SRPENTINE Symposium Particle Acceleration and Transport from heliospheric perspective, Toulouse, June 27-28, 2023

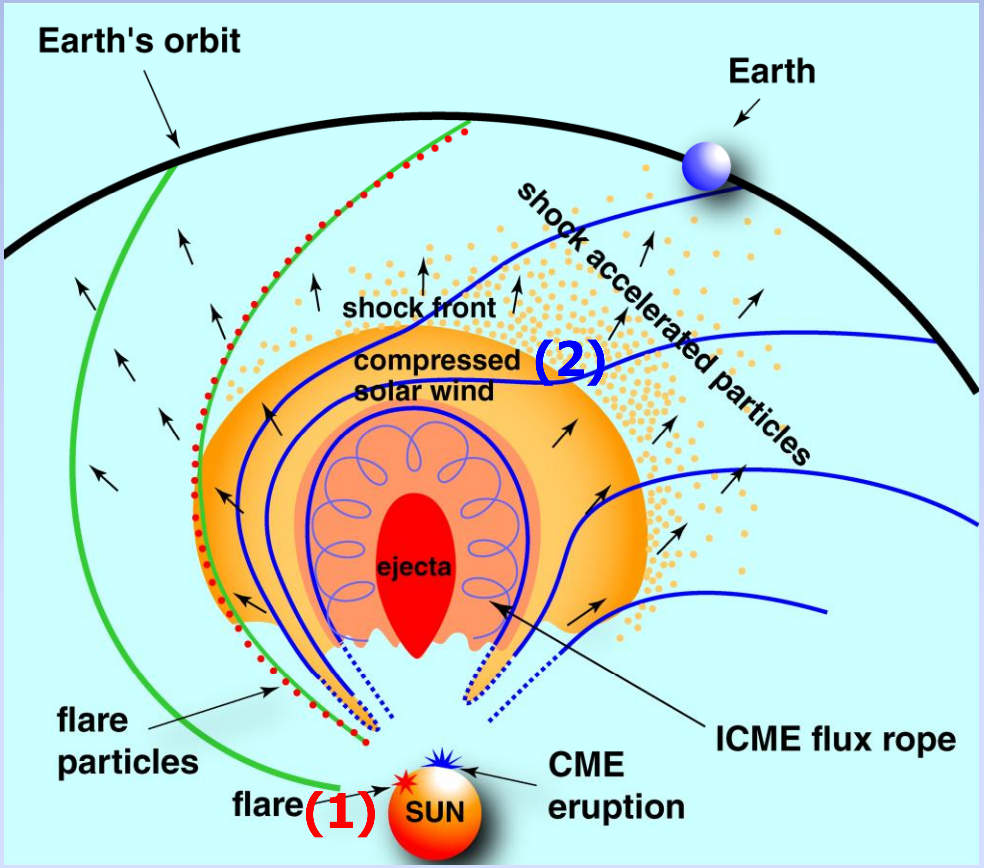
MODELING OF ENERGETIC PARTICLE TRANSPORT AND ACCELERATION BY A BLAST WAVE PROPAGATING IN A SPIRAL MAGNETIC FIELD

Y.Kartavykh [1,2] (CAU), W. Dröge [2] , D.Trotta [3]

(1) University of Kiel (CAU), (2) University of Würzburg,
(3) Imperial College (London)

This study has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101004159 (SERPENTINE).

energetic particles in the Heliosphere



**classical picture:
e.g., Reames (1999)**

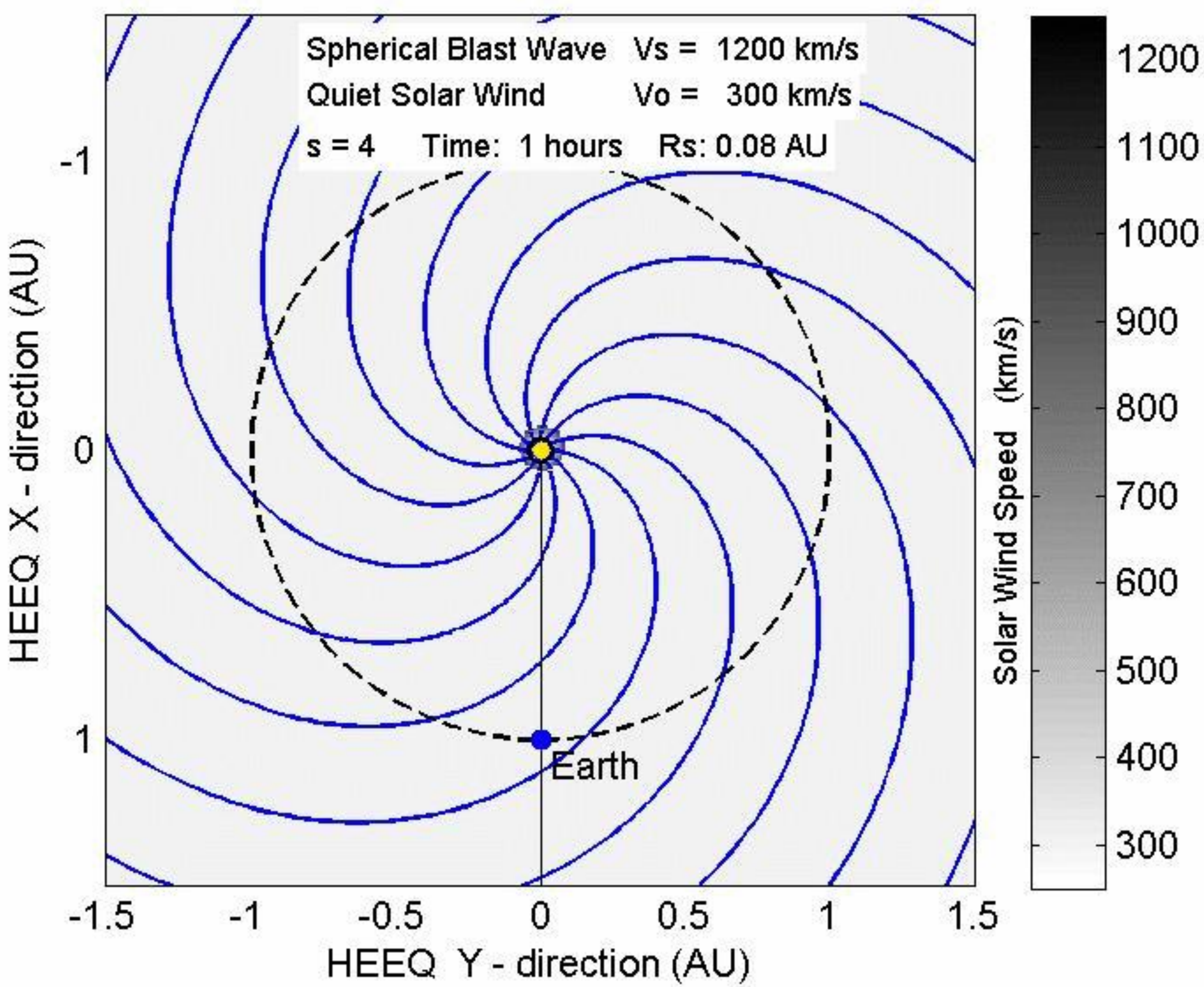
(1) impulsive events
- localized source (flare)
- electron-rich
- ^{3}He-rich

