# Energetic particles

- Overview
  - Particle populations in the heliosphere
  - Solar energetic particles and classes of flares
  - Interplanetary propagation – formal basics
  - Interplanetary propagation – observations
  - Particle acceleration at shocks – theory
  - Particle acceleration at shocks – observations
  - Galactic cosmic rays

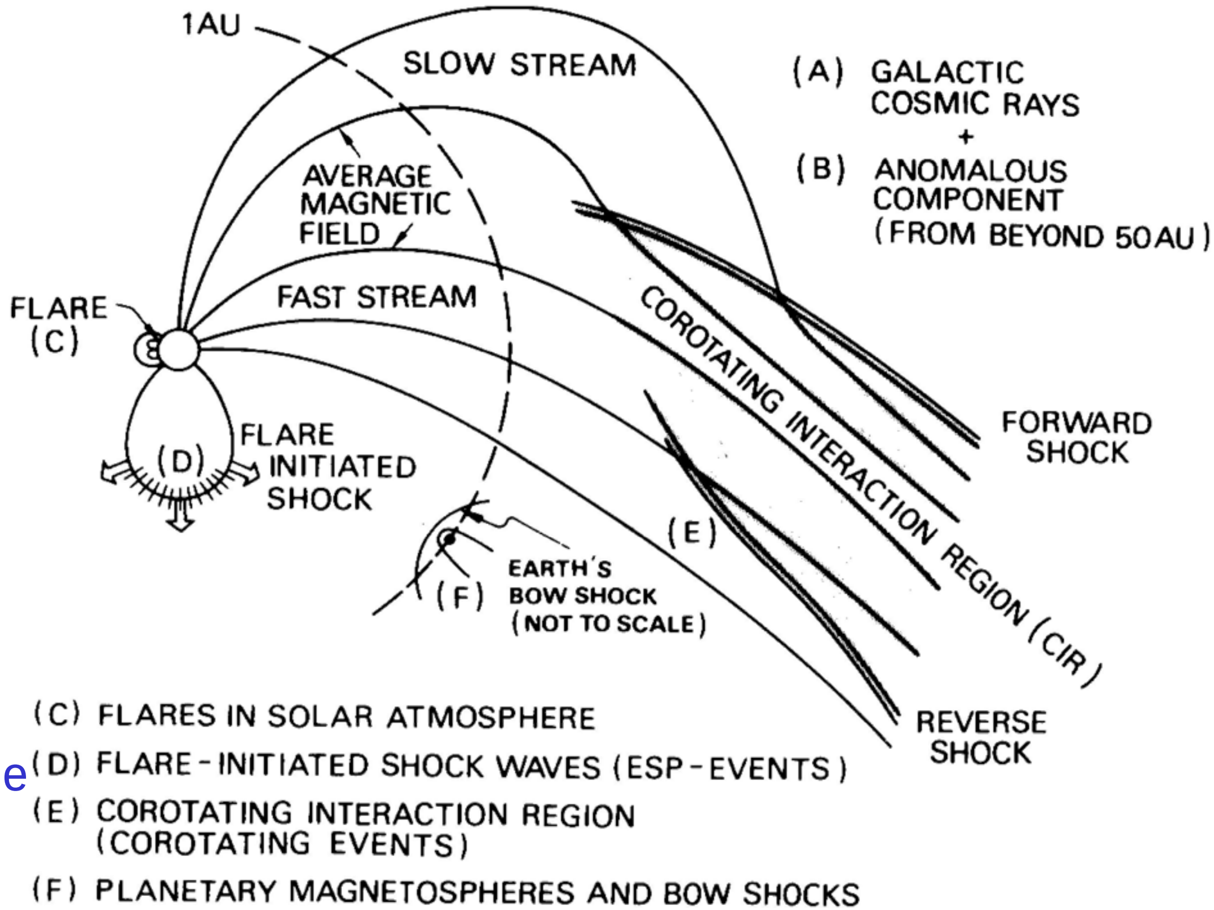
- Pre-requisites:
  - Structure of the interplanetary medium
  - Magnetohydrodynamic waves
  - shocks

# Energetic particles

- Energy exceeds the thermal energy of the plasma:
  - From a few keV up to the GeV range,
  - Galactic cosmic rays up to 1E20 eV.
- Charged particles (e.g. Fe XX, particles with small masses are completely ionized).
- Composition:
  - Main components: e, p, to a smaller amount also $\alpha$,
  - Small contributions of heavy ions up to iron.

# Particle populations I

- Differences in particle populations:
  - Temporal variation,
  - Spectra,
  - Composition,
  - Anisotropies,
  - Charge states.
- Sources:
  - Sun and solar activity,
  - Interplanetary space (acceleration out of the solar wind),
  - Galaxis.



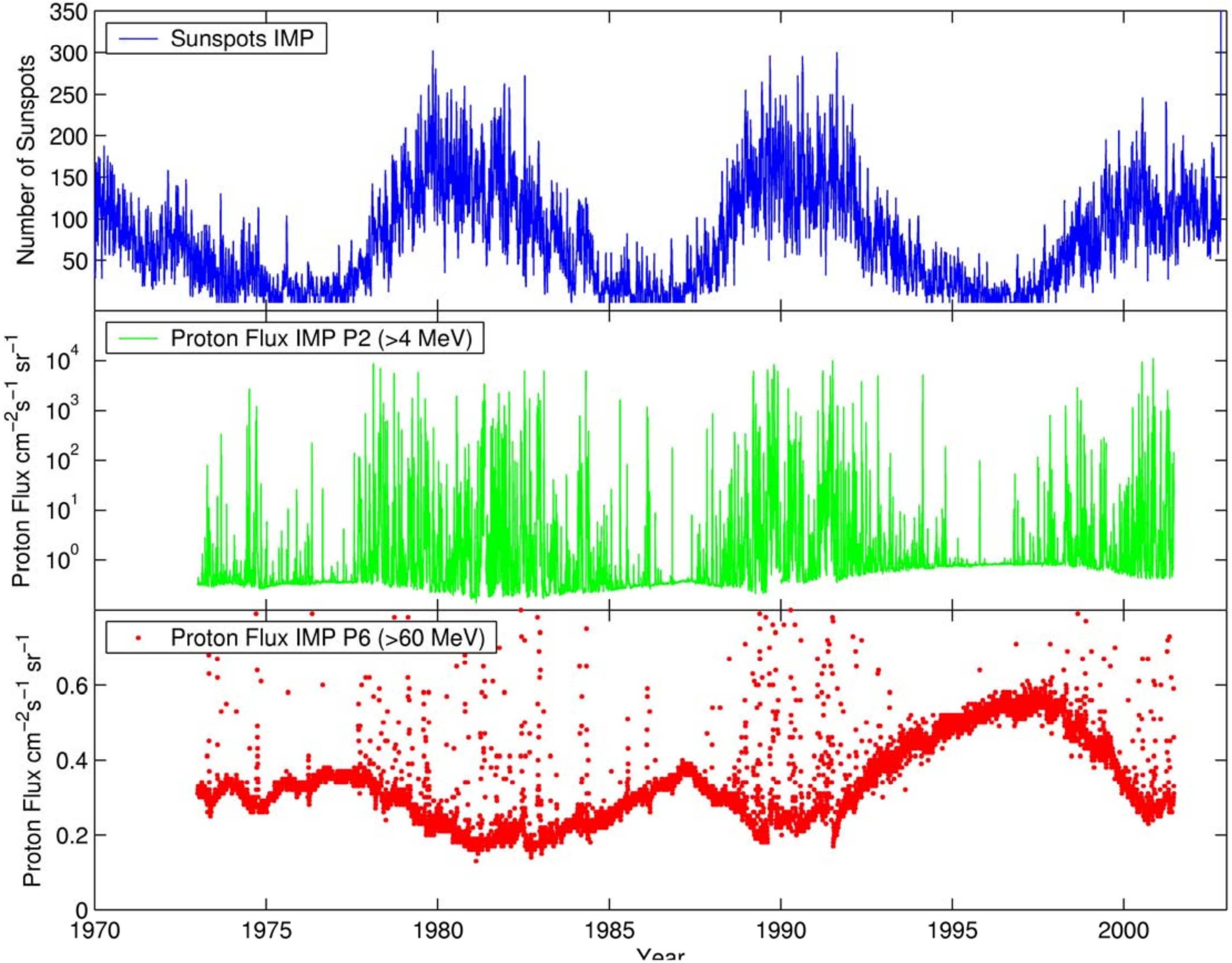

Kunow et al., 1991, Physics of the inner heliosphere, Springer

# Particle populations II

| | Temporal scales | Spatial scales | Energy range | Acceleration mechanisms |
|---|---|---|---|---|
| A | continuous | global | GeV–> TeV | diffusive shock |
| B | continuous | global | 10–100 MeV | shock? |
| C | $\delta$ | $\delta$ | keV–100 MeV | reconnection, stochastic, selective heating, shock |
| D | days | extended | keV–10 MeV | diffusive shock, shock-drift, stochastic |
| E | 27 days | large-scale | keV–10 MeV | diffusive shock |
| F | continuous | local | keV–MeV | diffusive shock, shock drift |

# Particles during the solar cycle

- Spikes are solar energetic particles (SEPs): individual events of solar origin (flares, CMEs)
- SEPs are observed during solar minimum although with smaller likelihood
- Background anti-correlated with the solar cycle.




Daten von http://spidr.ngdc.noaa.gov/spidr

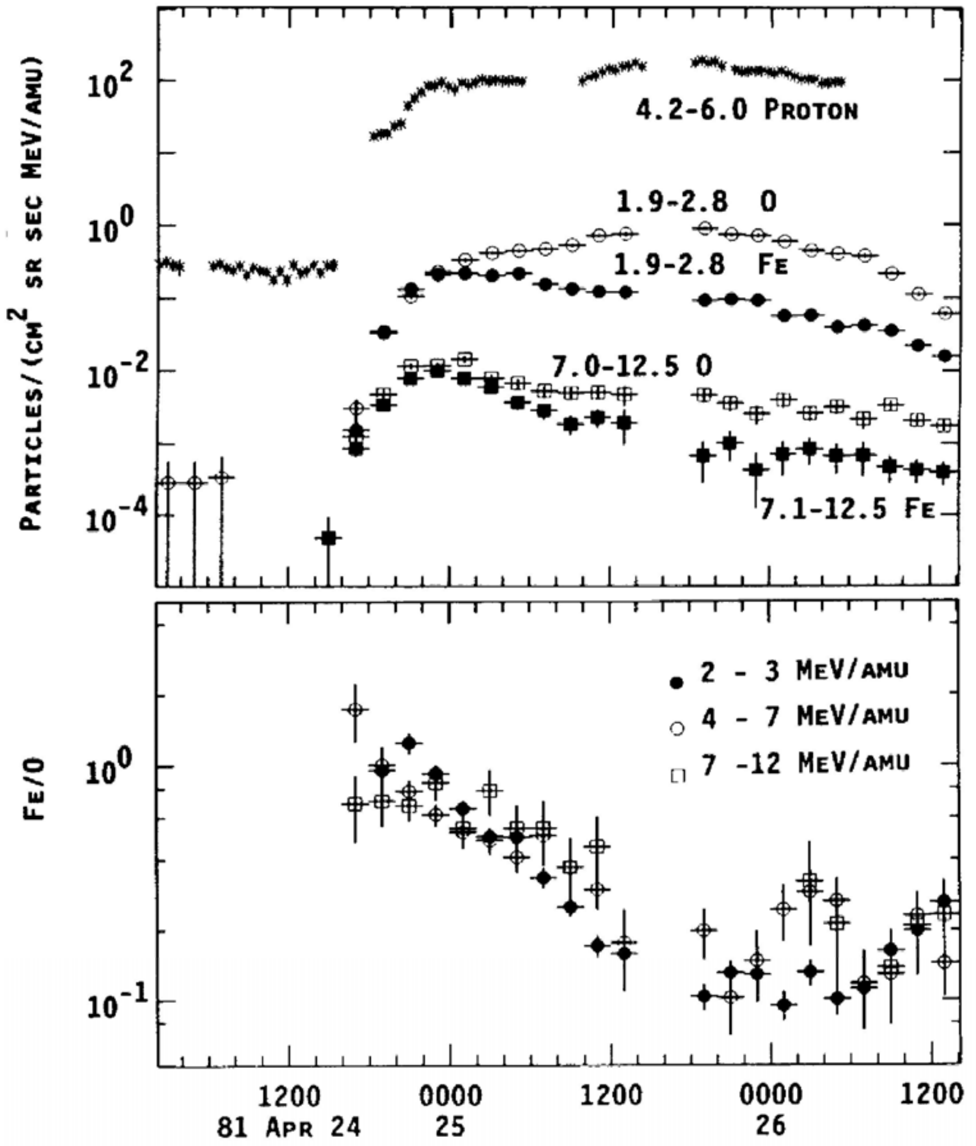
# Solar energetic particles (SEPs)

- Particles accelerated in the flare or at a shock driven by the CME.
- Two classes of events corresponding to the two classes of parent flares (impulsive or gradual)

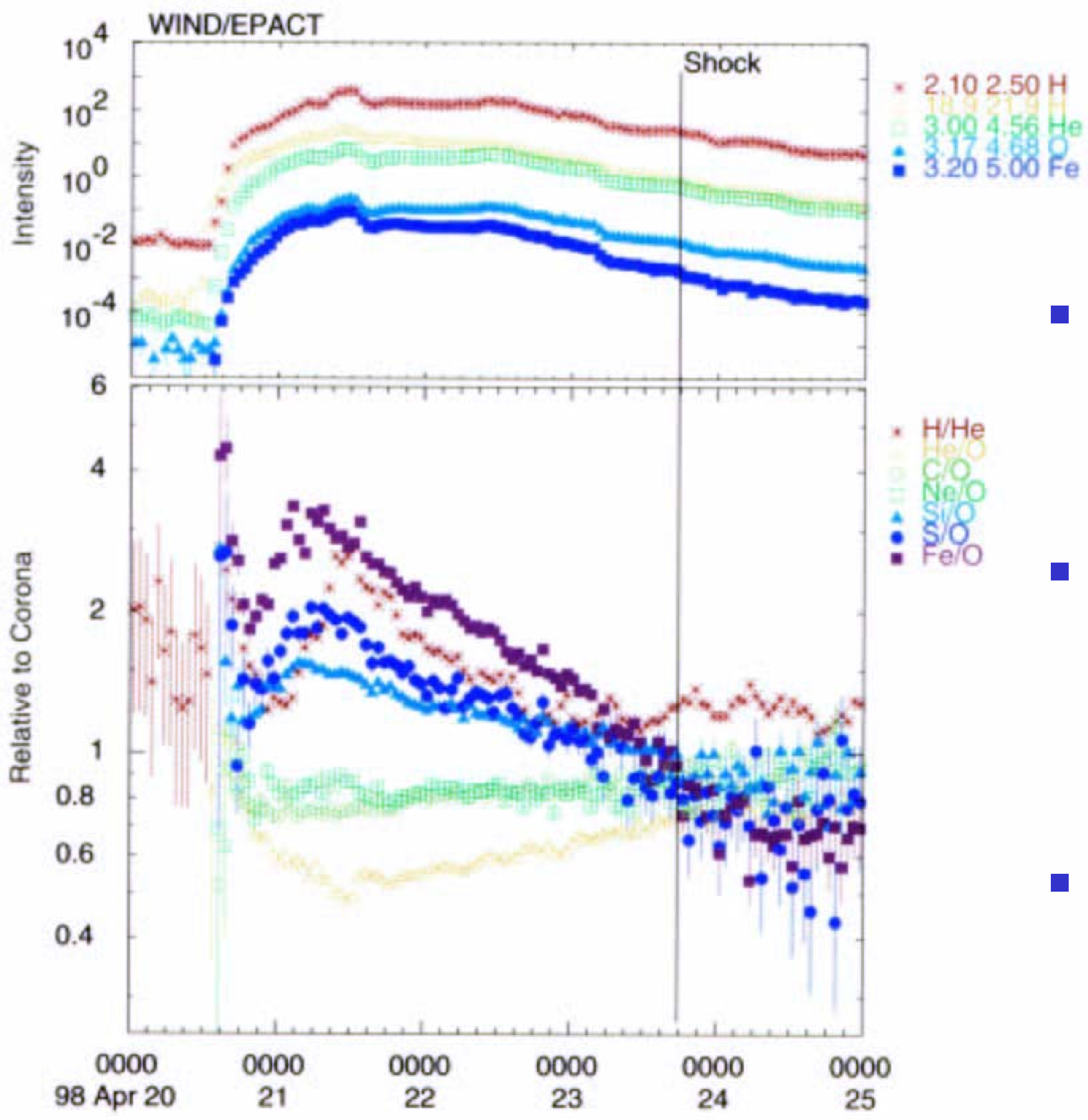
| | $^3$He-rich | gradual |
|---|---|---|
| Particles | electron-rich | proton-rich |
| $^3$He/$^4$He | $\sim 1$ (enrichment 2000 times) | $\sim 0.0005$ |
| Fe/O | $\sim 1.234$ (enrichment 8 times) | $\sim 0.155$ |
| H/He | 10 | 100 |
| $Q_{\mathrm{Fe}}$ | $\sim +20$ | $\sim +14$ |
| Duration | hours | days |
| Longitudinal cone | $< 30°$ | $\leq 180°$ |
| Metric radio bursts | III, V | II, III, IV, V |
| Coronograph | – | CME |
| Solar wind | – | ipl. shock |
| Event rate/a | $\sim 1000$ | $\sim 10$ |

# Classification denied

- Onset:
  - high Fe/O as expected from selective heating in impulsive flares.
- Shock arrival:
  - low Fe/O as expected for acceleration out of the ambient solar wind.
- Transition:
  - Slow development from flare-like to shock-like.




Reames et al., 1991, Astrophys. J. 357, 259




Tylka et al., 1999, Geophys. Res. Lett 26, 2141

# Classification denied II

- Early phase:
  - Enrichment in heavies, flare-like.
- Shock arrival:
  - Background composition, more representative for acceleration at a shock.
- Transition
  - Continuous, not sharp.

# Interplanetary propagation

- Formal basics:
  - Spatial diffusion
  - Pitch angle diffusion
  - Diffusion in momentum space
  - Wave particle interaction
  - Electromagnetic waves
  - Transport equations

- Observations:
  - Fits with a transport equation
  - Analysis of magnetic field fluctuations
  - Comparison of both attempts

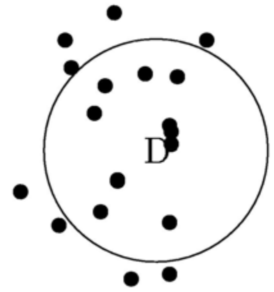
# Spatial diffusion

- Superposition of many small, statistically distributed changes in propagation direction:
  - Single particle approach not useful,
  - Instead ensembles (phase space density),
  - Fokker-Planck as equation of motion in phase space.

