. Mewaldt, G. Mason, T. von Rosenvinge, M. Looper*), and justify values of free parameters
- Study spectral breaks/rollovers for different ion species (*R. Mewaldt, M. Lee*);
- Vary ratio of flare/SW particles to verify transport model and fit observed time-intensity profiles (*H. Cane, R. Mewaldt*);
- Model different abundance ratios (Fe/O, etc.) (*C. Cohen);*
- Organize profiles for different species by velocity or by rigidity (*G. Mason*)