(2) gradual events
- extended source (shock / CME)
- high ion flux
- lower e/p ratio

(3) mixed events – seed flare particles +shock-accelerated (Cane et al., 2003)

realistic transport models required to reconstruct particle properties at the Sun from spacecraft observations:

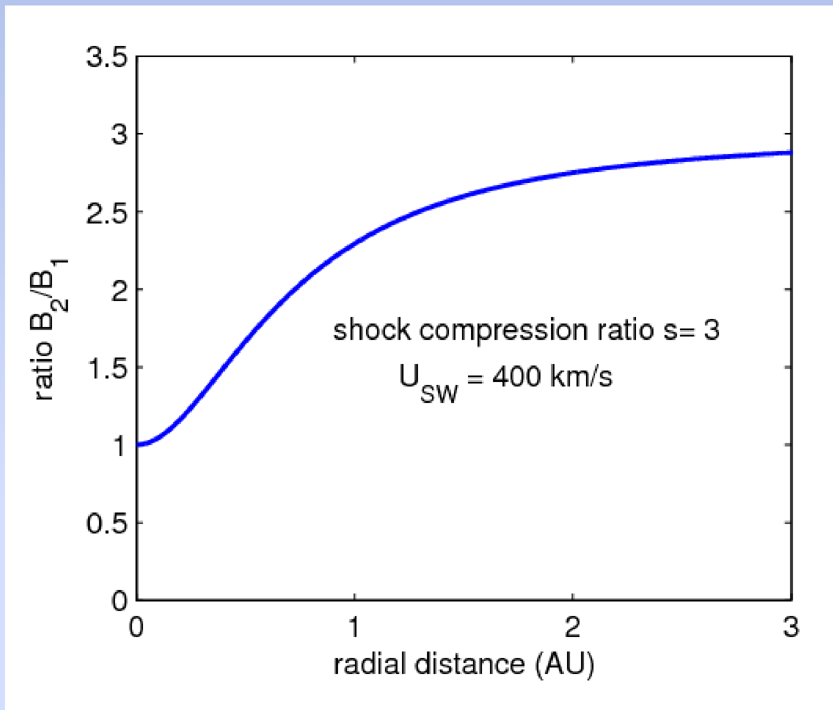
acceleration time scales, energy and charge spectra, PAD, relation to electromagnetic emission close to the Sun (radio, X-ray, gamma-ray)



Spherical Blast Wave Vs = 1200 km/s
Quiet Solar Wind Vo = 300 km/s
s = 4 Time: 1 hours Rs: 0.08 AU
-1
0
1
HEEQ X - direction (AU)
-1.5
-1
-0.5
0
0.5
1
1.5
HEEQ Y - direction (AU)
Earth
Solar Wind Speed (km/s)
1200
1100
1000
900
800
700
600
500
400
300

Blast wave in spiral magnetic field

Parker, ApJ, 1961, 133, 1014



$$B_r = B_0 \left(\frac{r_\odot}{r}\right)^2$$

$$B_\varphi = \frac{\Omega r_\odot}{U_{SW}} B_0 \left(\frac{r_\odot}{r}\right) sin\theta$$

If $r > R_{sh}$ – standard Parker field

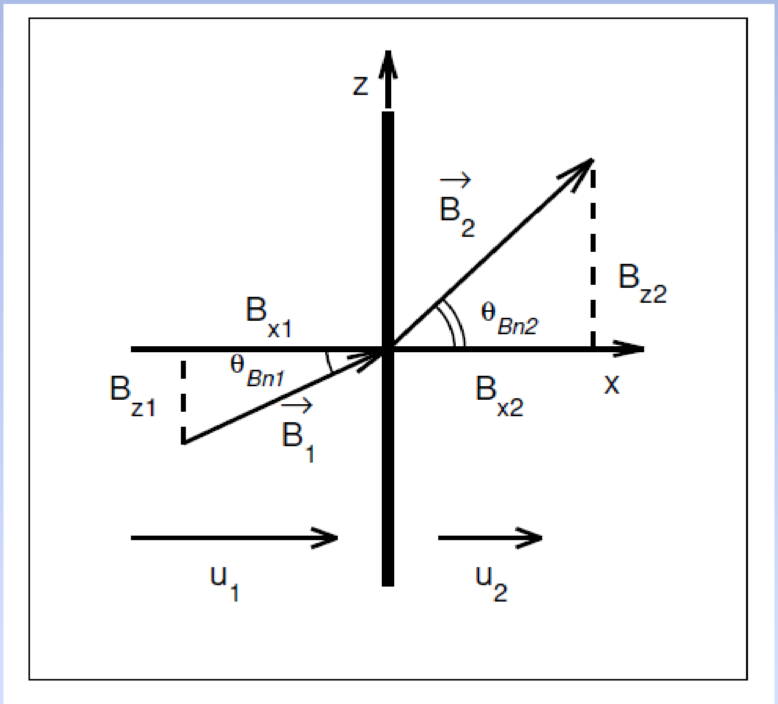
If $r = R_{sh}$ – jump in B_φ , if $r < R_{sh}$ then

$$B_\varphi = B_0 \frac{\Omega r_\odot^2 S\, sin\theta}{U_{SW} R_{sh}} \left(\frac{r}{R_{sh}}\right)^2$$

B_r – same as for $r > R_{sh}$

Simulations are performed in the de Hoffmann-Teller frame

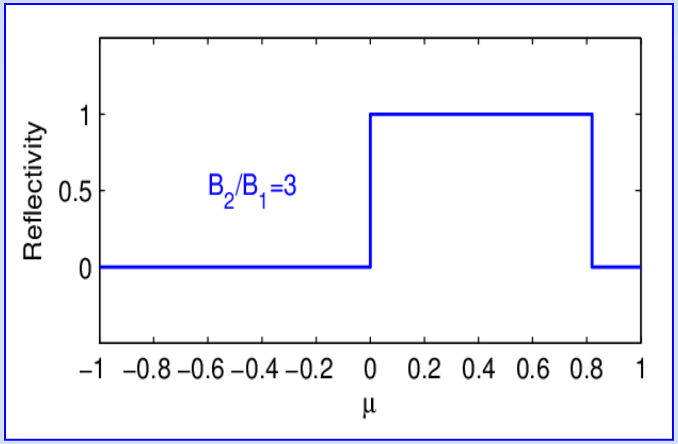
Oblique shock



Compression ratio S

$$S = \frac{B_{z2}}{B_{z1}} = \frac{u_1}{u_2}$$

Reflection when particles go from upstream to downstream is added. If first adiabatic invariant is conserved than



$$\mu_1^2 \geq 1 - \frac{B_1}{B_2}$$

particles go from upstream to downstream and

$$\mu_2^2 = 1 - \frac{B_2}{B_1}(1 - \mu_1^2)$$

$$\mu_1^2 = 1 - \frac{B_1}{B_2}(1 - \mu_2^2)$$

particles go from downstream to upstream with changing PA

The Fokker-Planck equation will be in this case:

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial s} + \frac{1-\mu^2}{2L} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu} D_{\mu\mu} \frac{\partial f}{\partial \mu} = q(s,\mu,t)$$

Stochastic differential equations for changes in s and μ

$$d\,\vec{s}(t) = \mu v\, dt\, \vec{e_s}$$

$$d\mu = \sqrt{D_{\mu\mu}}\, dW_\mu(t) + \left(\frac{v}{2L}(1-\mu^2) + \frac{\partial D_{\mu\mu}}{\partial \mu}\right) dt$$

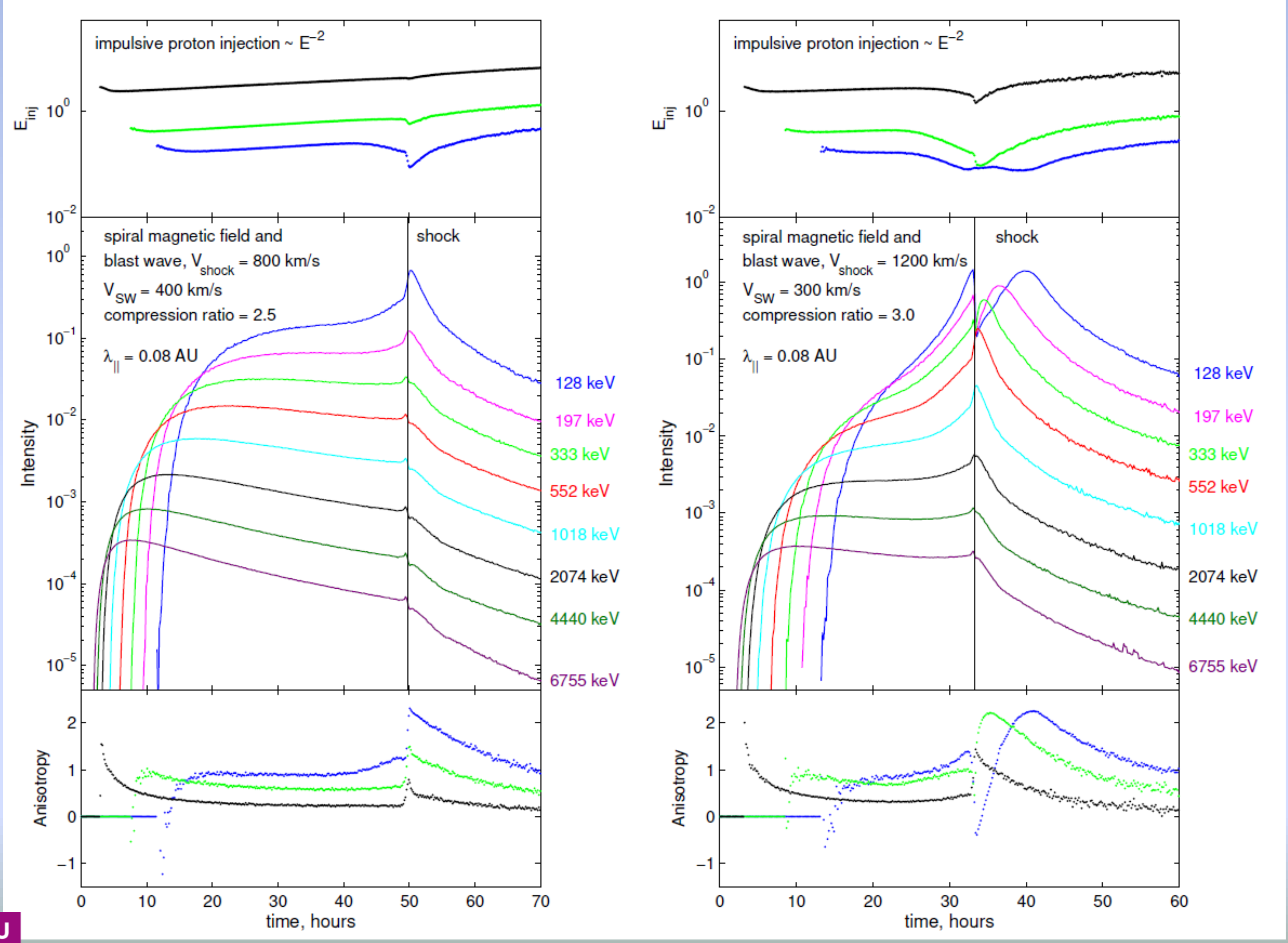
$$D_{\mu\mu} = k_0(r,R)\{|\mu|^{q-1} + H\}(1-\mu^2)$$

The pitch angle diffusion coefficient

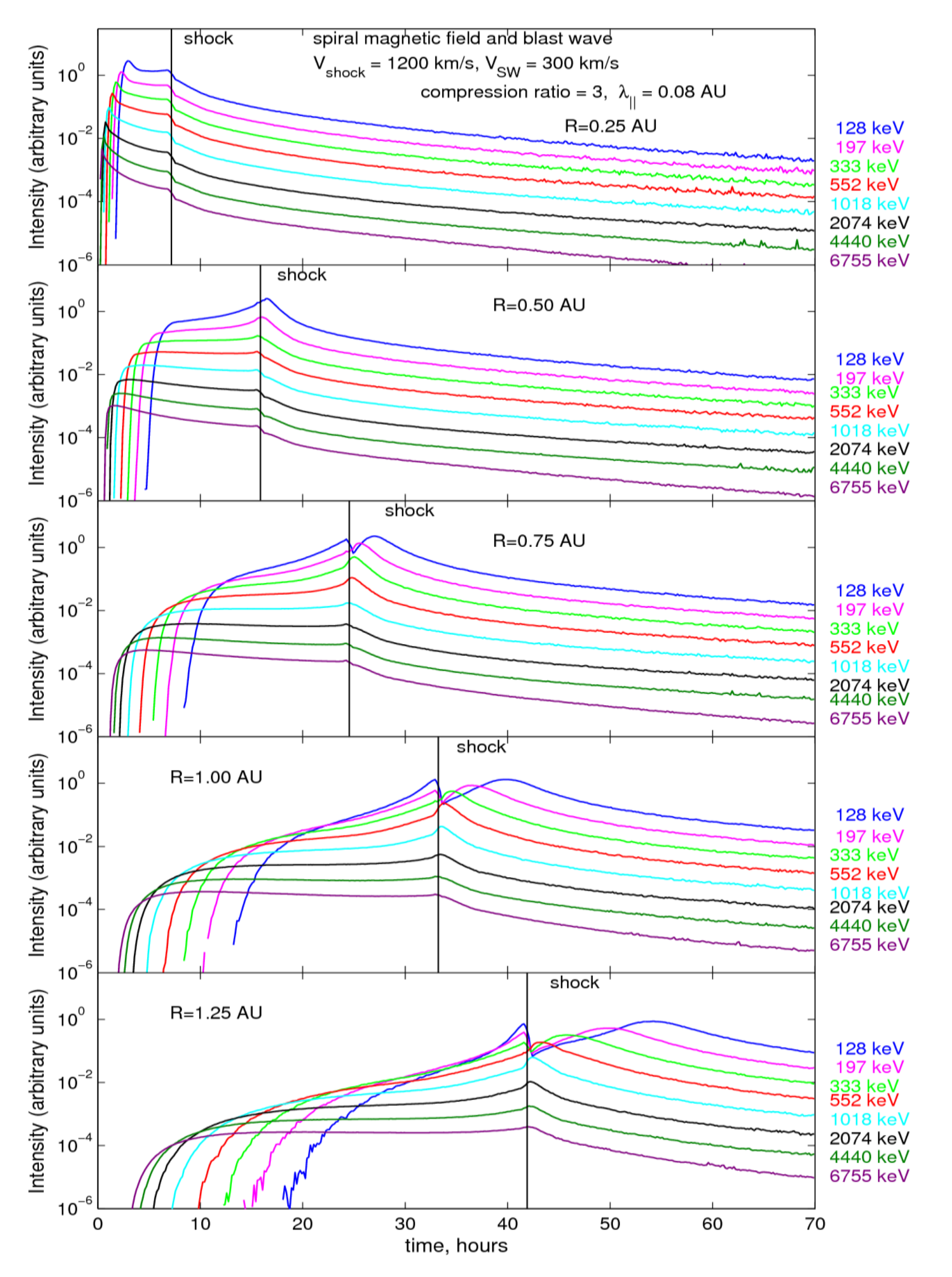
$$\frac{\partial b_i}{\partial x_i} \equiv -\frac{1}{L} = \frac{1}{B}\frac{dB}{d\xi}$$