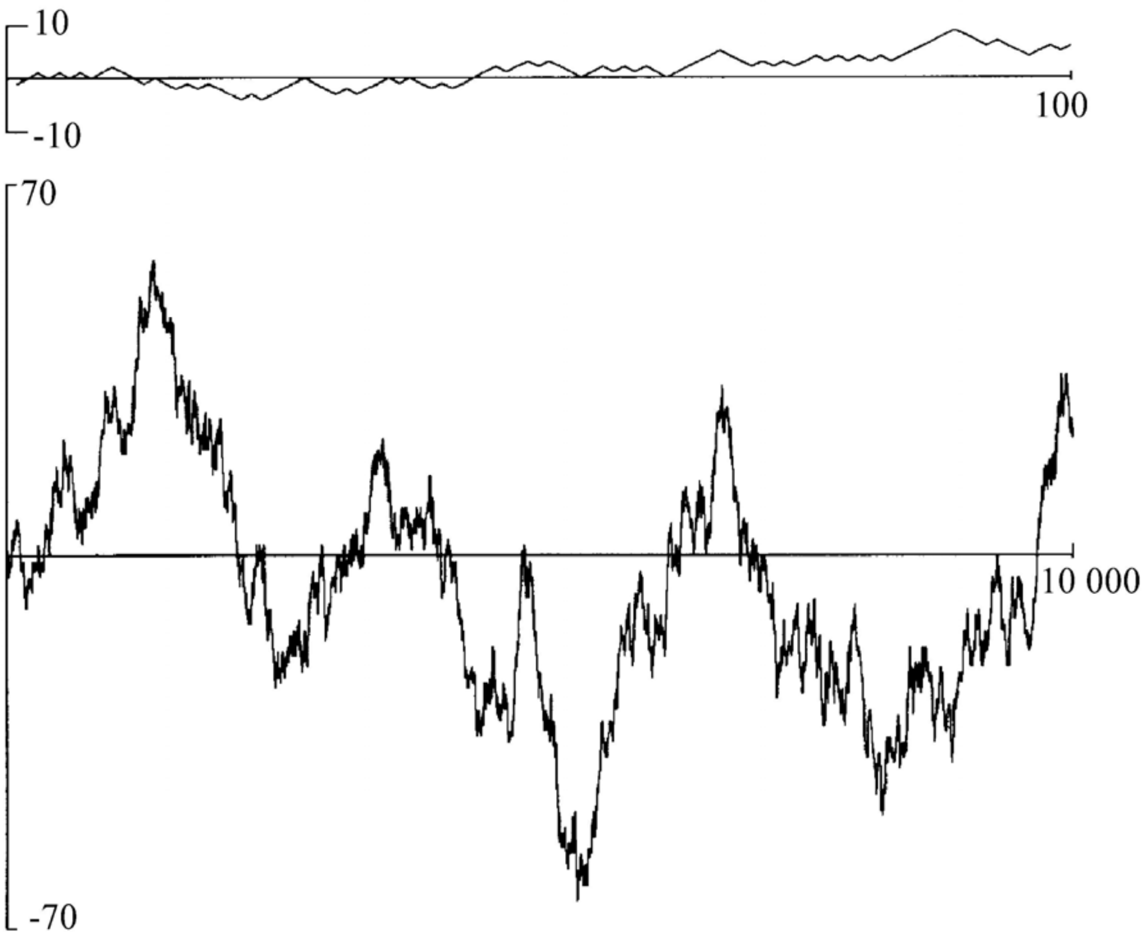
- Graphical examples:
  - Drop of ink in water.
  - Not exactly: cream in a cup of steaming hot tea (also diffusion in momentum space).

- Causes:
  - Collisions between particles (Brownian motion),
  - Resonant wave particle interaction.

# Gains and losses




- Limitation: 1D-motion.
- Each interaction equals a motion by $\pm\lambda$.
- Thus on average no displacement from the origin expected.
- Contradictory observation: widening of the distribution.
- Characteristic quantity: average squared distance



# Average squared distance

- 1D motion along the x-axis:

$$(\Delta x)^2 = \left(\sum_{i=1}^{N} \mathrm{d}x_i\right)^2 = (\mathrm{d}x_1 + \mathrm{d}x_2 + ... + \mathrm{d}x_N)^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} \mathrm{d}x_i \mathrm{d}x_j \; .$$

- displacement $\Delta x = \pm\lambda$: for $i \neq j$ on average same number of positive and negative products, thus only i=j survives:

$$\langle \Delta x \rangle^2 = N\lambda^2$$

- Traveled distance $s=vt=N\lambda$, thus

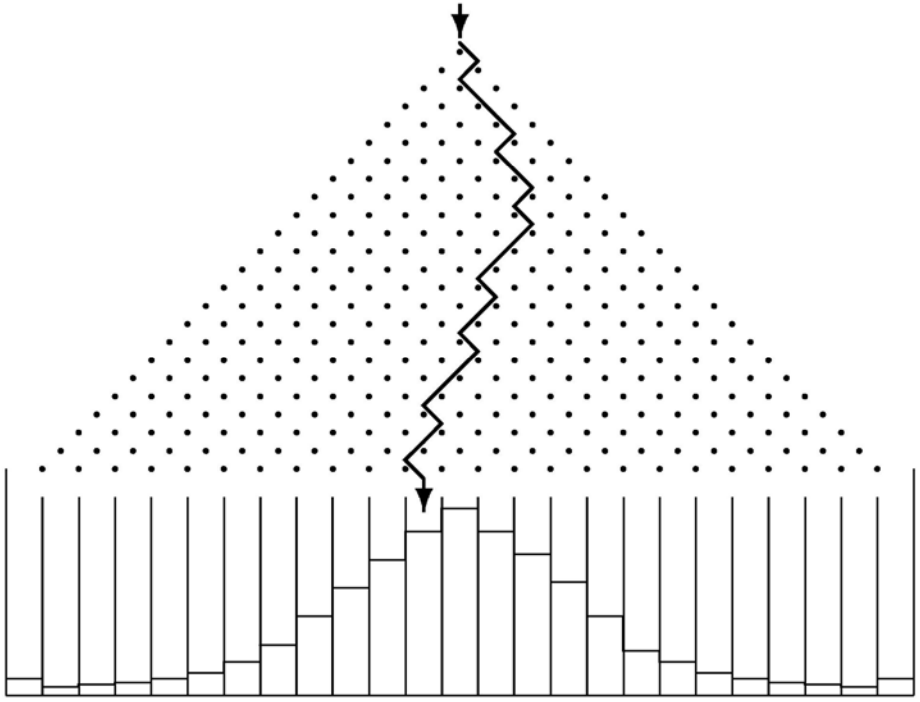
$$\langle \Delta x \rangle^2 = N\lambda^2 = v\lambda t = 2Dt$$

with diffusion coefficients in 1D and 3D:

$$D = \tfrac{1}{2} v\lambda \; . \qquad\qquad D = \tfrac{1}{3} v\lambda \; .$$

# Galton-board

- Transition from a single partic to a distribution.



- Result: Gauß distribution

$$P(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-x_o)^2}{2\sigma^2}\right)$$

with standard deviation:

$$\sigma^2 = \frac{1}{n}\sum(x-x_o)^2 =: \langle\Delta x\rangle^2$$

- With mean free path λ the standard deviation is

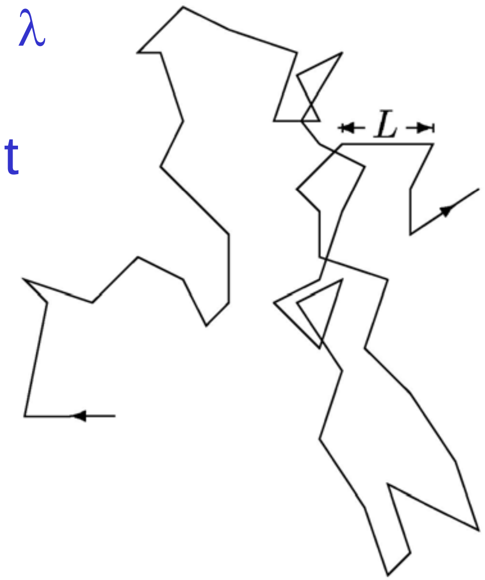
$$\sigma = \sqrt{\langle\Delta x\rangle^2} = \sqrt{2Dt} = \sqrt{v\lambda t}$$

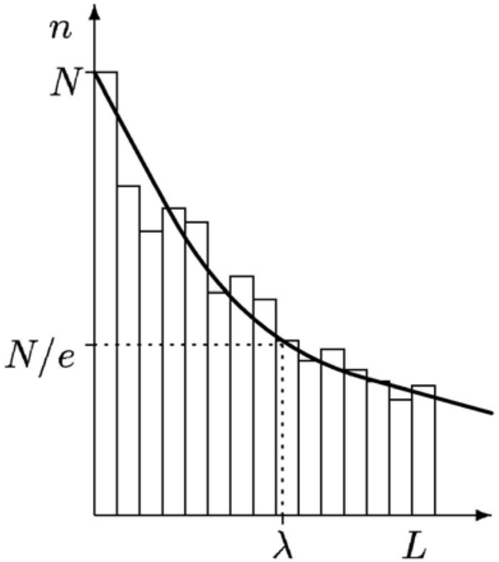
and the distribution: $P(x) = \frac{1}{\sqrt{2\pi v\lambda t}} \exp\left(-\frac{(x-x_o)^2}{2v\lambda t}\right)$ .

# Mean free path

- Definition of the mean free path λ from the distribution of path lengths between two subsequent collisions.

- Reduction of a particle beam in matter with particle number density n and scttering cross section σ



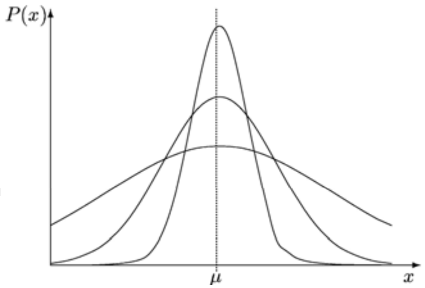

$$N(x) = N_o \exp(-\sigma n_s x) = N_o \exp(-x/\lambda)$$

$$\lambda = \frac{1}{n_s \sigma}$$

# Diffusion equation

- The transport process diffusion is driven by a density gradient.
- Diffusion current: $\vec{S} = -\mathtt{D}\nabla U$
- Equation of continuity for the particle number: $\dfrac{\partial N}{\partial t} + \oint\limits_{O(S)} \vec{S}\mathrm{d}\vec{\sigma} = 0 \,.$
- Rewrite for density: $\dfrac{\partial}{\partial t}\int\limits_{V} U\mathrm{d}^3x + \oint\limits_{O(V)} \vec{S}\mathrm{d}\vec{\sigma} = 0$
- Differentials form: $\dfrac{\partial U}{\partial t} + \nabla\vec{S} = 0$ or $\dfrac{\partial U}{\partial t} = \nabla\cdot(\mathtt{D}\,\nabla U)\,.$
- Isotropic diffusion only: $\dfrac{\partial U}{\partial t} = \nabla\cdot(D\,\nabla U)\,.$
- D independent of position: $\dfrac{\partial U}{\partial t} = D\Delta U\,.$

# Solution diffusion equation



Widening of the distribution around the injection site

- Delta-source (flare):

$$\frac{\partial U}{\partial t} - D\Delta U = Q(r_o, t) \ .$$

- Spherical symmetric geometry

$$\frac{\partial U}{\partial t} - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D_r \frac{\partial U}{\partial r}\right) = Q(r_o, t)$$

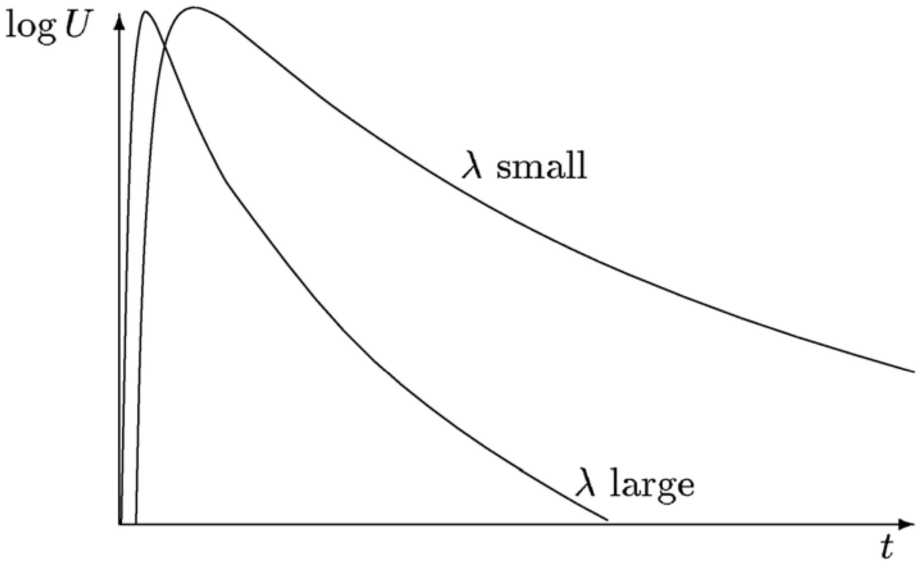
- Solution:

$$U(r,t) = \frac{N_o}{\sqrt{(4\pi D_r t)^3}} \exp\left(-\frac{r^2}{4D_r t}\right)$$

- Time to maximum $t_m(r) = \dfrac{r^2}{6D_r}$

- Intensity at time of maximum

$$U(r, t_m) = \frac{N_o}{\sqrt{(4\pi r^2/6)^3}} \exp\left(-\frac{3}{2}\right) \sim \frac{N_o}{r^3} \ .$$



Time profil at a fixed position (different from injection site)

**Application:**

First guess on mean free path from the time to maximum:

$$\lambda_r = \frac{r^2}{2vt_m} \ .$$

# Geometrical problem

- Assumption of a radial symmetric geometry, in particular:
  - Assumption of radial propagation.

- Problem: charged particles are guided by the interplanetary magnetic field
  - propagation along the archimedian spiral.

- Formally: diffusion coefficient divided into two parts parallel and perpendicular to the field with only the parallel part surviving:

$$\lambda_r = \lambda_{||} \cdot \cos^2 \psi \qquad \text{or} \qquad D_r = D_{||} \cdot \cos^2 \psi$$

# Diffusion convection equation

- Interplanetary propagation happens in a moving medium.
- Scattering centers move with the fluid.
- Formally: diffusion convection equation

$$\frac{\partial U}{\partial t} + \nabla(U\vec{u}) = \nabla(\mathtt{D}\nabla U)$$

- Special case: isotropic diffusion

$$\frac{\partial U}{\partial t} + \vec{u}\nabla U = D\Delta U$$

- With solution ($\delta$-injection):

$$U(r,t) = \frac{N_\mathrm{o}}{\sqrt{(4\pi D_\mathrm{r} t)^3}} \exp\left\{-\frac{(r-ut)^2}{4D_\mathrm{r} t}\right\}$$

# Pitch angle diffusion

- Elementary process in interplanetary space:
  - No collisions because density too low, instead
  - Wave particle interaction, leading to
  - Pitch angle diffusion: particle propagation is modified by many small changes in pitch angle.

- Formally: pitch angle diffusion coefficient with $\mu = \cos\alpha$

$$\frac{\partial}{\partial \mu}\left(\kappa(\mu)\frac{\partial f}{\partial \mu}\right)$$

- Propagation than a combination of field-parallel motion with v cos $\alpha$ = $\mu$v and pitch angle diffusion:

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial s} = \frac{\partial}{\partial \mu}\left(\kappa(\mu)\frac{\partial f}{\partial \mu}\right) \ .$$

# Diffusion in momentum space

- Collision with moving scattering center: change in momentum.
- Solar wind convects scattering centers outwards $\Rightarrow$ in addition to convection also scattering in momentum space.
- Formal description analogous to pitch angle diffusion with a diffusion stream:

$$S_{\mathrm{p}} = -D_{\mathrm{pp}} \frac{\partial f}{\partial p} + \frac{\mathrm{d}p}{\mathrm{d}t} f \, .$$

- Application: adiabatic deceleration shock acceleration.

# Wave particle interaction

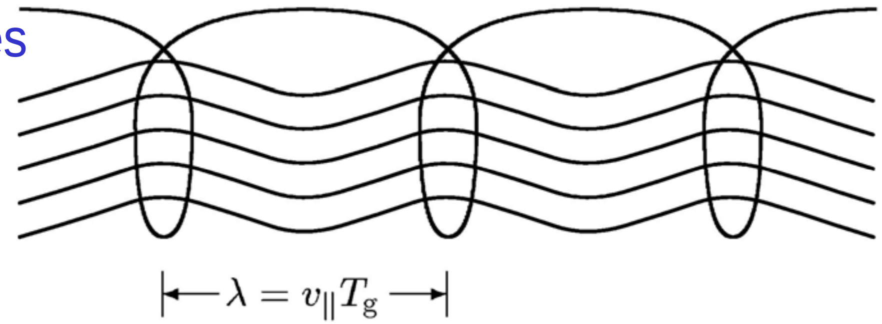
- Collisions between particles can be neglected because densities are too low.
- Instead scattering at electromagnetic waves:
  - As at a shock the magnetic field provides the coupling between the particles.
- Ansatz: quasi-linear theory, thus Vlasov equation with additional term can be used:

$$\frac{\partial f_o}{\partial t} + \vec{v} \cdot \nabla f_o + \frac{q}{m} \vec{v} \times \vec{B}_o \cdot \frac{\partial F_o}{\partial \vec{v}} = -\frac{q}{m} \left\langle \left( \vec{E}_1 + \vec{v} \times \vec{B}_1 \right) \cdot \frac{\partial f_1}{\partial \vec{v}} \right\rangle \, .$$

- Separation into average and fluctuating quantities (see chap. 3). Here only the slow changes are of interest; fast changes lead to waves (see chap. 4).

# Resonant wave particle interaction

- Basic idea: energetic particles interact with waves in resonance with them:




- $$k_{\|} = \frac{\omega_c}{v_{\|}} = \frac{\omega_c}{\mu v} \; .$$

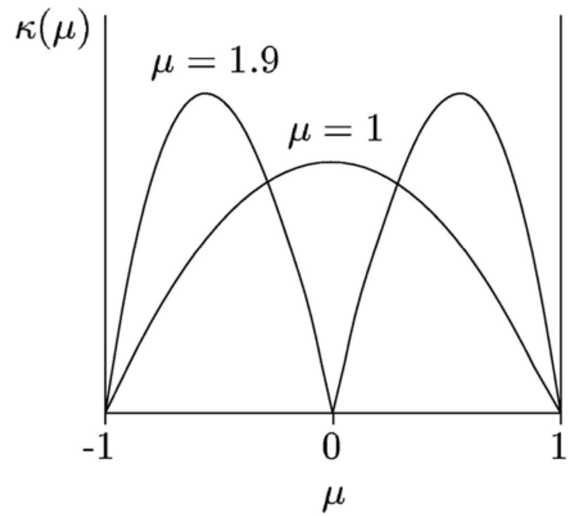
- Wave number depends on the particle speed parallel to the field:
  - For a given energy the resonant wave number depends on pitch angle, and
  - For given pitch angle it depends on energy.

- Scattering properties can be determined from the spectrum of the magnetic field fluctuations.

# Pitch angle diffusion coefficient

- Magnetic field power density spectrum

$$f(k_\parallel) = C\, k_\parallel^{-q}$$




- Yields pitch angle diffusion coefficient

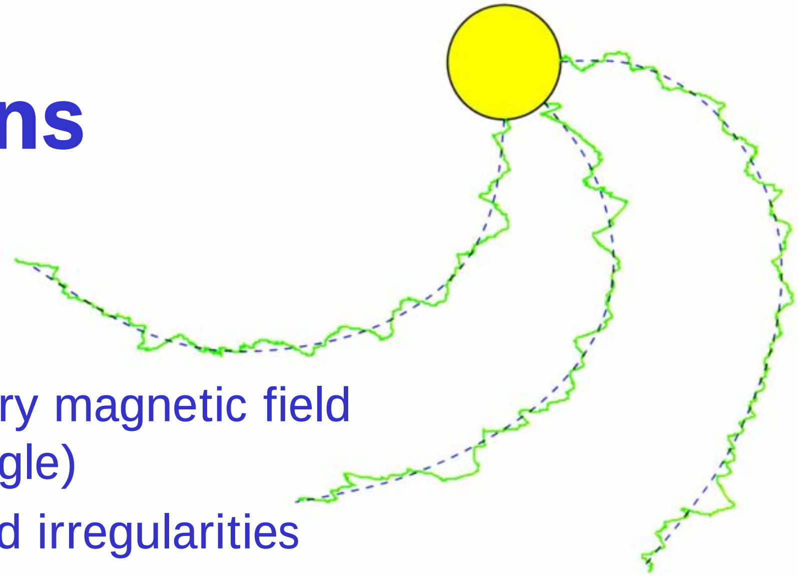
$$\kappa(\mu) = A(1-\mu^2)|\mu|^{q-1}$$

with the level A of scattering depending on the level of turbulence and the details of the scattering process depending on the steepness q of the spectrum.

- Mean free path and turbulence:

$$\lambda_\parallel := \frac{3}{8} v \int_{-1}^{+1} \frac{(1-\mu^2)^2}{\kappa(\mu)}\, \mathrm{d}\mu \ .$$

# Transport equations



- Effects influencing transport:
  - Focusing in the diverging interplanetary magnetic field (systematic effect, decreases pitch angle)
  - Pitch angle scattering at magnetic field irregularities (stochastic), and
  - Field-parallel propagation (depends on pitch angle).

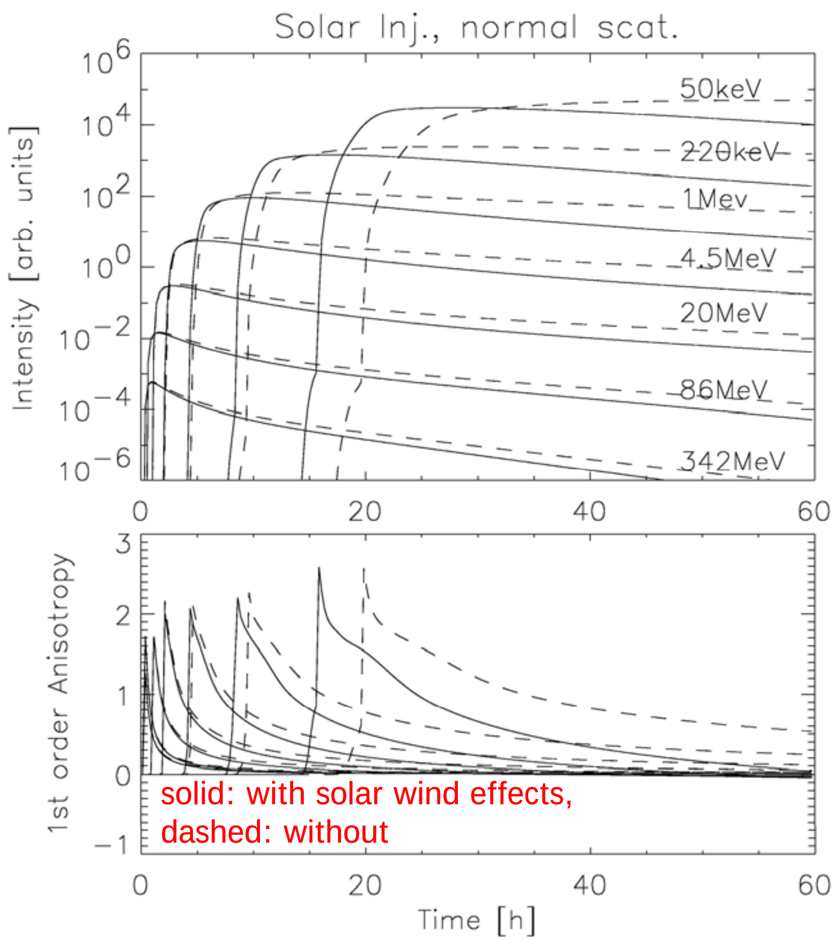
- Transport equation (focused transport; Roelof, 1968):

$$\frac{\partial f}{\partial t} + \underbrace{\mu v \frac{\partial f}{\partial s}}_{\text{Field-parallel propagation}} + \underbrace{\frac{1-\mu^2}{2\zeta} v \frac{\partial f}{\partial \mu}}_{\text{Focusing}} - \underbrace{\frac{\partial}{\partial \mu}\left(\kappa(\mu)\frac{\partial f}{\partial \mu}\right)}_{\text{Pitch angle scattering}} = \underbrace{Q(r,\mu,v,t)}_{\text{Source}}$$

# Focused + Solar Wind Effects

- In addition:
  - Convection with the solar wind,
  - Adiabatic deceleration (transport in momentum space!)

- Consequences:
  - Earlier onset,
  - Earlier maximum,
  - Faster decrease.




Kallenrode and Hatzky, 1999

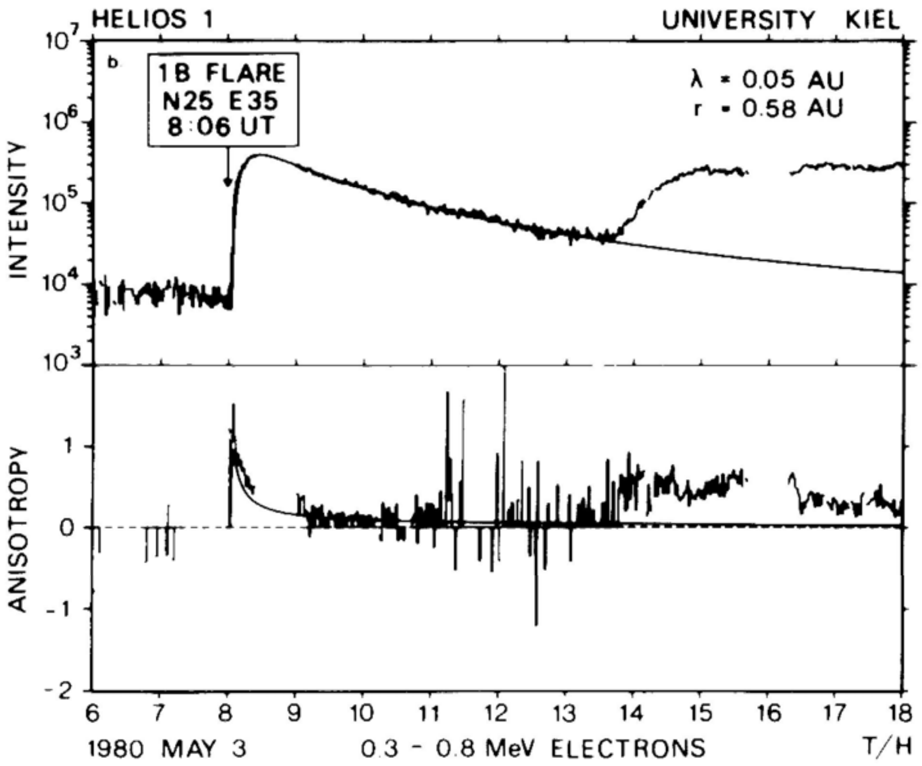
- Transport equation (Ruffolo, 1995):

$$
\begin{aligned}
\frac{\partial F}{\partial t} \quad &+ \quad \frac{\partial}{\partial s}\left(\left[\mu' v' + \left\{1 - \frac{(\mu' v')^2}{c^2}\right\} v_{\mathrm{sowi}} \sec\, \psi\right] F\right) \\
&- \quad \frac{\partial}{\partial p'}\left(p' v_{\mathrm{sowi}} \left[\frac{\sec\psi}{2\zeta}(1-\mu'^2) + \cos\psi \frac{\mathrm{d}}{\mathrm{d}r} \sec\psi \mu'^2\right] F\right) \\
&+ \quad \frac{\partial}{\partial \mu'}\left(v' \frac{1-\mu'^2}{2\zeta} F - \kappa(s,\mu') \frac{\partial F}{\partial \mu'}\right) = Q(t, s, \mu', p') \, .
\end{aligned}
$$

# Transport parameter: fits

- Fit of a solution of a transport equation in intensity and anisotropy time profiles observed in ipl. space,

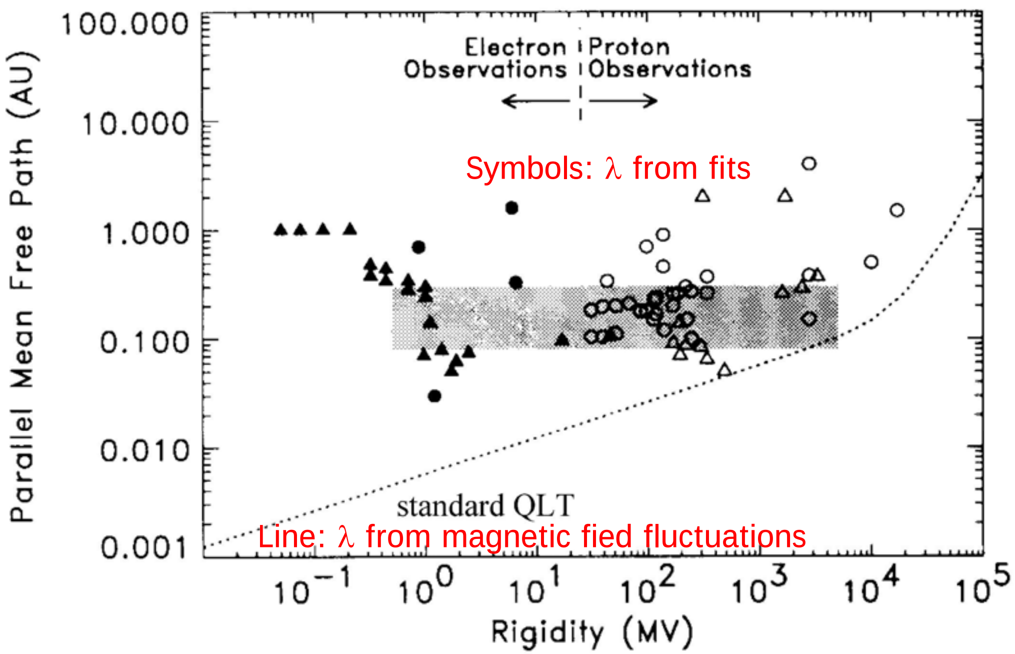
- Gives mean free path and injection, thus
  - Hints on the acceleration or at least release of particles at the sun
  - Hints on scattering properties in interplanetary space.




Kallenrode et al., 1992, Astrophys. J. 394, 351

# Palmer consensus range

- Propagation parameters are determined for a large number of events
- Palmer consensus range: mean free paths between 0.08 and 0.3 AU
  - With broad scatter even outside this range,
  - No obvious dependence on energy.

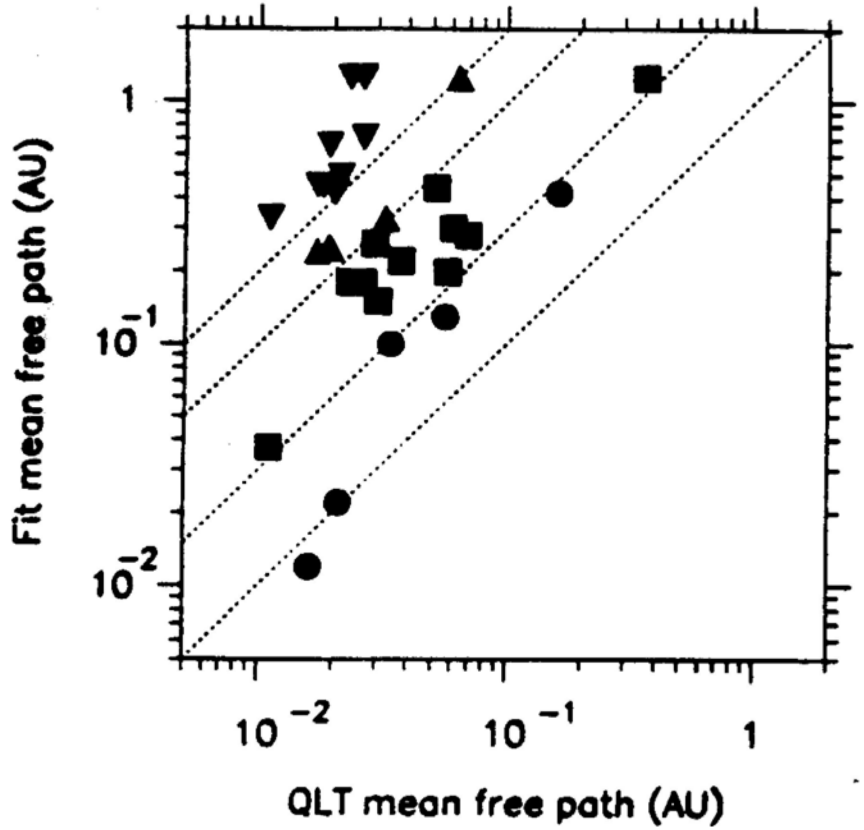



Bieber et al., 1994, Astrophys. J. 420, 294

Discrepancy problem: λs from fits do not agree with mean free paths determined from the analysis of magnetic field fluctuations!!!!

# Discrepancy problem

- Comparison not on a statistical but on an event-to-event basis:
  - $\lambda$fit always smaller than $\lambda$QLT
  - ratio $\lambda$fit/$\lambda$QLT highly variable
  - $\lambda e/\lambda p \approx 1.6$ (instead of 6 expected from QLT)
- Questions:
  - Interpretation of the field fluctuations?
  - Quality of fits?
  - Inappropriate mixing of data (electrons and protons)?

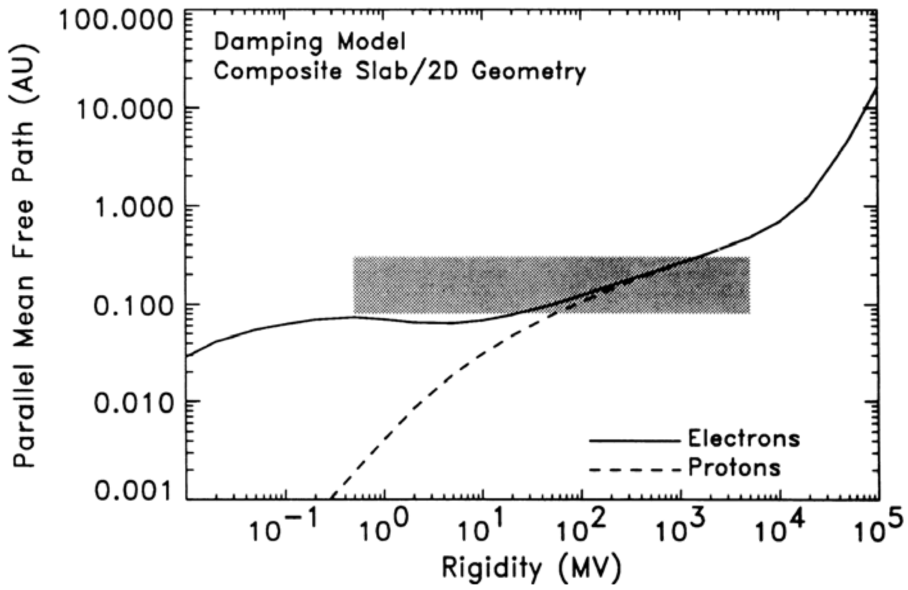



Wanner et al., 1993, Adv. Space Res. 13, (9)359

# 2D dynamical turbulence

- Standard interpretation: turbulence due to field-parallel propagating Alfven waves
  - Entire power contributes to the scattering

- More recent interpretation: dynamical turbulence propagating also perpendicular to the field
  - Reduction of field-parallel power and thus scattering,
  - Electrons and protons are affected differently!




Bieber et al., 1994, Astrophys. J. 420, 294

Hints:

Simulation of dynamical turbulece

Multi-spacecraft observations

# Summary interplanetary transport

- Stochastic process, thus transport equation required;

- Processes:
  - Focussing in the diverging magnetic field,
  - Pitch angle scattering at magnetic field fluctuations,
  - Field-parallel propagation,
  - Convection with the solar wind (relevant only for low energies),
  - Adiabatic deceleration due to the expansion of the solar wind.

- Problems:
  - Interpretation of the magnetic field fluctuations.

# Energetic particles and shocks

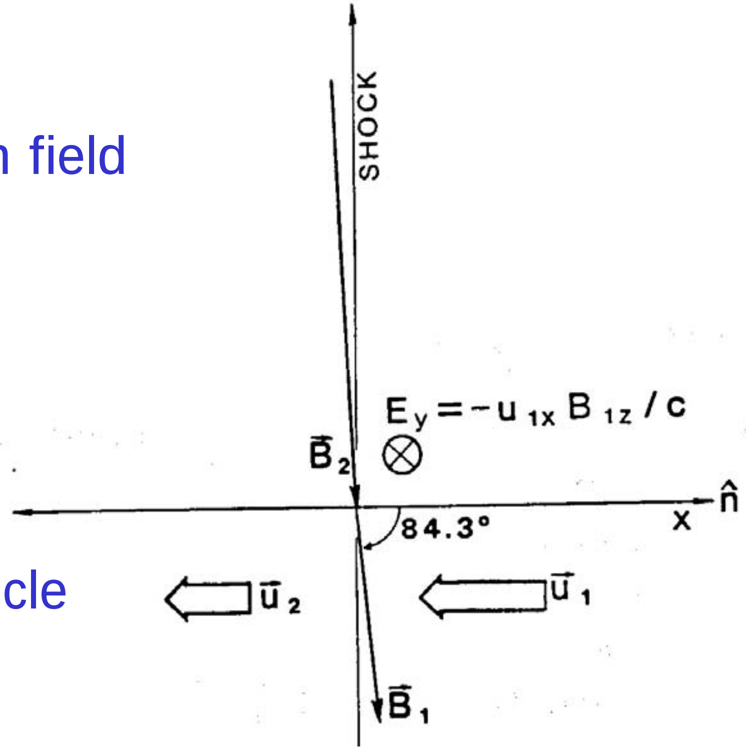
- Acceleration mechanisms:
  - Diffusive shock acceleration,
  - Shock drift acceleration (SDA),
  - Stochastic acceleration.