Convection and energy changes are included implicitly through the transformation between fluid/magnetic field lines systems (Kocharov et al., 1998; Vainio, Kocharov, Laitinen, 2000).

Depending on the parameters – profiles contain either 1 or 2 peaks at low energies



Development of time profiles with radial distance



Effect of shock speed and compression ratio (left – also effect of dV is involved (will be shown separately below)

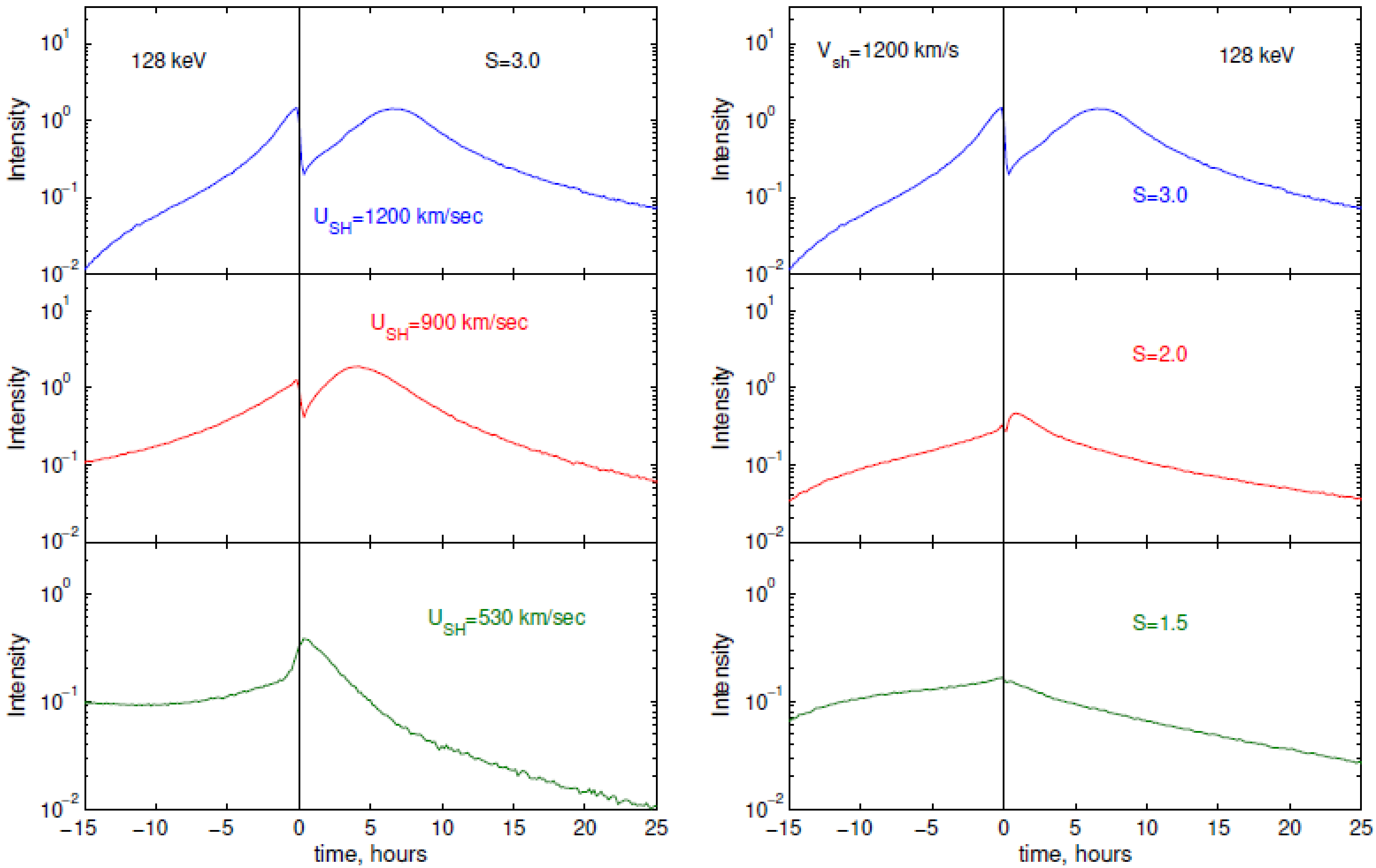


Figure 8. The dependence of profiles at 128 keV on the shock speed and compression ratio