- Problems:
  - Efficiency,
  - Evolution of the shock during its propagation.

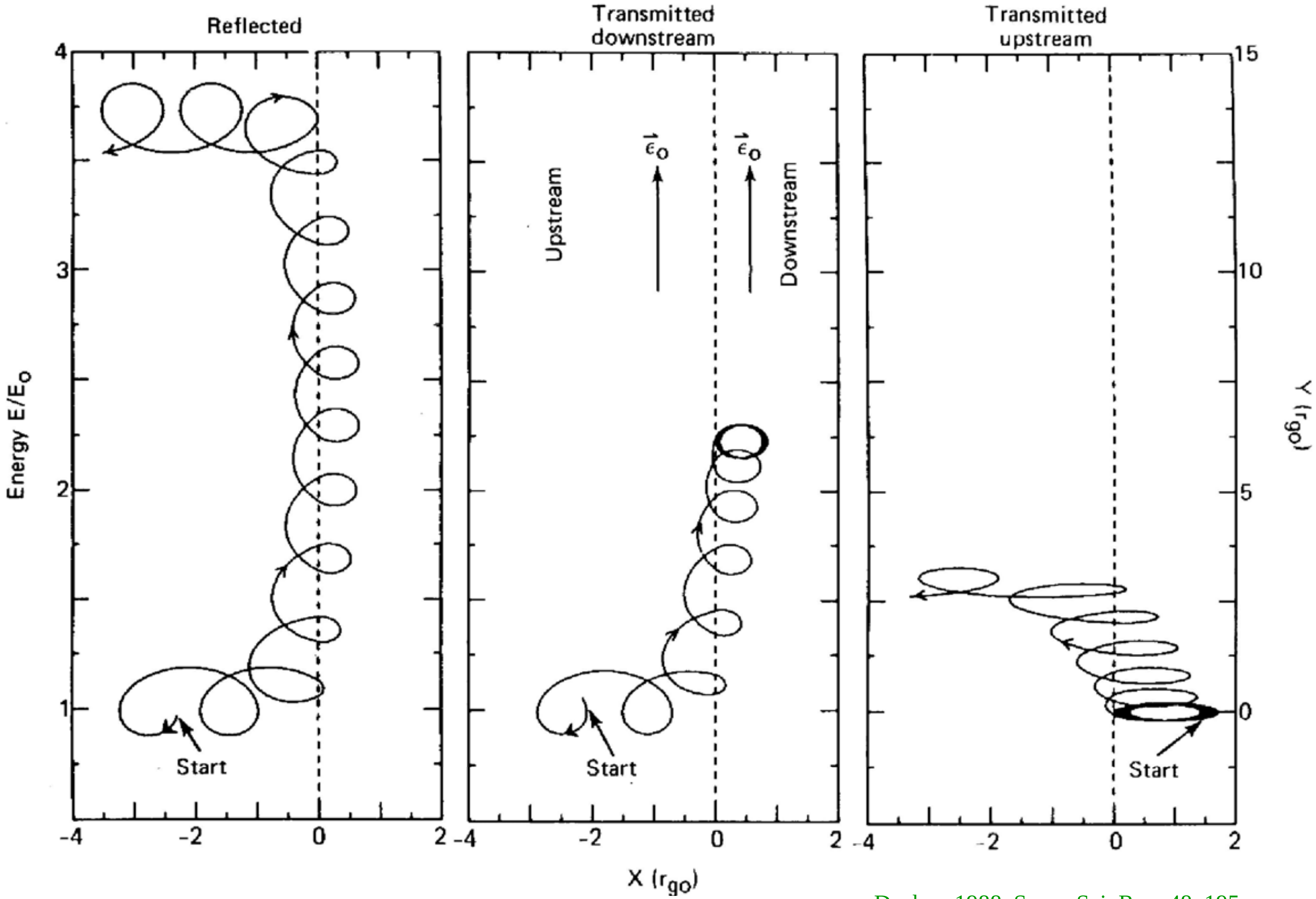
- Occurrence:
  - Interplanetary shocks,
  - Coronal shocks,
  - Bow shocks of the planets,
  - Supernova remnants, and many others ....

# Shock drift acceleration (SDA) - idea

- Acceleration in the uxB electric induction field in the shock front.
- Gradient drift leads to a particle drift depending on the charge sign.
- Drift direction always such that the particle gains energy.
- Reuqirement: quasi-perpendicular shock because than the induction field is maximum.



# SDA – sample orbits




Decker, 1988, Space Sci. Rev. 48, 195

# SDA - problems

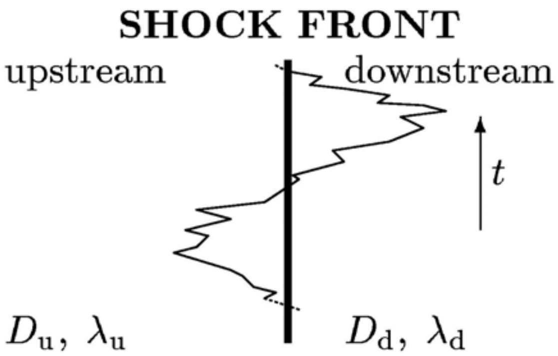
- Simple geometry: $\vec{E} = -\vec{u}_\mathrm{u} \times \vec{B}_\mathrm{u} = -\vec{u}_\mathrm{d} \times \vec{B}_\mathrm{d}$

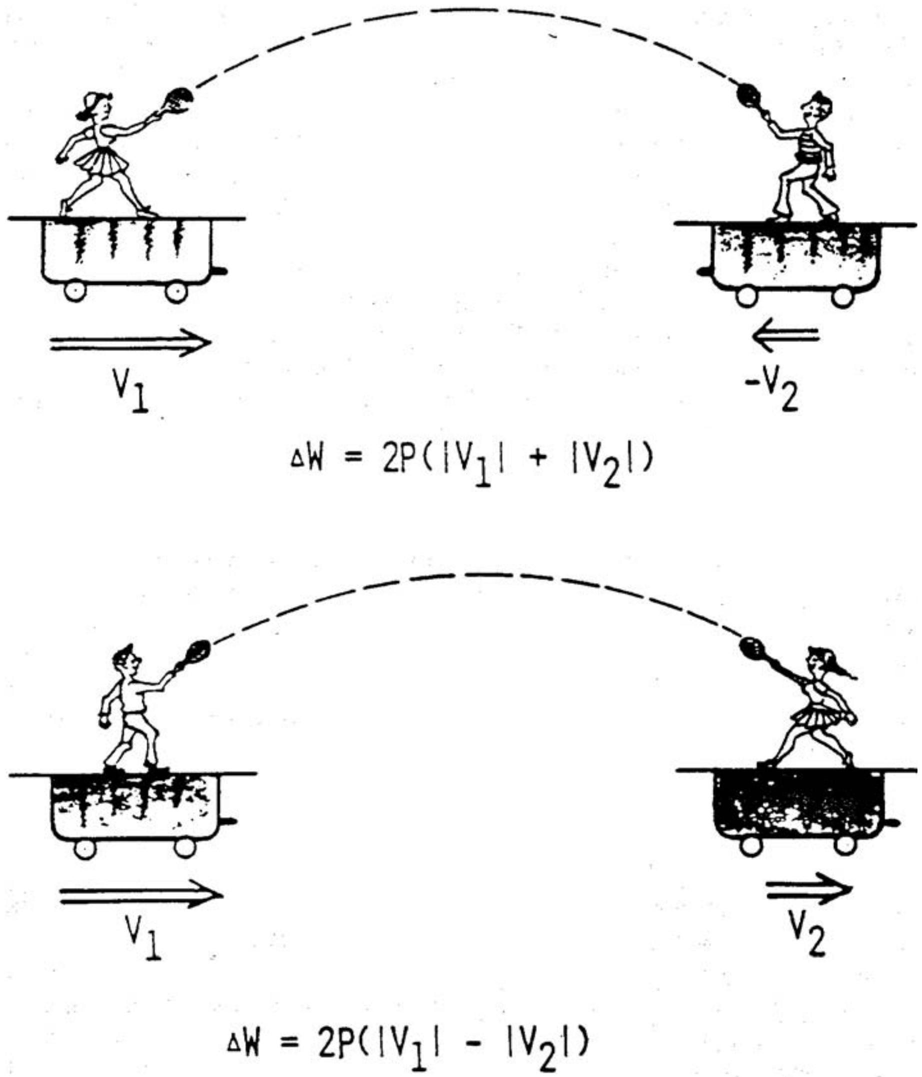
- Energy gain in each interaction only small:
  - Acceleration allows for escape from the shock front,
  - Scattering is small, thus only few particles are scattered back towards the shock for further acceleration,
  - Energy gain in each interaction can be determined from the constancy of the magnetic moment:

$$\frac{p_{2\perp}}{p_{1\perp}} = \frac{B_\mathrm{d}}{B_\mathrm{u}} = r_\mathrm{B}$$

- Acceleration from solar wind energies to the MeV range unlikely, more likely is a re-acceleration by a factor of about 2.

# Diffusive shock acceleration




- Idea: repeated scattering in the plasmas converging at the shock front

# Diffusive SA - formally

- Stochastic process $\Rightarrow$ transport equation

$$\frac{\partial f}{\partial t} + \overbrace{\vec{U}\nabla f}^{\text{Convection}} - \overbrace{\nabla\cdot(\mathtt{D}\,\nabla f)}^{\text{Spatial diffusion}} - \overbrace{\frac{\nabla\vec{U}}{3}p\frac{\partial f}{\partial p}}^{\text{Convection in momentum space}} + \overbrace{\frac{f}{T}}^{\text{losses}} + \overbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)f\right)}^{\text{Diffusion in momentum space (acceleration)}}$$
$$= Q(p,r,t)\ .$$

- Approximation: losses and convection in momentum space can be neglected

$$\frac{\partial f}{\partial t} + \vec{U}\nabla f - \nabla(\mathtt{D}\,\nabla f) - \frac{\nabla\cdot\vec{U}}{3}p\frac{\partial f}{\partial p} = Q(p,r,t)$$

- Results:
  - Characteristic acceleration times:

$$\tau_{\mathrm{a}} = \frac{p}{\mathrm{d}p/\mathrm{d}t} = \frac{3}{u_{\mathrm{u}}-u_{\mathrm{d}}}\left(\frac{D_{\mathrm{u}}}{u_{\mathrm{u}}} + \frac{D_{\mathrm{d}}}{u_{\mathrm{d}}}\right) \qquad \tau_{\mathrm{a}} = \frac{3r}{r-1}\frac{D_{\mathrm{u}}}{u_{\mathrm{u}}^2}$$

  - Energy spectrum: $J(E) = J_{\mathrm{o}}\,E^{-\gamma}$ with $\gamma = \frac{1}{2}\frac{r+2}{r-1}$

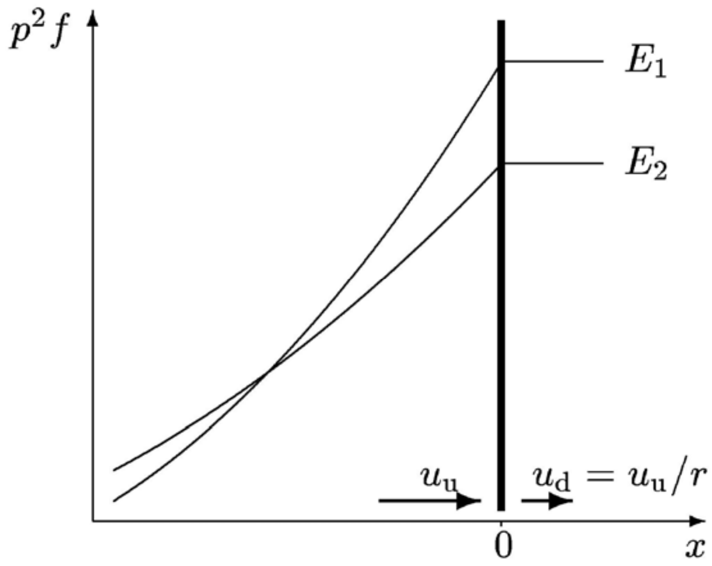
# Upstream Increase

- Steady state: exponential increase in the upstream medium

$$f(x,p) = f(0,p)\exp\{-\beta_i |x|\}$$

with scale length

$$\beta_i = \frac{u_i + \sqrt{u_i^2 + 4D_i/T}}{2D_i}$$




Application: determine scattering conditions upstream of the shock

# Self-generated turbulence

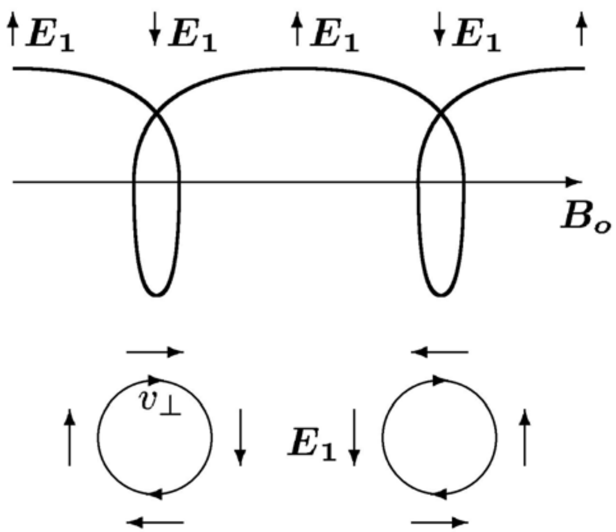
- Problem: acceleratioms long compared with the shock's travel time to 1 AU,
- But: accelerated particles can be observed.

- Bootstrapping mechanism:
  - Accelerated particles escape from the shock.
  - Particle beams excite waves in resonance with them.
  - Following particles are scattered at these waves:
    - They propagate back to the shocks,
    - They are accelerated to higher energies,
    - They escape from the shock front and excite waves .....
  - Development of a particle-wave field which allows acceleration to higher energies.
  - Ratio energy densities in particles and field

$$\frac{\varepsilon_{\mathrm{p}}}{\langle|\delta\vec{B}|^2\rangle/2\mu_{\mathrm{o}}} \propto \frac{u_{\mathrm{u}}}{v_{\mathrm{A}}}$$

# Stochastic acceleration

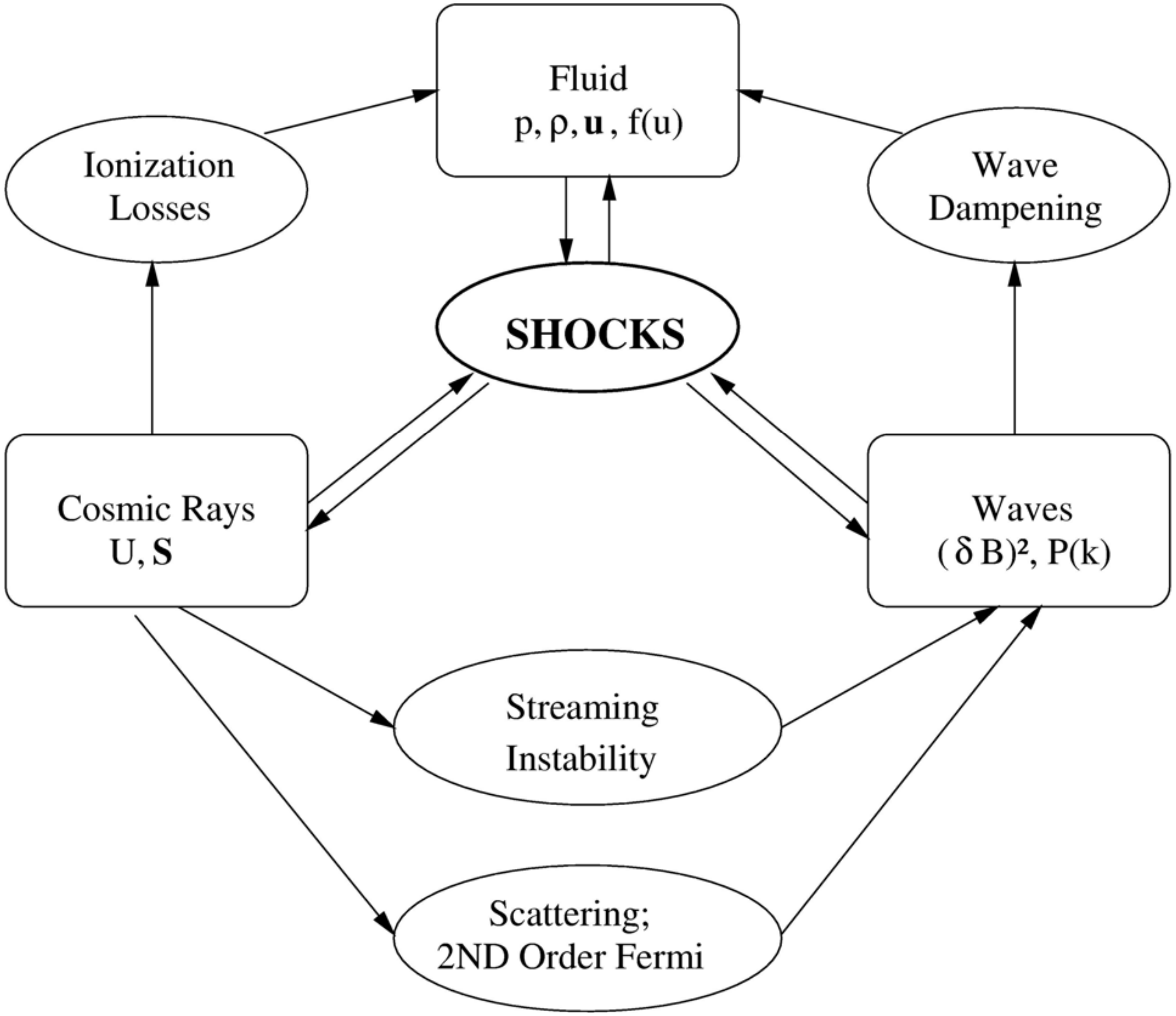
- Downstream medium extremely turbulent, thus scattering is strong:
  - Particles do not escape downstream,
  - Particles stay close to the shock and thus can be accelerated further,
  - Particles are stored in the turbulence (post shock increase).