Effect of dV and mean free path

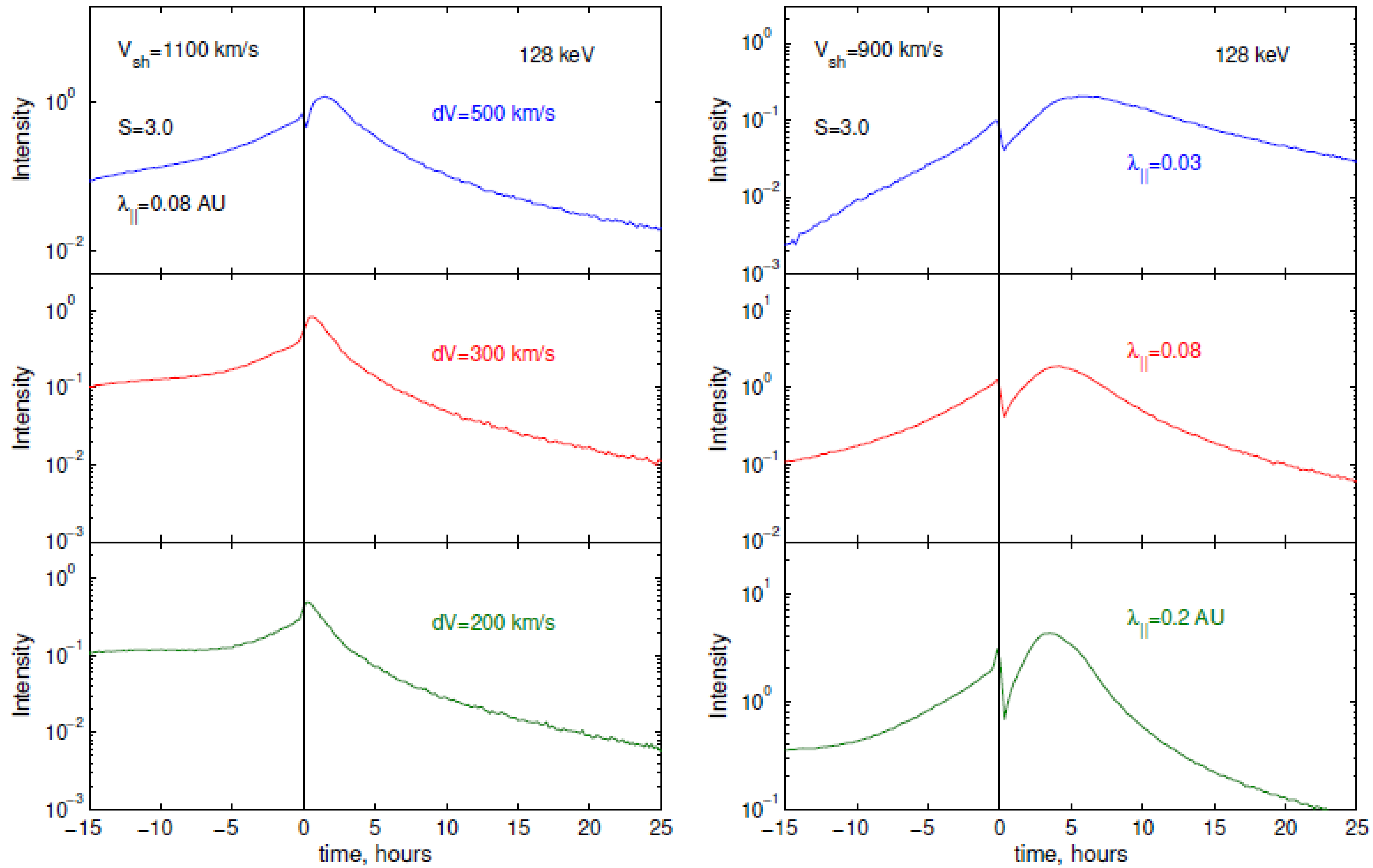
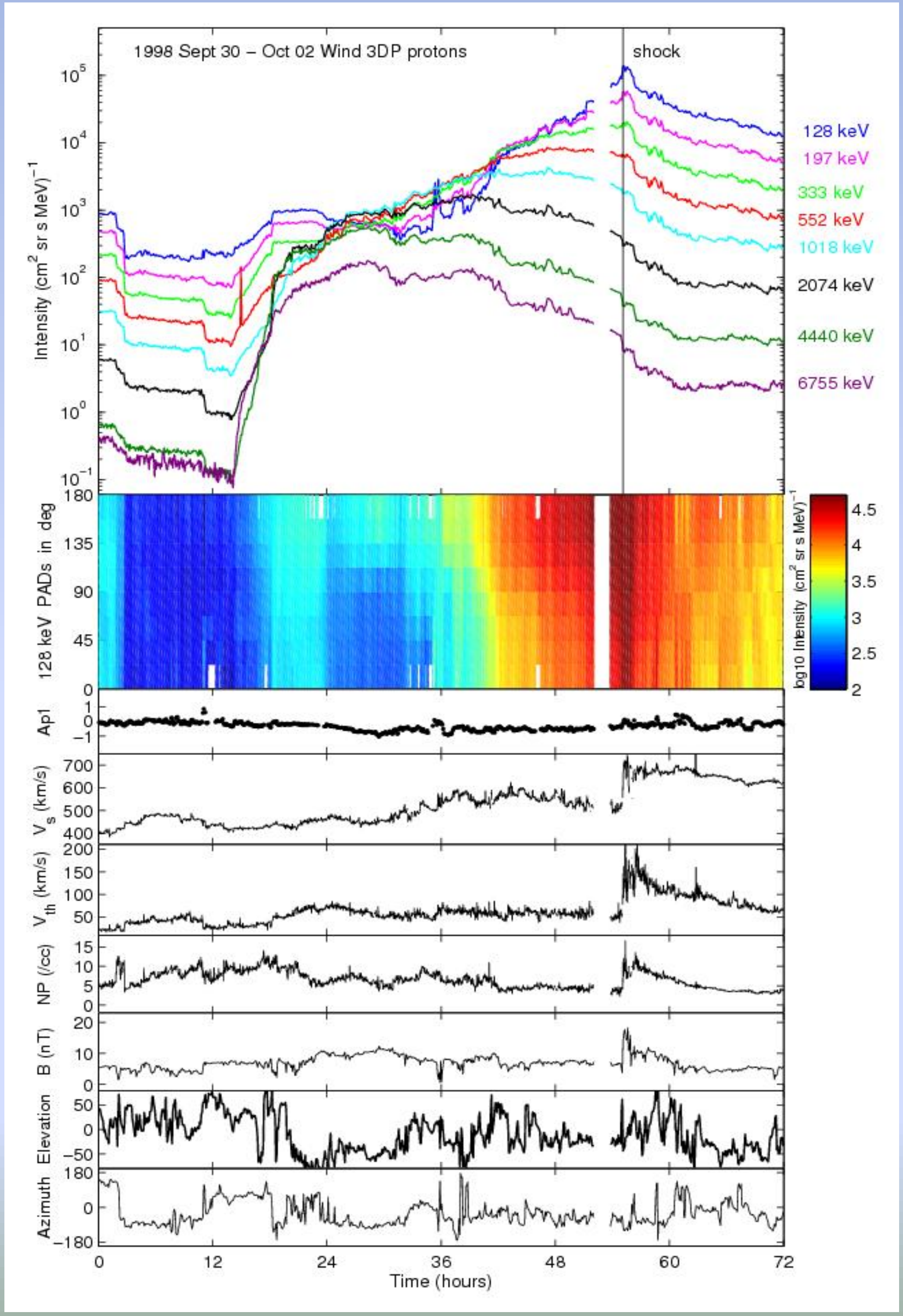


Figure 9. The dependence of profiles at 128 keV on the value of fluid speed difference

Figure 10. The dependence of profiles at 128 keV on the mean free path.