Idea acceleration mechanism:

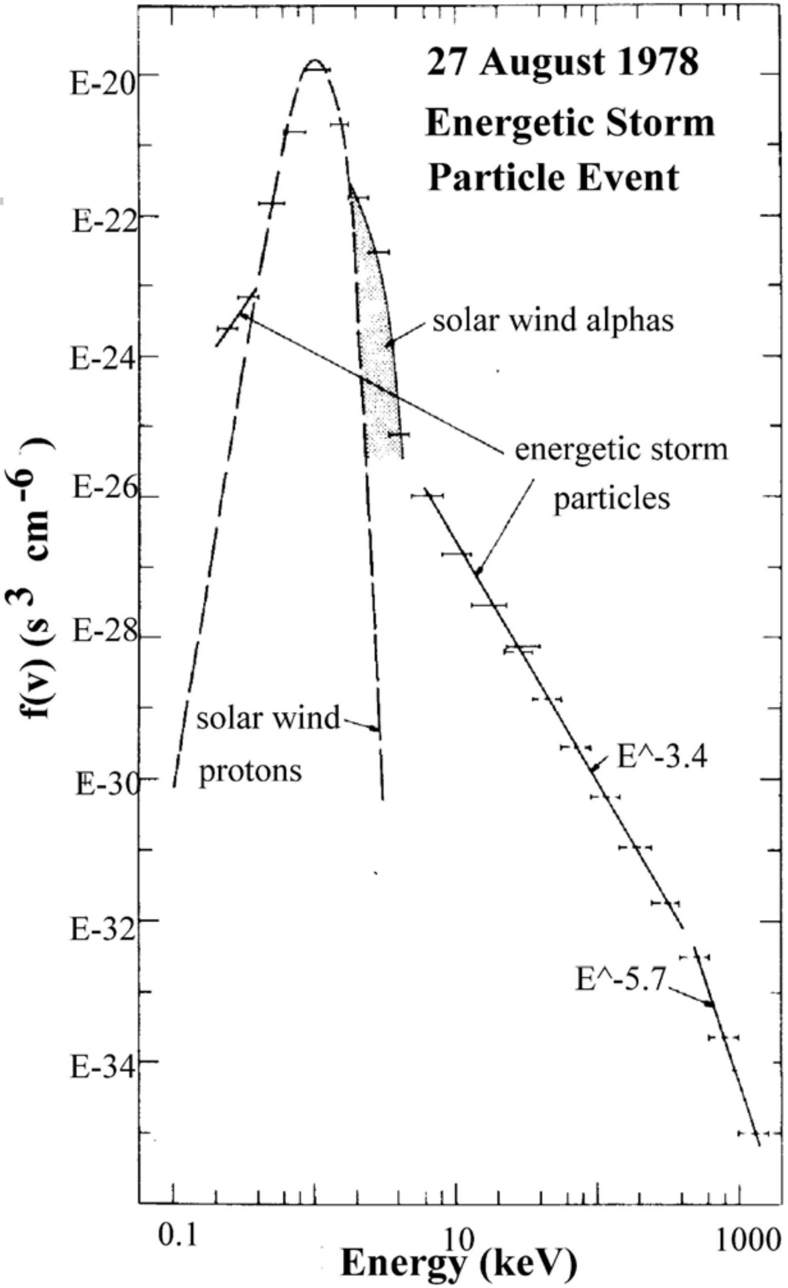
Resonant interaction with the electric field of a circularly polarized wave

# Shock as a non-linear system



# Energy spectrum

- Solar wind as thermal background.
- Superposed: energetic particles with power law spectrum (kappa distribution).
- Break in the spectrum around a few 100 keV:
  - Different acceleration mechanisms?
  - Steady-state not acquired at higher energies?

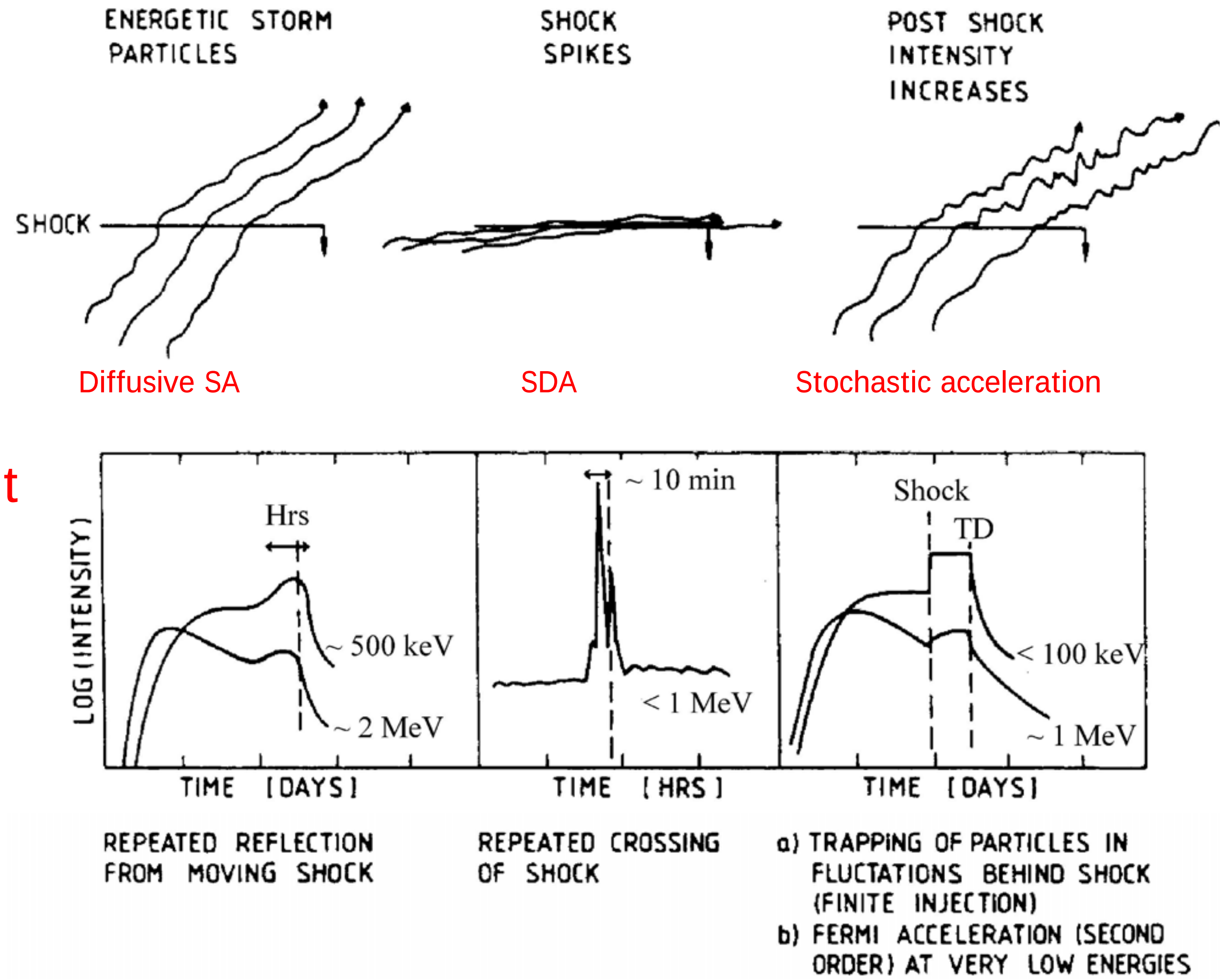



Gosling et al., 1981, J. Geophys. Res. 86, 547

# Particles at the shock – low energies (up to some 100 keV)

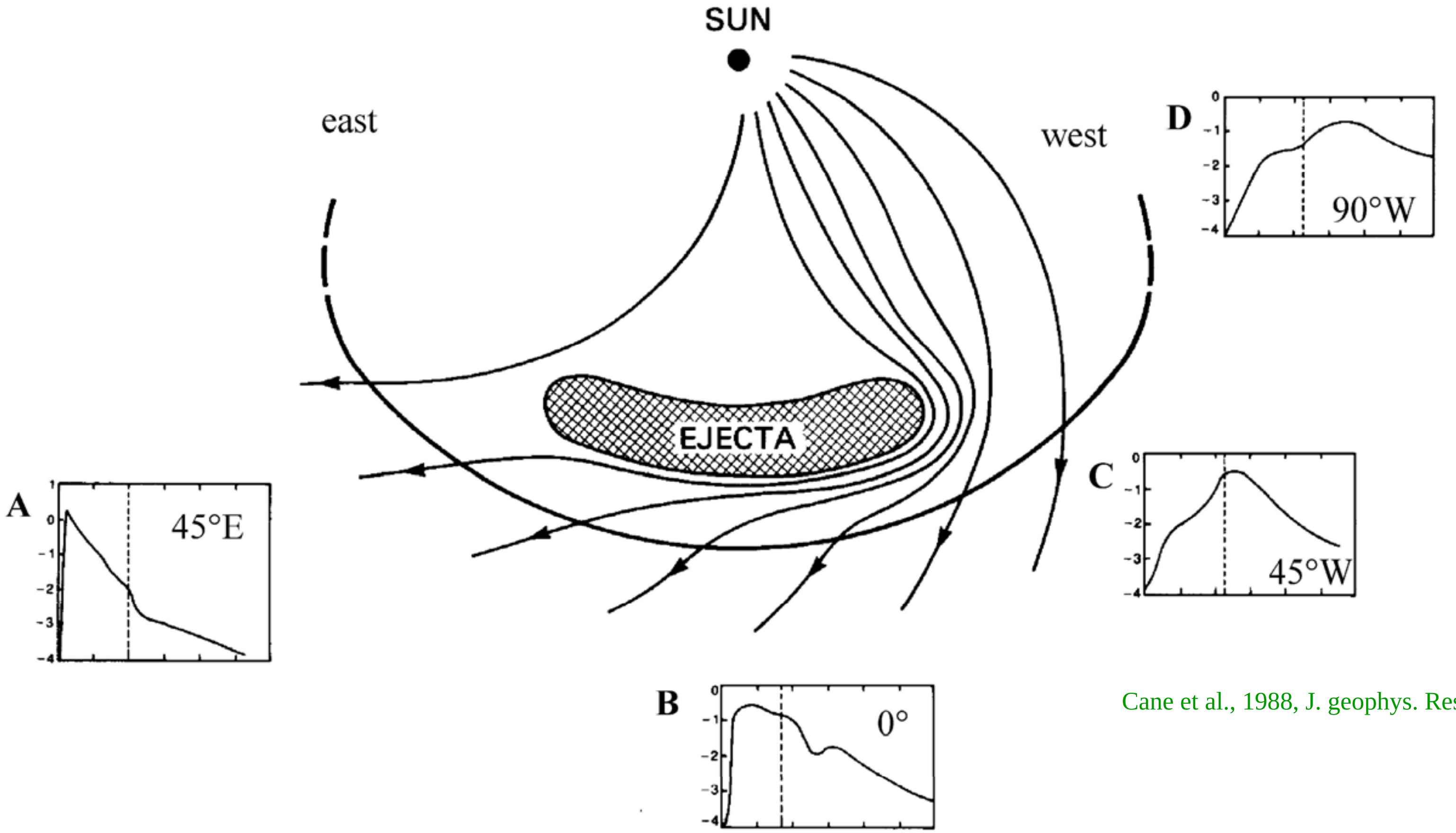
All three acceleration mechanisms can be observed!!!

Spectra and upstream increases in agreement with predictions from models




Scholer and Morfill, 1977, in Study of traveling interplanetary phenomena, AFGL

# Particles at shocks – higher energies

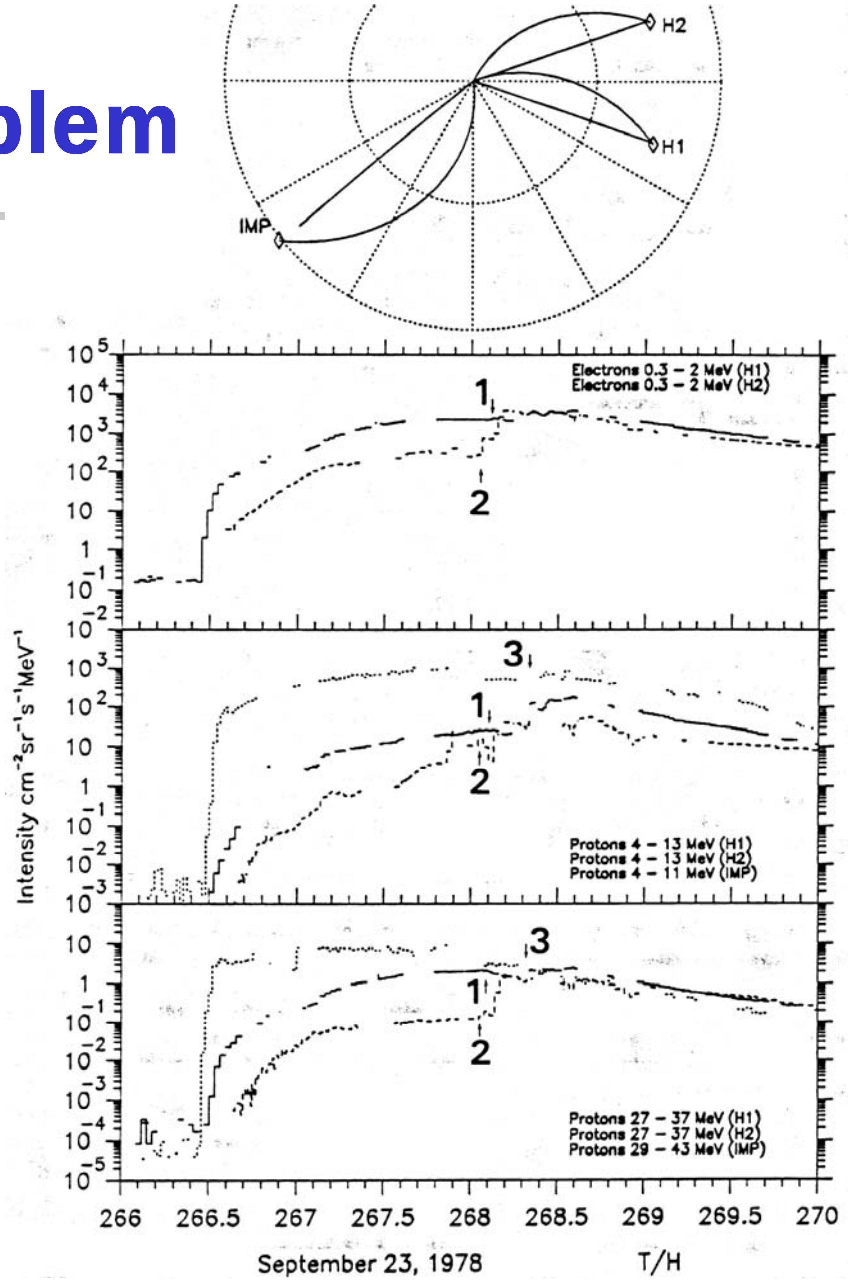



Cane et al., 1988, J. geophys. Res. 93, 9555

- Large particle speeds $\Rightarrow$ shock effects not only locally.
- Profiles collect particles accelerated at the shock all along the field line $\Rightarrow$ interpretation difficult

# Observational problem

- Statistical analysis gives dependence of particle event on observer's location as on previous slide
- Observations of individual events from different positions suggest smaller variations with observer's location ⇒ number of multi-spacecraft observations limited thus most models based on statistical analysis.



# Higher energies and theory

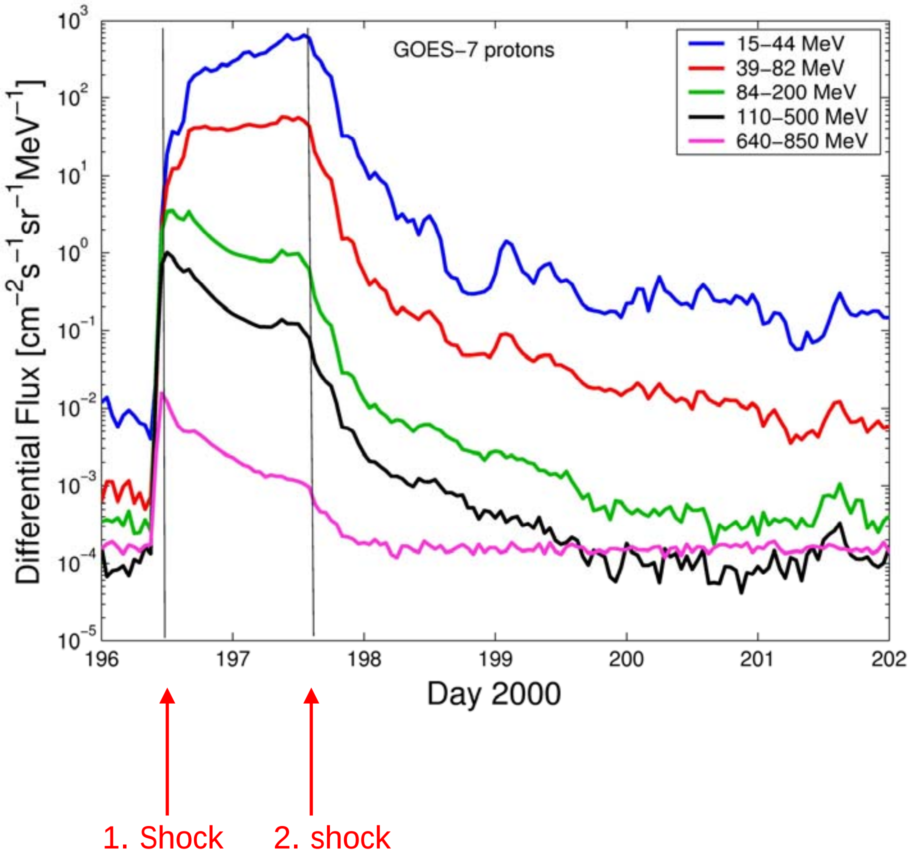
- Predictions from theory (spectral index, upstream increase, time scales of acceleration) are not in agreement with the observations.