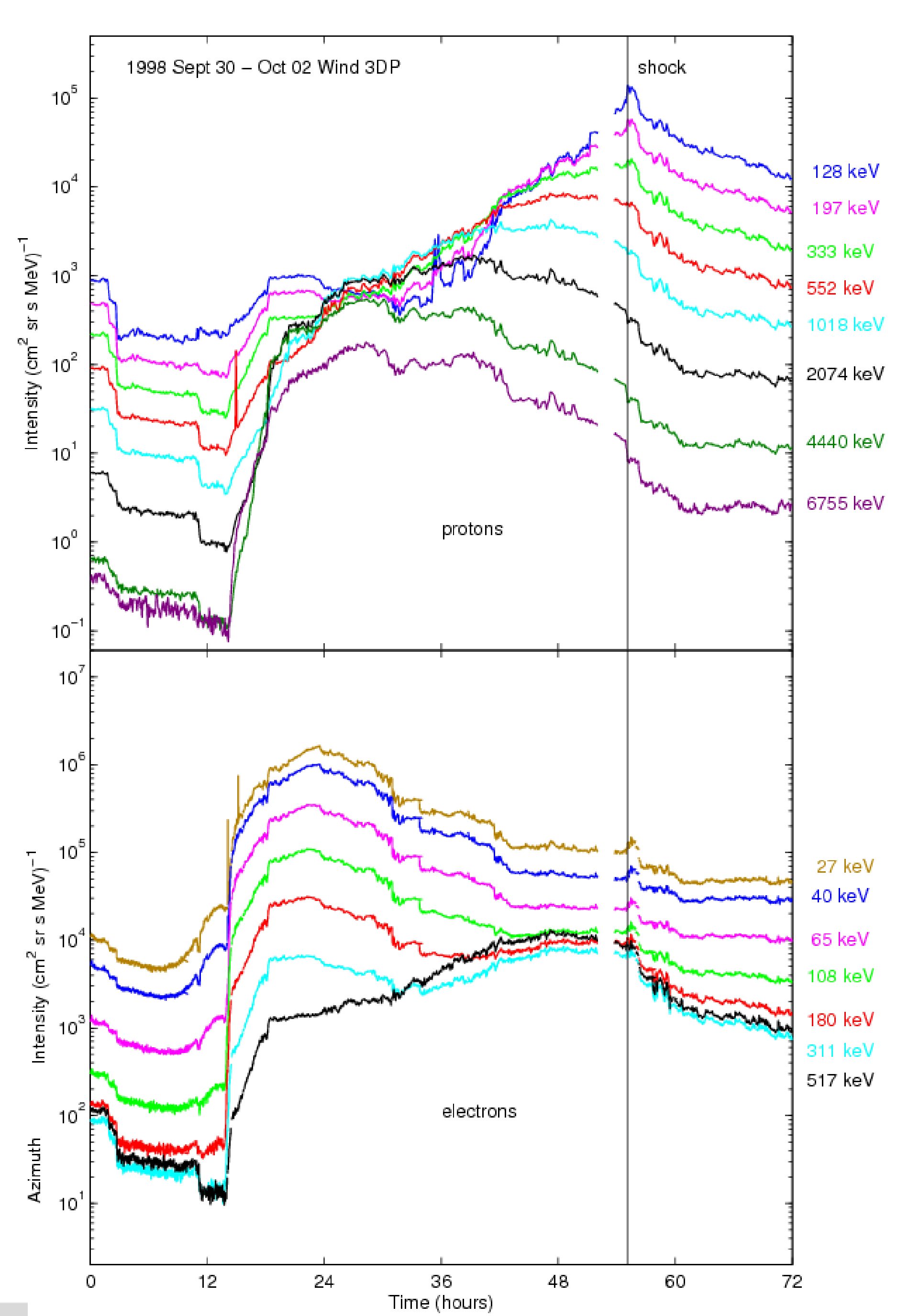
Two events which were considered for our modeling