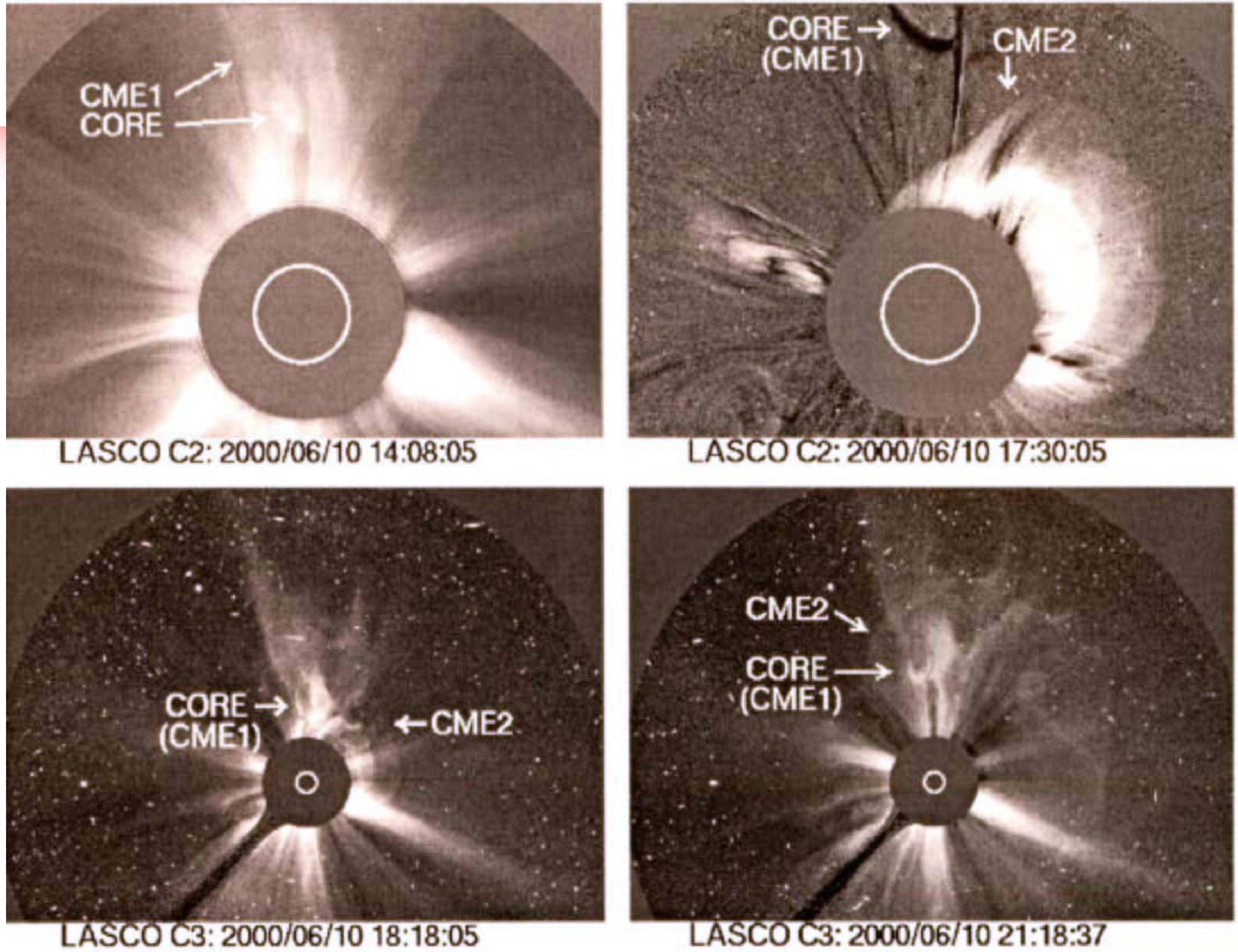
- Possible reasons:
  - Convolution of acceleration/injection and subsequent propagation not considered,
  - Incorrect application of the model (steady state not acquired),
  - Other acceleration mechanisms,
  - Acceleration not our of the solar wind but out of a pre-existing energetic particle component.

Particle acceleration in the MeV range not fully understood.

# Converging shocks

- More complications: extremely large particle events often are observed to occur between two shocks.
- Efficient acceleration by Fermi 1 effect.
- Conceptual problem: properties of particle events do not only depend on the sources flare and shock but also on the properties of the ipl. medium.






Gopalswamy et al., 2001, Astrophys. J. 548, L91

# Cannibalizing CMEs

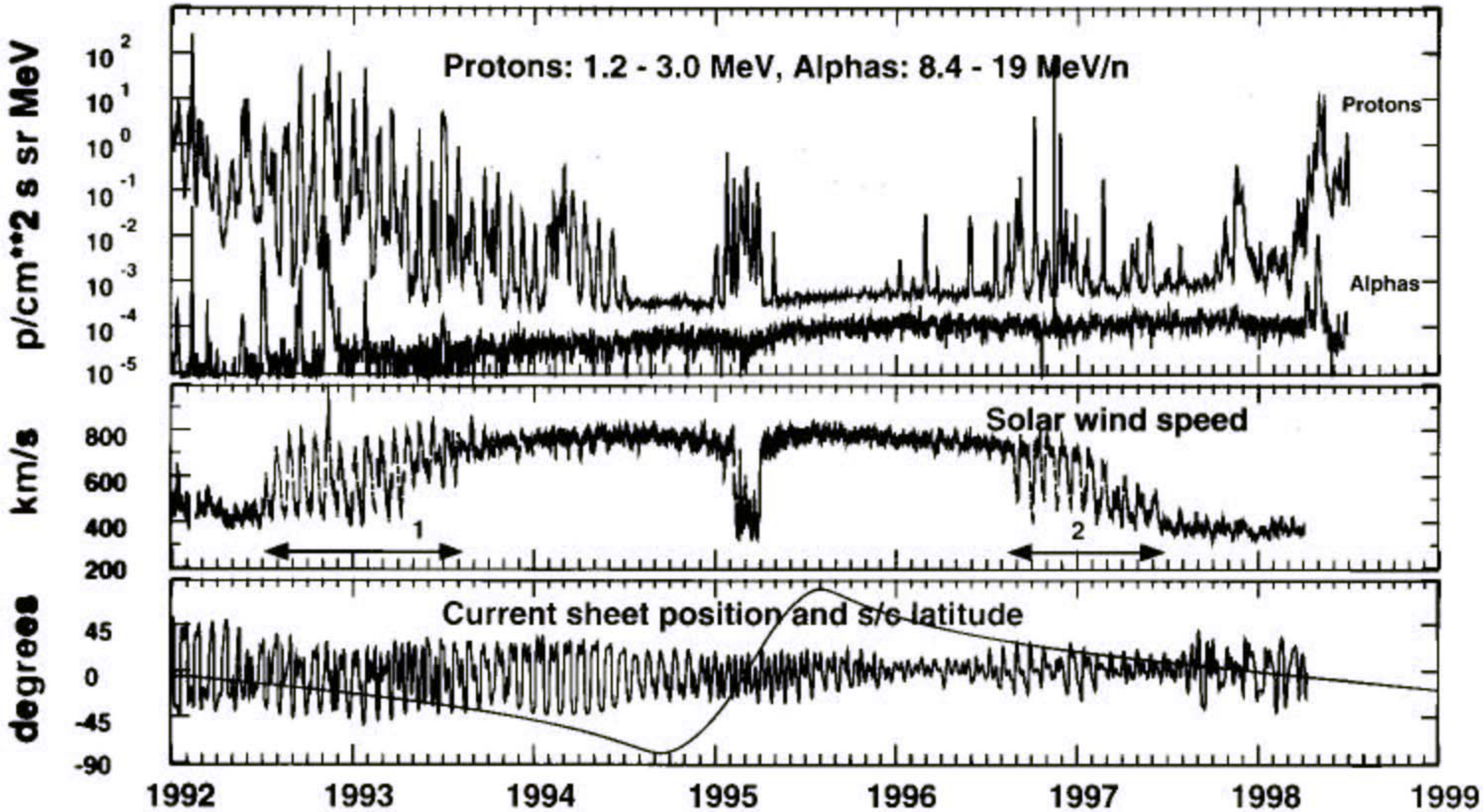
- CMEs overtaking each other and merging within the field of the coronograph.
- Complex structures of magnetic clouds in interplanetary space (can be observed).
- Efficient particle acceleration (statistical analysis).
- Mechanisms for particle acceleration:
  - Short period of convergence in the corona with Fermi 1?
  - Merged CME as driver of a super-shock?

# Particles at CIRs

- Shocks at corotating interaction regions (CIRs) can accelerated particles
- Comparison of particle properties with interplanetary shocks

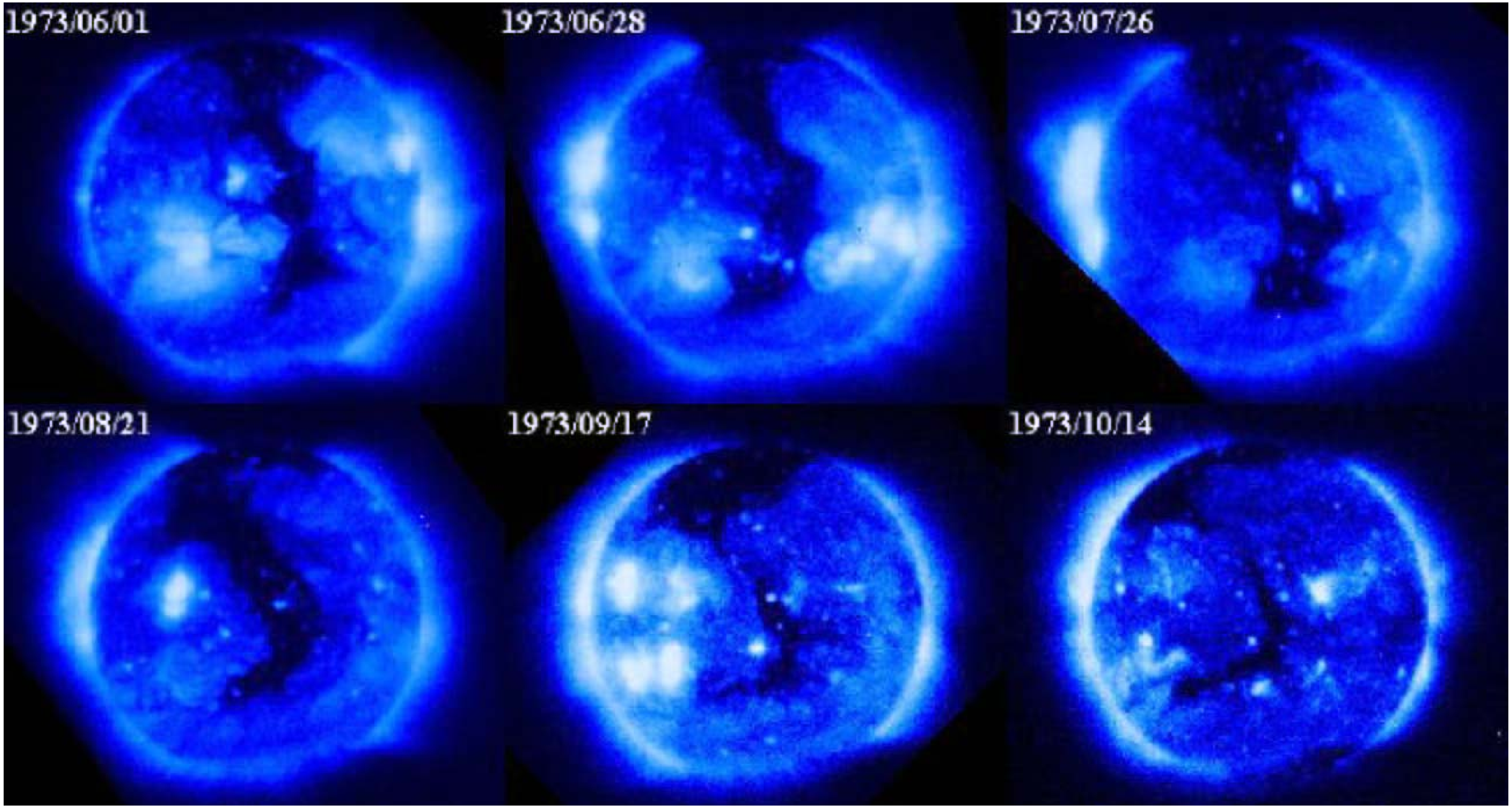
| Particles accelerated at CME-driven shocks | Particles accelerated at CIR-shocks |
|---|---|
| • particle energies up to some 100 MeV (protons) and some MeV (electrons). | • particle energies limited to about 10 MeV (protons) and 200 keV (electrons). |
| • particles stream away from the shock (sign of anisotropy changes as the shock passes by). | • at 1 AU particles stream towards the Sun. |
| • most efficient acceleration close to the Sun. | • most efficient acceleration at about 4 AU. |
| • in low energies mainly solar wind composition but there are exceptions (a) for individual events, (b) in energy, (c) with time. | • nearly solar system composition except for enhanced He and C relative to O. |
| • particles can be observed although the shock is not observed. | • low energy ions observed at 1 AU or high latitudes in the absence of shocks. |
| • no evidence for pickup of anomalous cosmic rays. | • singly charged He indicates pickup of ACRs. |

# Particles at CIRs - recurrence



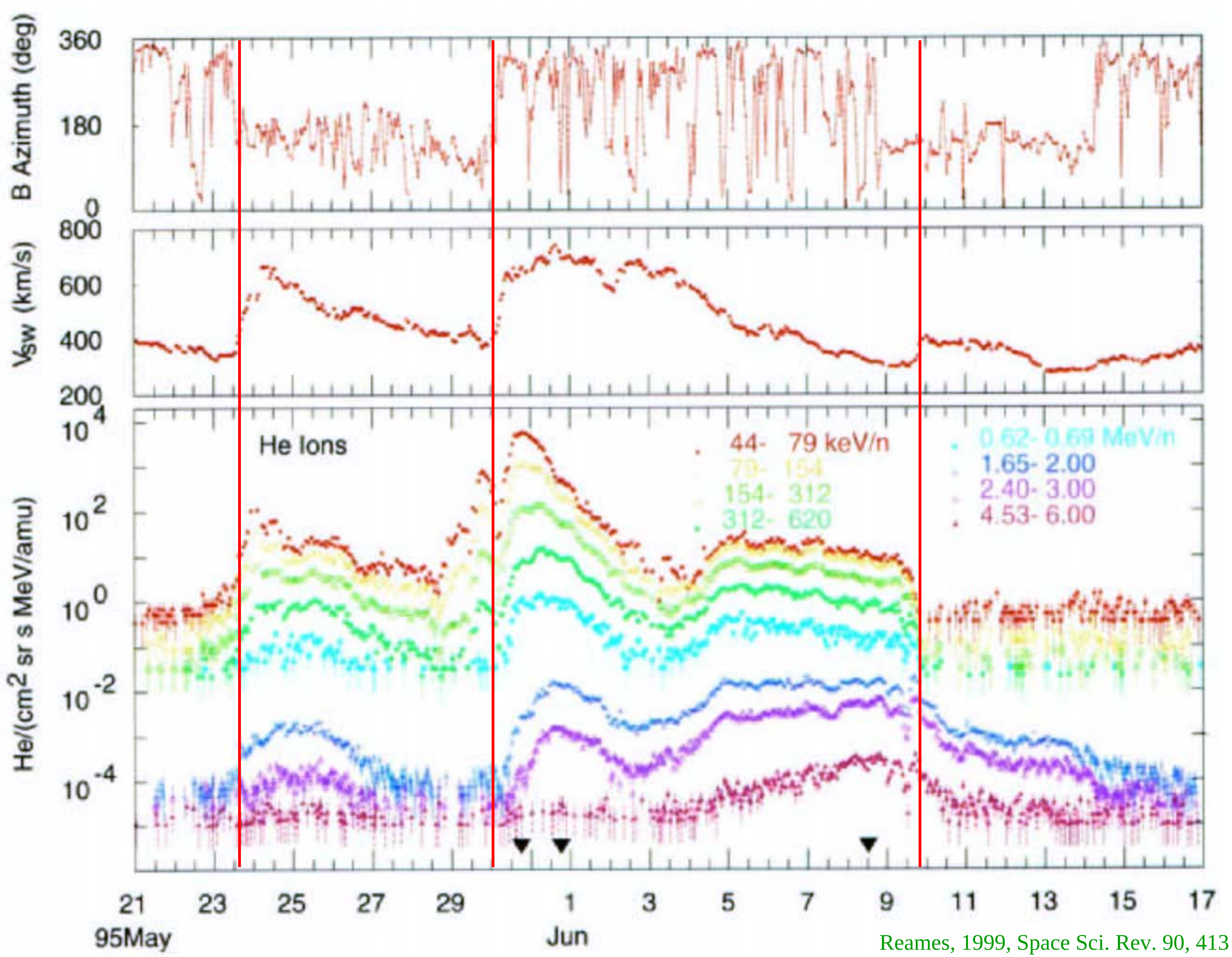

Sanderson et al., 1999, Geophys. Res. Lett. 26, 1785

# Coronal hole




http://sohowww.nascom.nasa.gov/

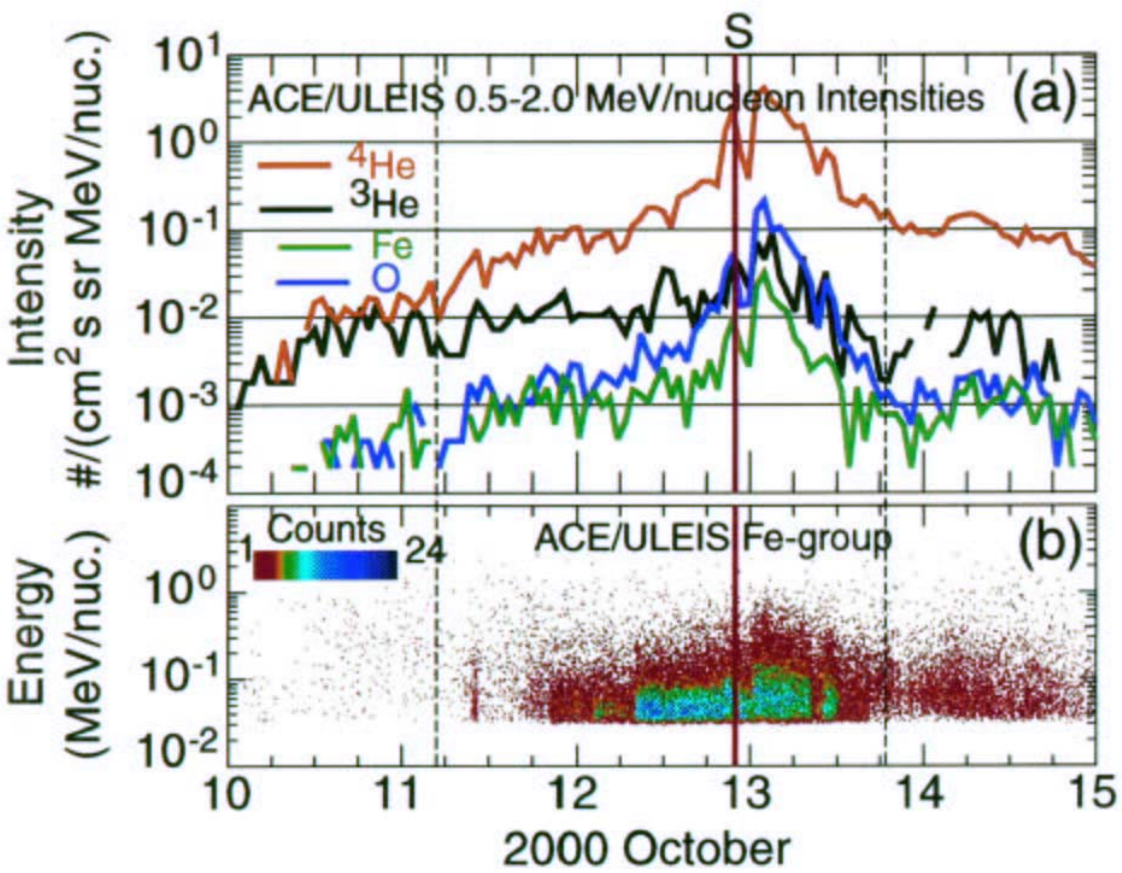
# Particles at CIRs – one rotation




Reames, 1999, Space Sci. Rev. 90, 413

# 3He-rich CIRs

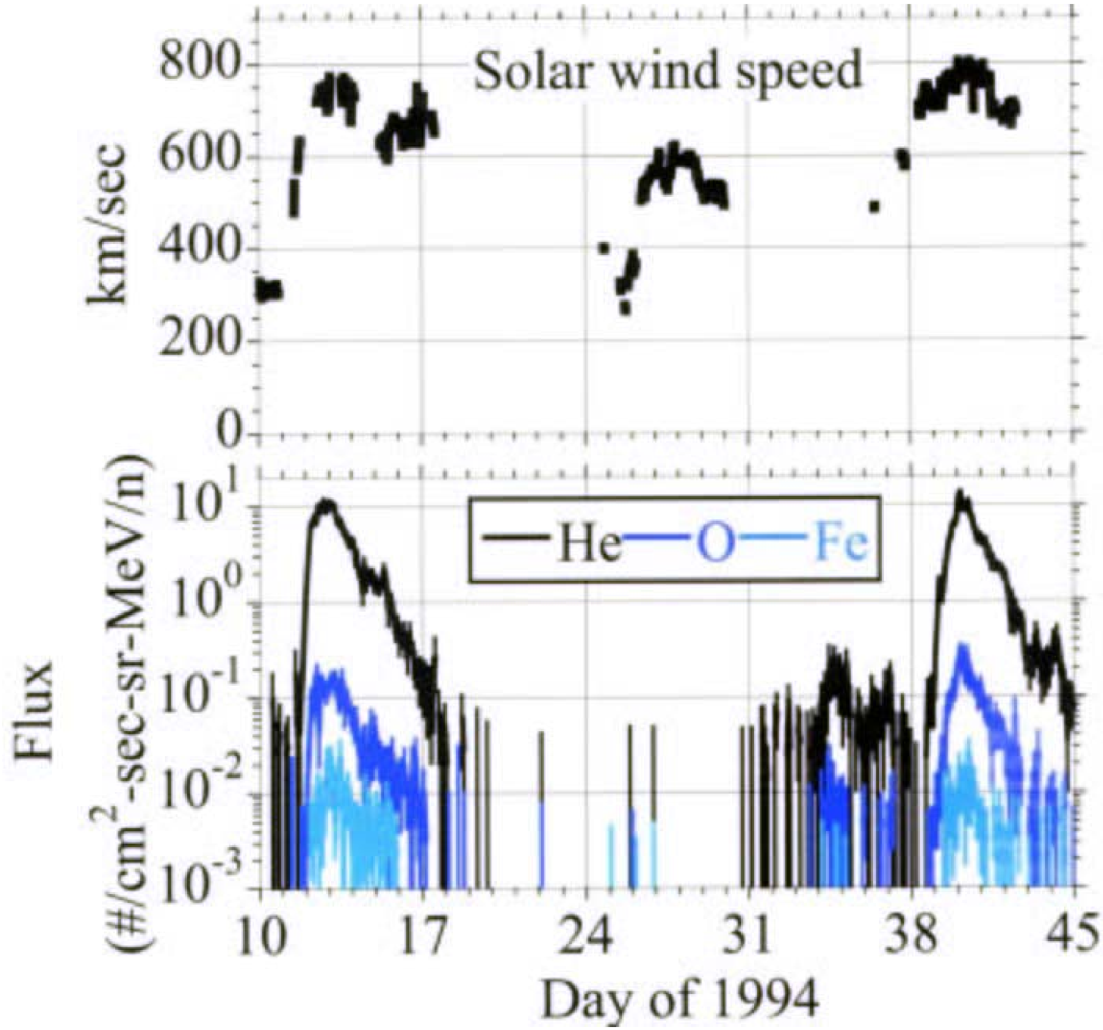
- Enrichment in 3He by a factor of 3 to 600.
- Likelihood for 3He-enrichment increases with solar activity.
- Particle acceleration not only out of the solar wind but also out of a background population from earlier events.




Desai et al., 2001, Astrophys. J. 553, L89

# Pick up ions at CIRs?

- Supra-thermal H+ and He+ frequently observed.
- Heavy ions comparable to the ones at ipl. shocks.
- High charge states: acceleration mechanism unknown.




Mazur et al., 2002, Astrophys. J. 566, 555

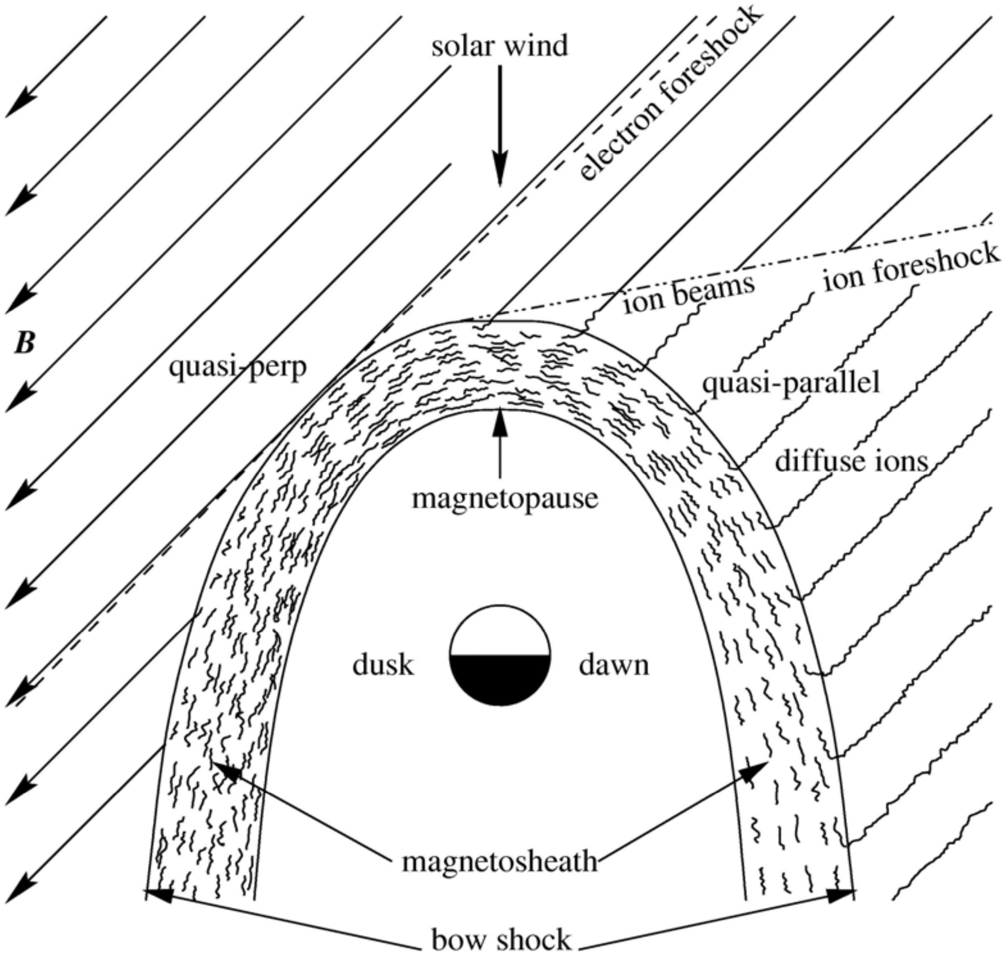
# CIR particles and theory

- Acceleration times and spectra in agreement with predictions from theory.

- but: acceleration not only out of the solar wind
  - Pick-up ions,
  - Particles from earlier impulsive events,
  - Particles from earlier gradual events cannot be identified because they have the same properties as particles accelerated at the CIR shocks.

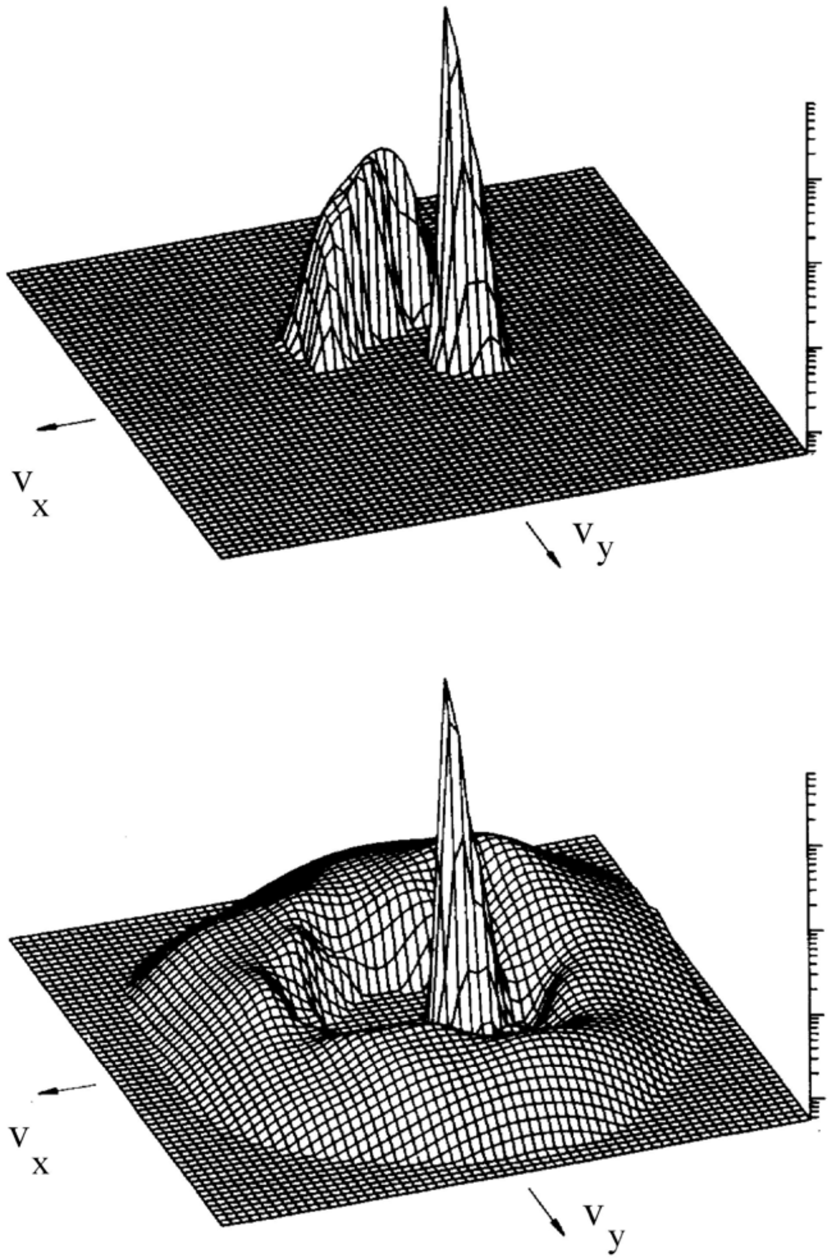
# Particles at the bow shock I

- Low energies.
- Properties of particles in agreement with theory, this holds also for the spatial distribution of event types.
- Similar patterns at other planetary bow shocks.



# Particles at the bow shock II

- Peak in the middle: incident solar wind.
- Top: rather confined distribution propagates into the solar wind as expected for shock drift acceleration.
- Bottom: roughly isotropic distribution as expected for diffusive shock acceleration.



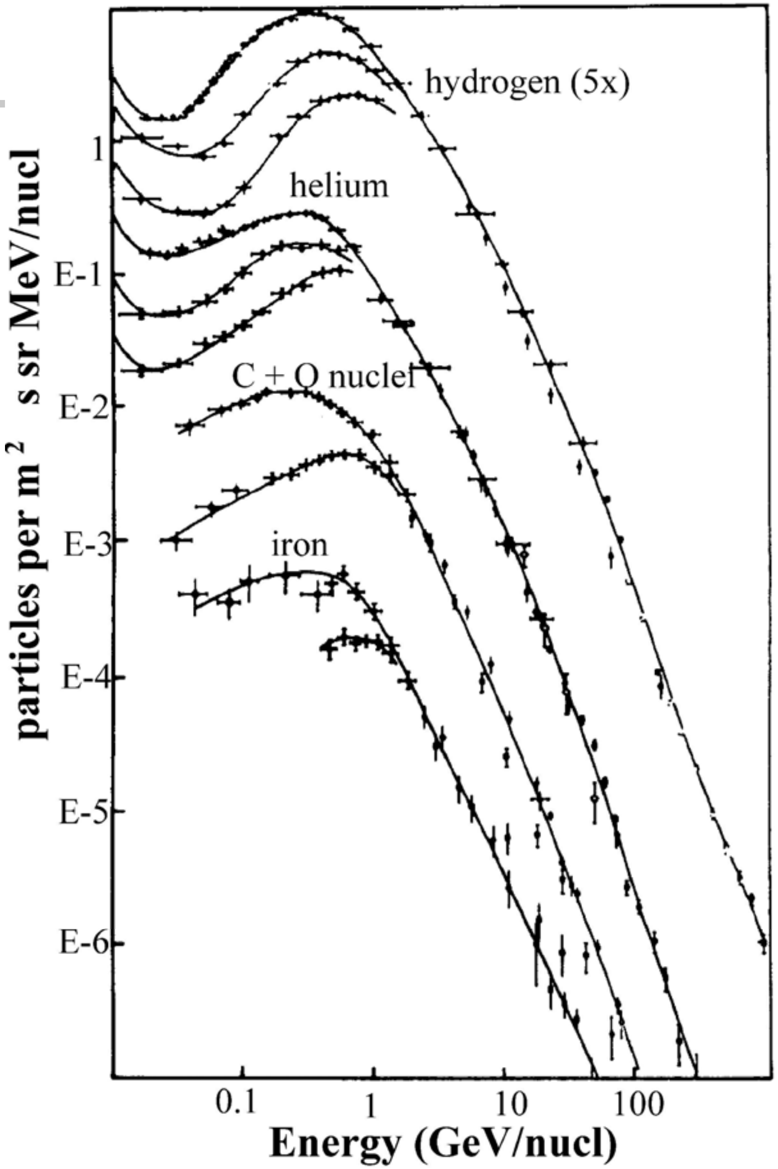

Paschmann et al., 1981, J. Geophys. Res. 86, 4355

# Galactic cosmic rays (GCRs)

- Particles are incident isotropically on the solar system.
- Composition mainly e, p und $\alpha$ with small contributions of heavier nuclei such as C, O and Fe.
- Flux at earth: 1000/m^2s.
- Modulation with the solar cycle.
- Sub-population: anomalous cosmic rays (ACRs, lower charge states, different temporal development).

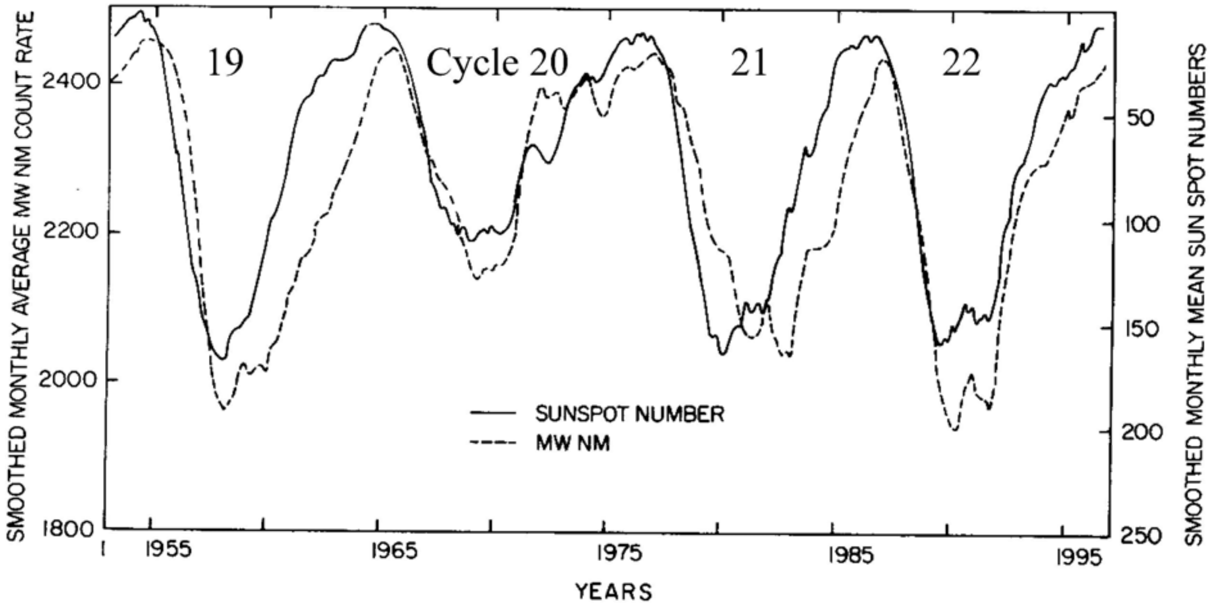
# GCRs: spectrum

- Spectrum gives the continuation from SEP energies up to 1E20 eV.
- Spectrum increases up to 100 MeV, at higher energies power law with $\gamma$ = -2.5




Meyer et al., 1974, Physics Today 27, 10

# GCRs: modulation

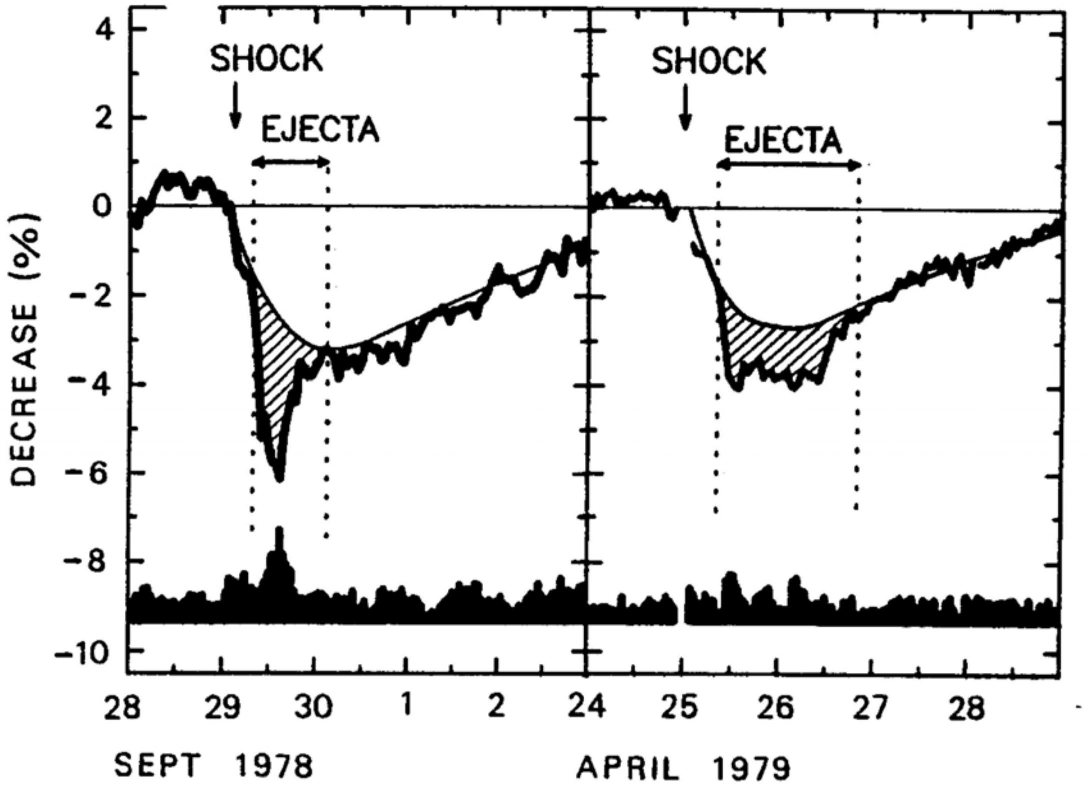



Lockwood and Webber, 1997, J. Geophys. Res. 102, 24221

- Modulation with the solar cycle at energies below a few GeV,
- Amplitude maximum at 100 MeV (about 1 order of magnitude),
- Amplitude at 4 GeV about 15-20%,
- Time lag: GCR variation follows sunspot variation.