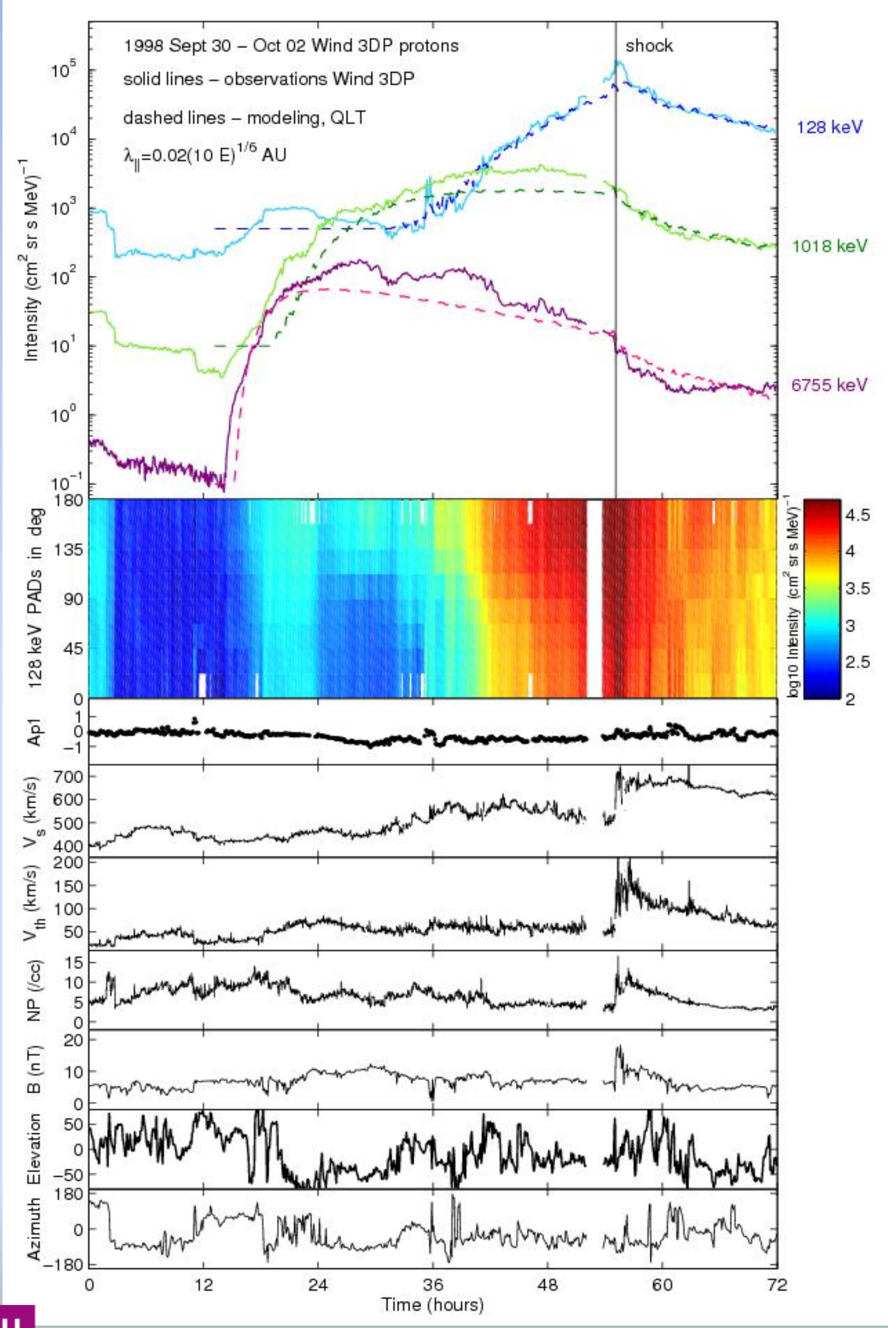


Flare M2.8
September, 30, 13:08 UT
~ N19W91

C | A | U
Kiel University
Christian-Albrechts-Universität zu Kiel

Contamination by electrons in proton channels



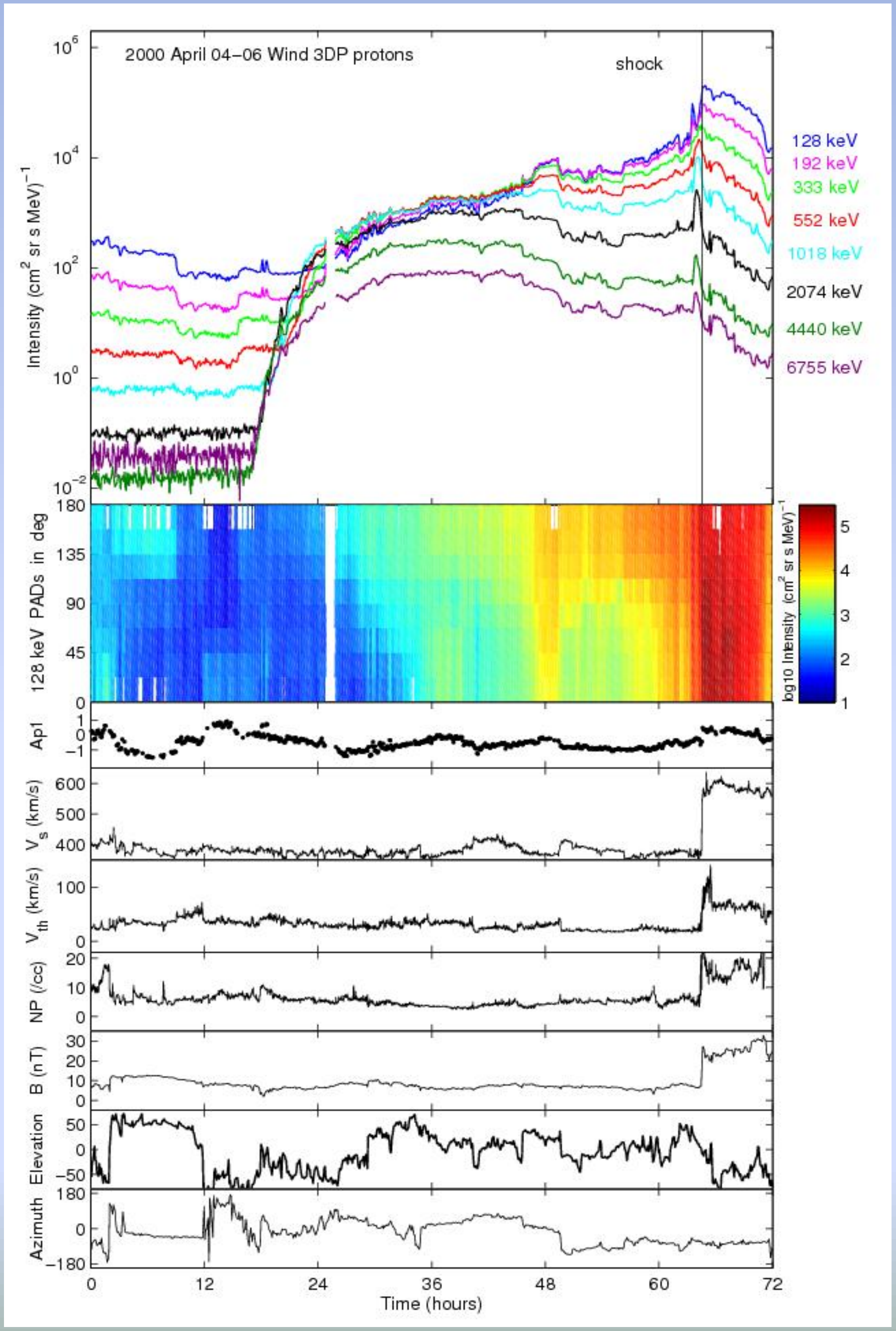


$$\lambda_{||} = 0.02\,(10E)^{\alpha}$$ AU

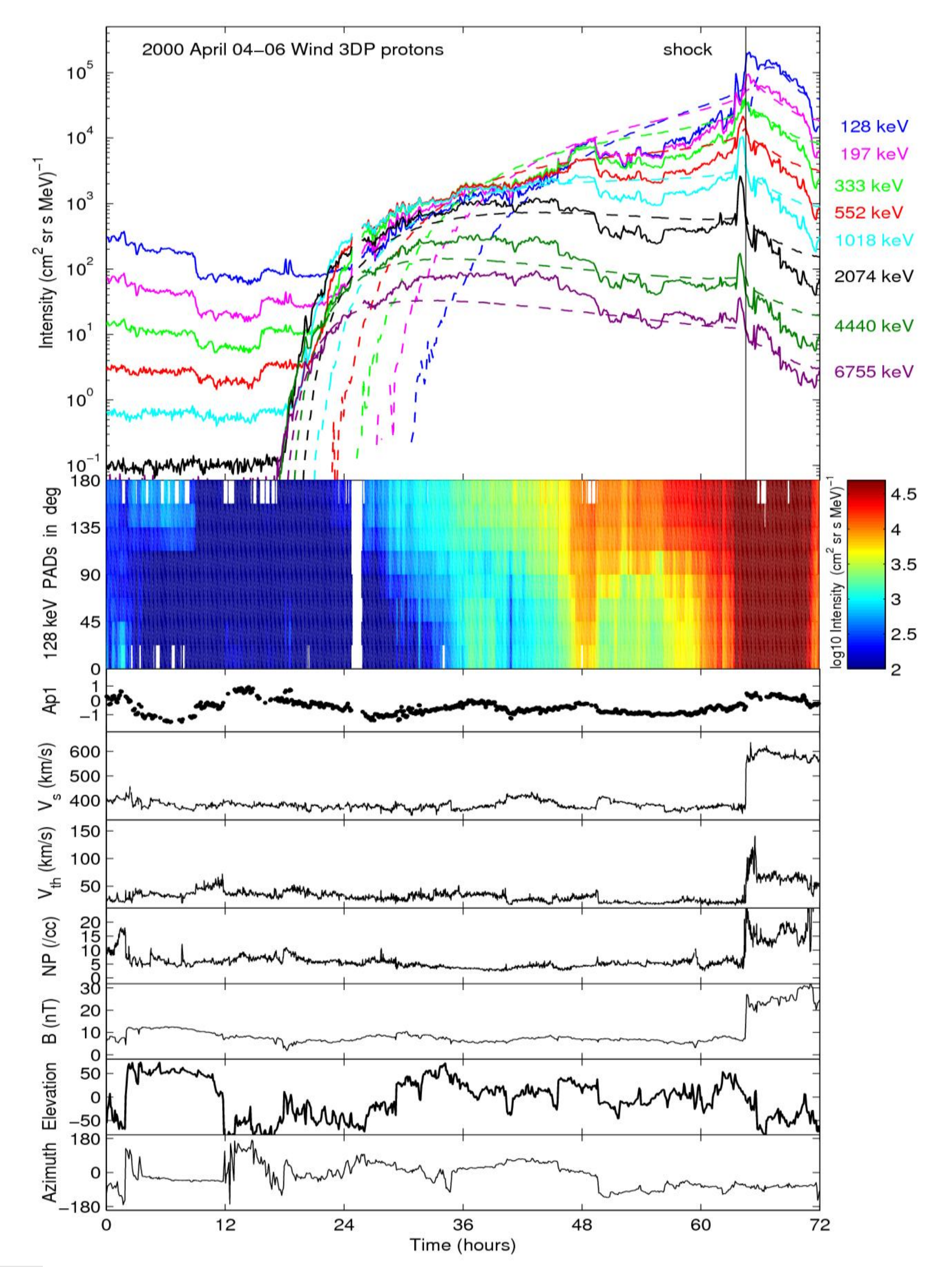
$$\alpha = 1/6$$

Upstream – radial mfp is const
Downstream – parallel mfp is const

Quasi-linear theory of particle-turbulence interaction gives E $E^{1/4}$ or $E^{1/6}$ depending on the type of the turbulence (Kraichnan’s or Kolmogorov’s)



Flare C9.7
April, 4, 15:22 UT
N16W66



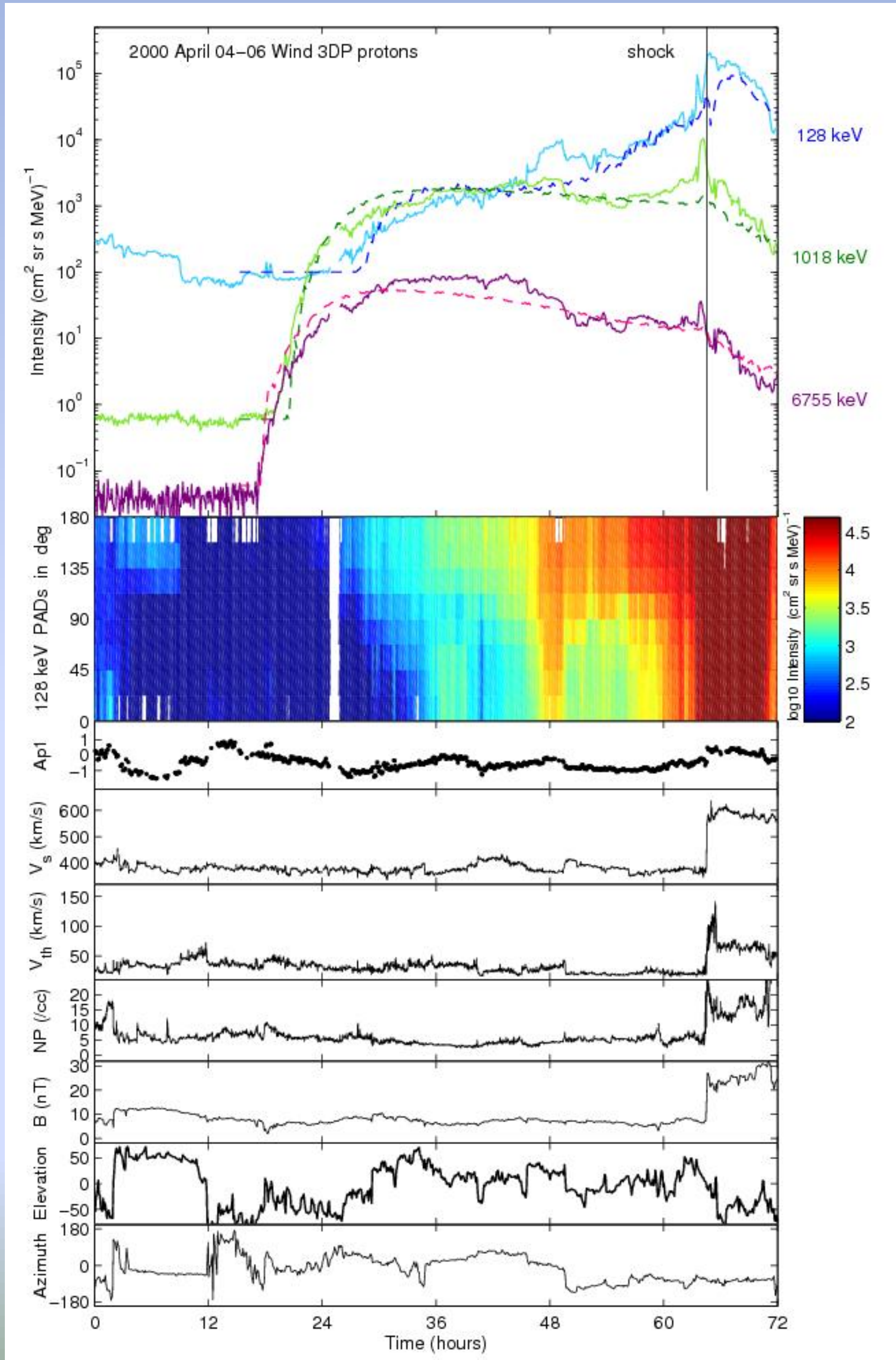
λ = 0.03 AU

Upstream – radial mfp is const
Downstream – parallel mfp is const

U_{SH} ~ 800 km/s

$S = 3.3$

Even considering mfp constant in energy gives too late arrival at energies below 4-6 MeV



Changing $\lambda_{||}$

Close to the onset the mfp at low energies is higher than at high energies!

128 keV -- 0.12 – 0.08 – 0.015 AU

1 MeV -- 0.05 – 0.04 – 0.03 AU

6.7 MeV -- 0.04 – 0.03 – 0.02 AU

After some time after the injection the mfp is decreasing towards the shock

Unfortunately no single injection spectrum was obtained so far and no common rule

Nevertheless in principally it is possible to fit, assuming the energy dependence of the mfp obeying the resonance broadening

C O N C L U S I O N S

- simulations for particles injected at the Sun together with a traveling interplanetary blast wave were performed
- these simulations resemble well the observed intensity–time profiles of ions in the energy ranges of hundreds of keV/nucleon to several MeV/nucleon in mixed SEP events
- in case of oblique geometry (blast waves in spiral magnetic field) the enhancements in time profiles of energetic particles are larger than for parallel geometry (the case of radial magnetic field)
- the energy dependence of the mean free path can either follow the law which follows from quasi-linear theory of particles-turbulence interaction or exhibit the opposite dependence, which is most likely related to the resonance broadening
- apparently in some cases the mean free path is decreasing towards the shock front

Thanks for your attention !