# GCRs: Forbush decreases

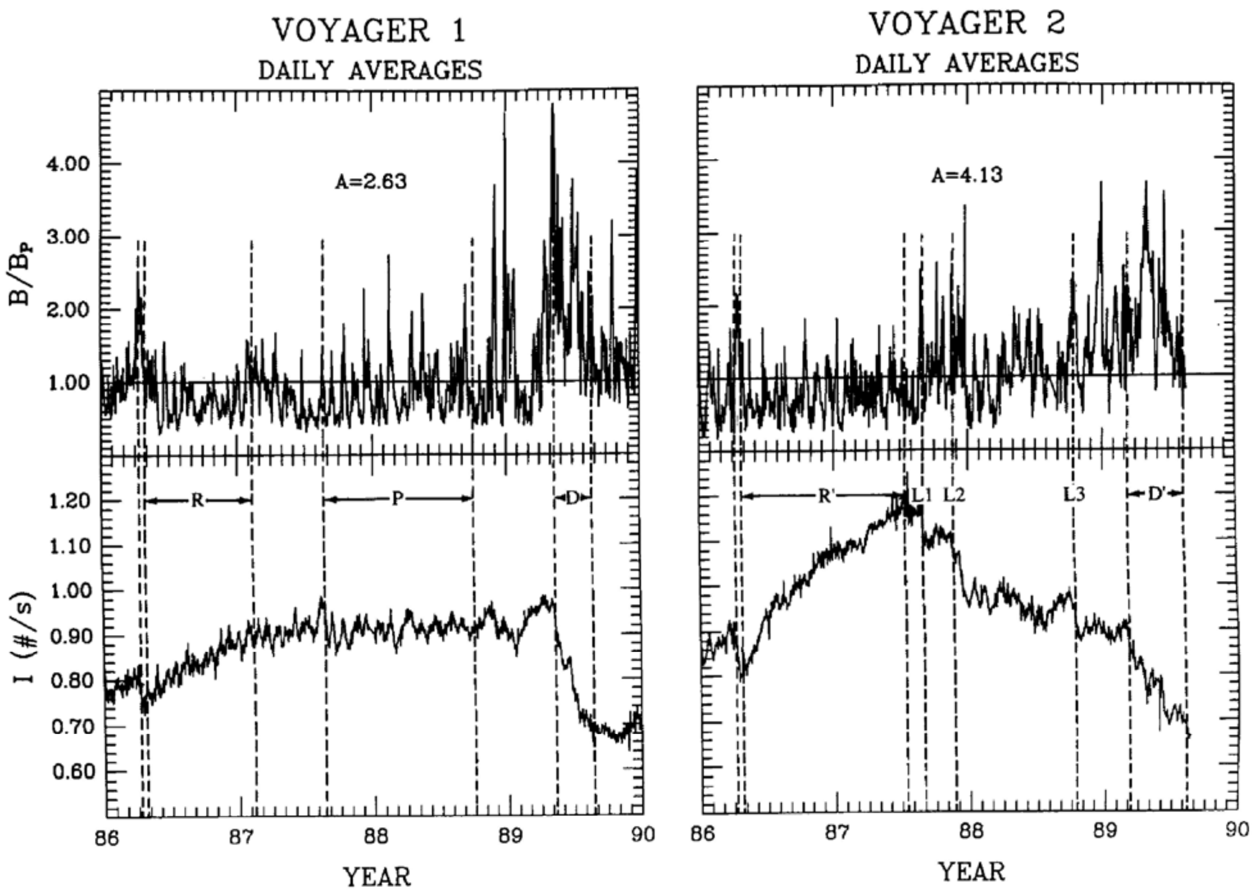
- Decrease in GCRs at related to the passage of a shock and/or magnetic cloud.
- Amplitude at the shock about 2%, at the cloud about 5% at 500 MeV.
- CIRs also contribute to the modulation of GCRs.




Wibberenz, 1998, Space Sci. Rev., 83, 310

# CRB-Relation

- MIR: merged interaction region:
  - LMIR: local
  - CMIR: corotating
  - GMIR: global.
- All reduce GCRs
- CRB-relation:




Burlaga, 1993, J. Geophys. Res. 98, 1

$$\frac{\mathrm{d}J}{\mathrm{d}t} = -D\left(\frac{B}{B_\mathrm{P}} - 1\right) \qquad \text{for } B > B_\mathrm{P}$$

$$\frac{\mathrm{d}J}{\mathrm{d}t} = R \qquad \text{for } B < B_\mathrm{P}$$

(Bp: Parker field)

# GCRs: gradients

- Variation of GCR intensity with radial distance r and latitude $\lambda$:

$$\frac{1}{J}\,\mathrm{d}J = g_{\mathrm{r}}\,\mathrm{d}r + g_{\lambda}\,\mathrm{d}\lambda$$

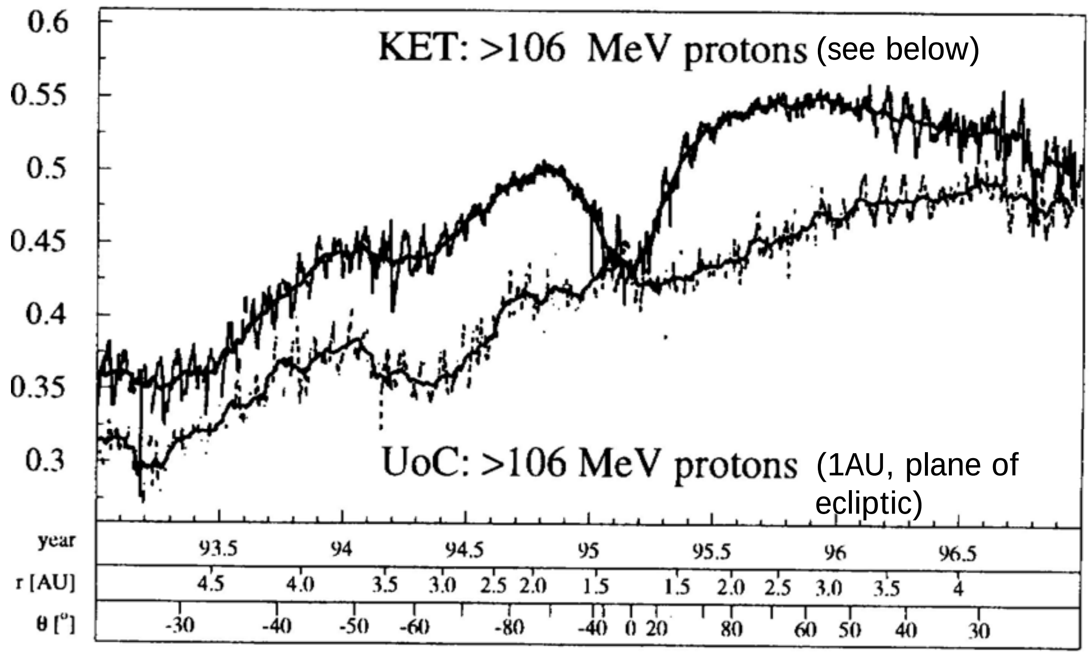
  with the local gradients:

$$g_{\mathrm{r}} = \frac{1}{J}\frac{\mathrm{d}J}{\mathrm{d}r} \qquad \text{and} \qquad g_{\lambda} = \frac{1}{J}\frac{\mathrm{d}J}{\mathrm{d}\lambda}$$

- Problem: measurements only from widely-spaced spacecraft, thus local gradients cannot be measured directly.

- Radialer gradient $g_{\mathrm{r}} = G_{\mathrm{o}}\,r^{\alpha}$ with G and $\alpha$ time dependent in a rather complex manner.

# GCRs: latitudinal gradient




Heber et al., 1998, J. Geophys. Res. 103, 4809

- Pronounced latitudinal gradient only as long as Ulysses is inside the coronal hole.
- The latitudinal gradient vanishes in the streamer belt where fast and slow solar wind streams are observed .

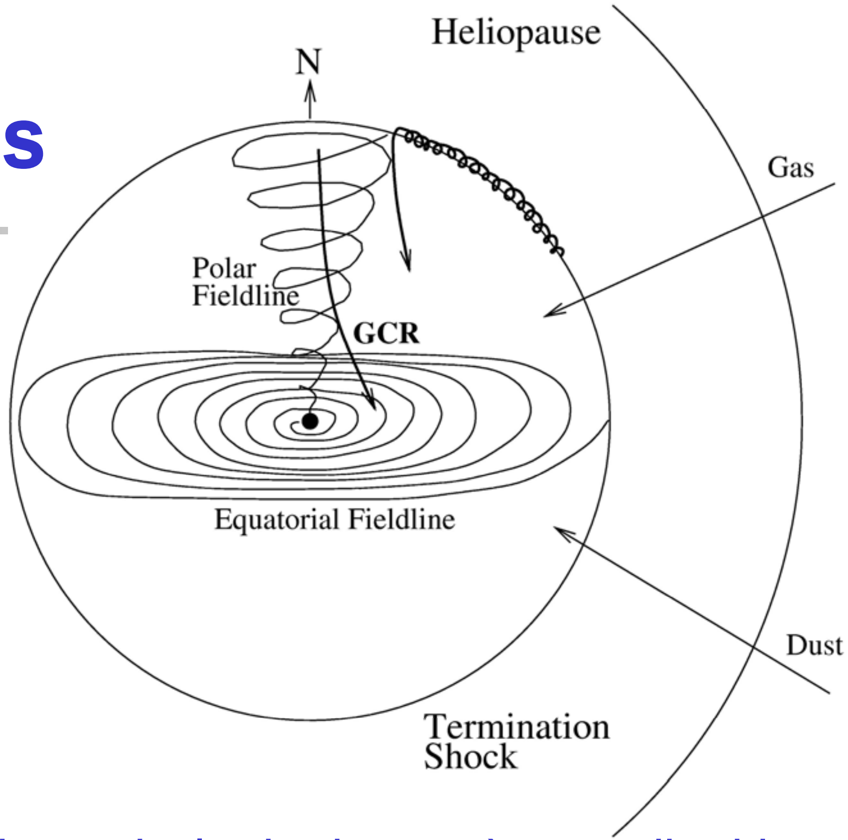
# Modulation models

- Relevant effects:
  - Diffusion (parallel and perpendicular to the field):

$$\kappa_\perp = \frac{v r_\mathrm{L}}{3}\frac{\lambda_\|/r_\mathrm{L}}{1+(\lambda_\perp/r_\mathrm{L})^2}$$

radial $\kappa$:

$$\kappa_\mathrm{rr} = \kappa_\| \cos^2\psi + \kappa_\perp \sin^2\psi$$




  - Drift (curvature and gradient drift, in particular in the HCS). Described by a drift speed

$$\vec{v}_\mathrm{D} = \frac{cvp}{3q}\left[\nabla \times \frac{\vec{B}_\mathrm{o}}{B_\mathrm{o}^2}\right]$$

or as antisymmetric part of the diffusion tensor

$$\kappa = \begin{pmatrix} \kappa_\| & 0 & 0 \\ 0 & \kappa_\perp & \kappa^\mathrm{T} \\ 0 & -\kappa^\mathrm{T} & \kappa_\perp \end{pmatrix}$$

# Transport equation modulation

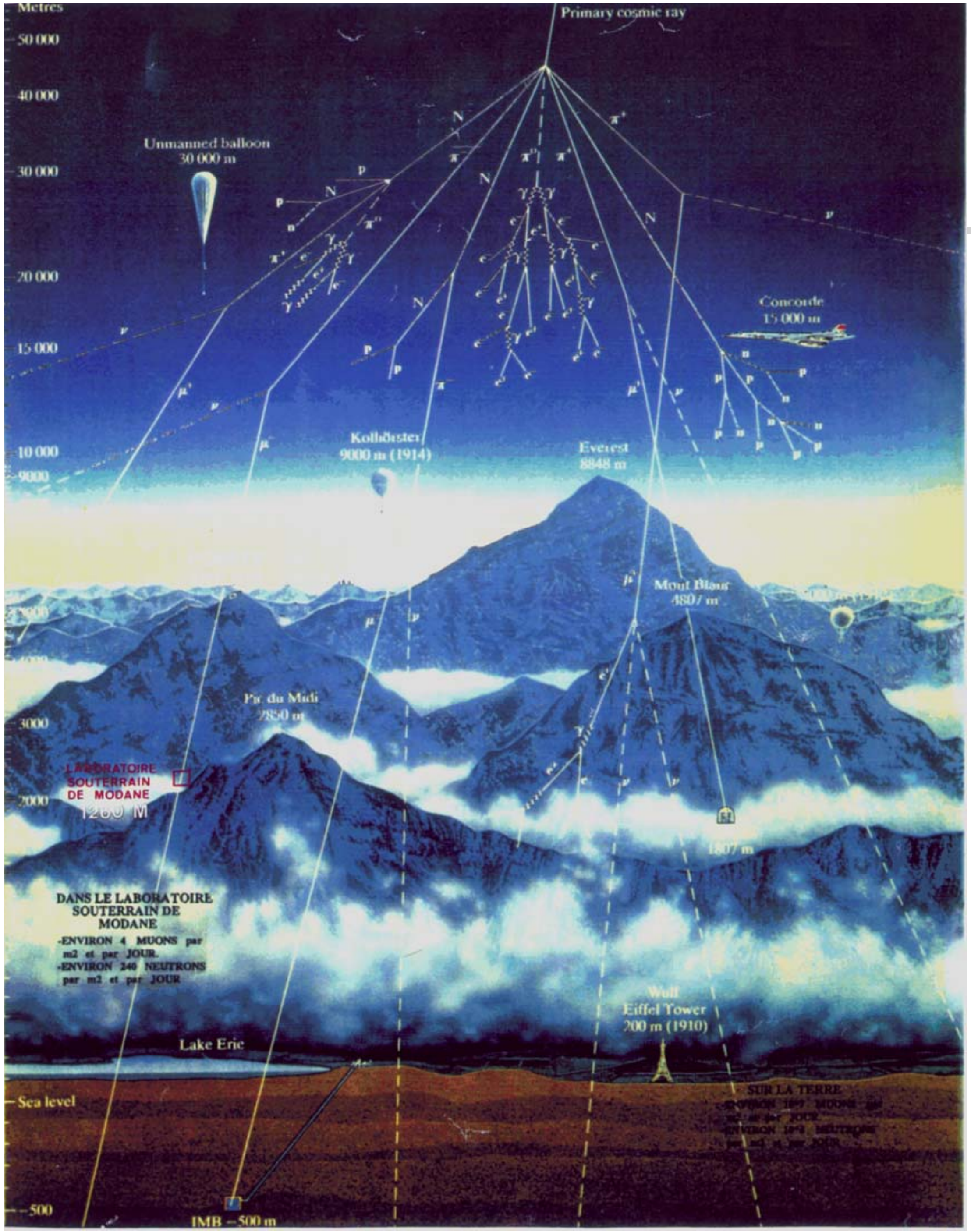
- Transport equation:

$$\frac{\partial U}{\partial t} = \underbrace{\nabla \left( \kappa^{\mathrm{s}} \, \nabla U \right)}_{\substack{\text{Diffusion} \\ \text{(symmetrical part of} \\ \text{the diffusion tensor)}}} - \underbrace{\left( \vec{v}_{\mathrm{sowi}} + \vec{v}_{\mathrm{D}} \right) \cdot \nabla U}_{\substack{\text{„bulk motion“:} \\ \text{convection with the} \\ \text{solar wind and drift}}} + \underbrace{\frac{1}{3} \nabla \, v_{\mathrm{sowi}} \frac{\mathrm{d}(\alpha T U)}{\mathrm{d}T}}_{\substack{\text{Adiabatic deceleration in the} \\ \text{expanding solar wind (T: particle} \\ \text{energy)}}} \, .$$

- Modulation parameter: simple approximation in steady-state neglecting drifts

$$\Phi = \int_{r}^{R} \frac{v_{\mathrm{sowi}} \mathrm{d}r}{3\kappa(r, P)}$$

corresponds to the average energy loss due to adiabatic deceleration for a particle propagating from the outer boundary R of the heliosphere to an observer at r (some 100 MeV between 100 AU and 1 AU).




http://lyoinfo.in2p3.fr/manoir/montagne.gif

# GCRs in the atmosphere

- Ionization
  - Mesosphere and above
  - Small because particles are minimally ionizing
- Air shower
  - Stratosphere and troposphere
  - Cosmogenic nuclides
  - Neutrons
  - Electromagnetic cascade
  - Many other elementary particles (myon, pion ...)

# Summary

- Energetic particles have different sources with different composition, energy spectra and temporal variation.

- Particle acceleration due to reconnection and in particular at shocks:
  - Many open questions
  - Frequent changes in current paradigm

- Particle propagation determined by (pitch angle) scattering, drift and the large-scale magnetic field (focusing, convection, adiabatic deceleration).