Workshop on High Energy Flare Physics   University of Glasgow, 25 – 26 June 2012

Transport of Solar Energetic Particles

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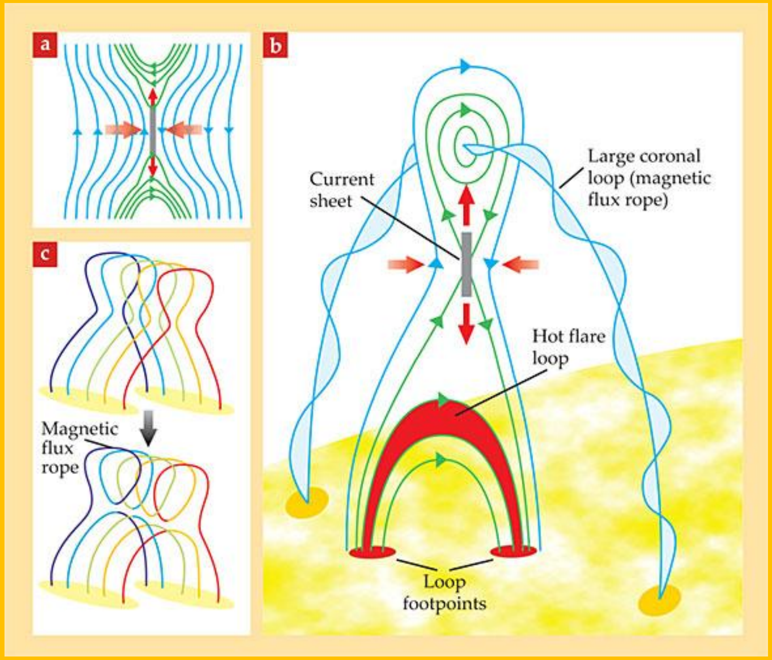
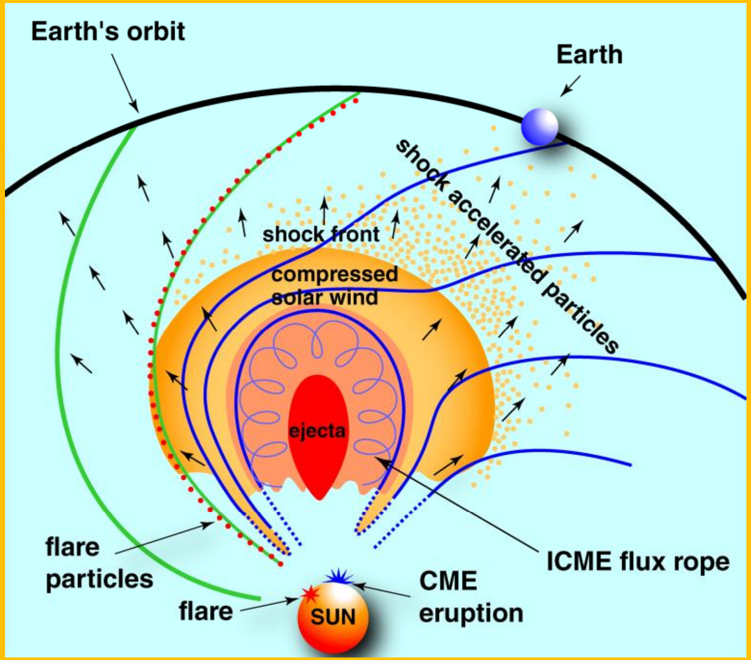
- **Multi – spacecraft observations of energetic particles**
- **Interaction of energetic particles with a magnetically turbulent fluid**
- **Anisotropic three – dimensional transport in the Heliosphere**
  - diffusion parallel and perpendicular to the average magnetic field
- **diagnostics for energetic processes at the Sun:**
  nature of acceleration processes
  ratio of accelerated to escaping particles
  magnetic structures of the corona
  emission processes (photons, neutrons)

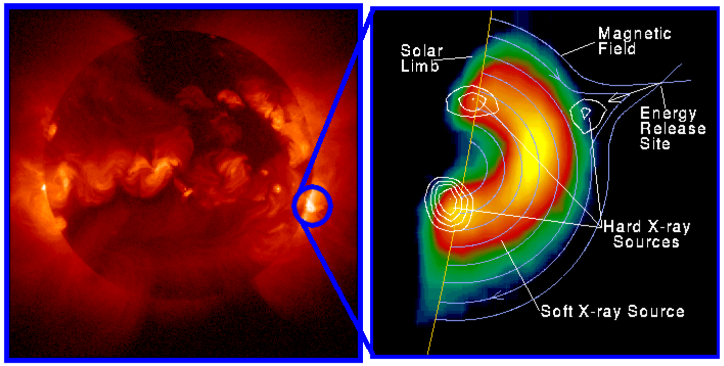
Collaborators: **R. Gomez-Herrero, B. Heber, J. Kartavykh, A. Klassen, B. Klecker, G.A. Kovaltsov, S. Krucker**

Solar Eruptive Events: Flares and Coronal Mass Ejections (CMEs)

- **both lead to acceleration of energetic particles**
- **energy sources: magnetic reconnection, turbulence, shock waves**







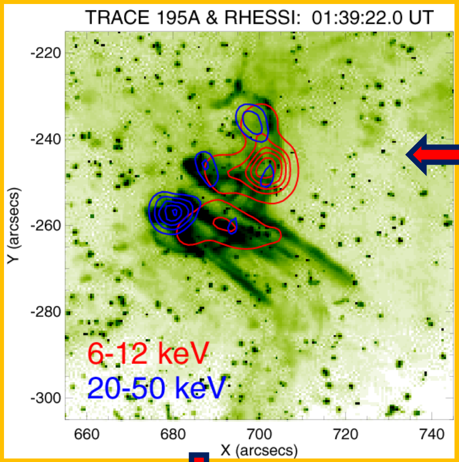
Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

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

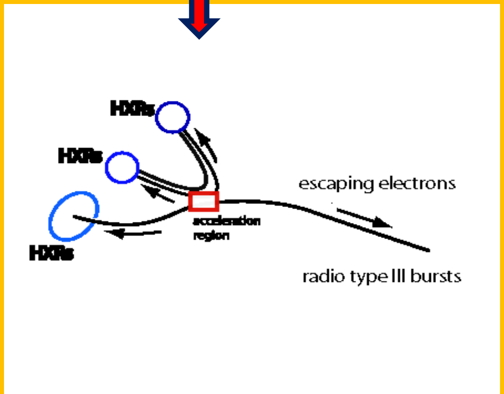
acceleration time scales, energy and charge spectra, relation to electro-magnetic emission close to the Sun (radio, X-ray, gamma-ray)

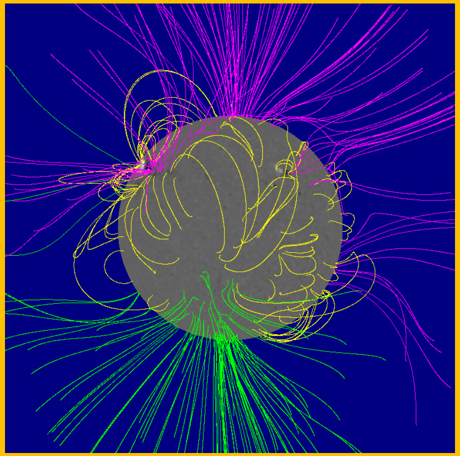
are there more than one acceleration processes, stages, phases?

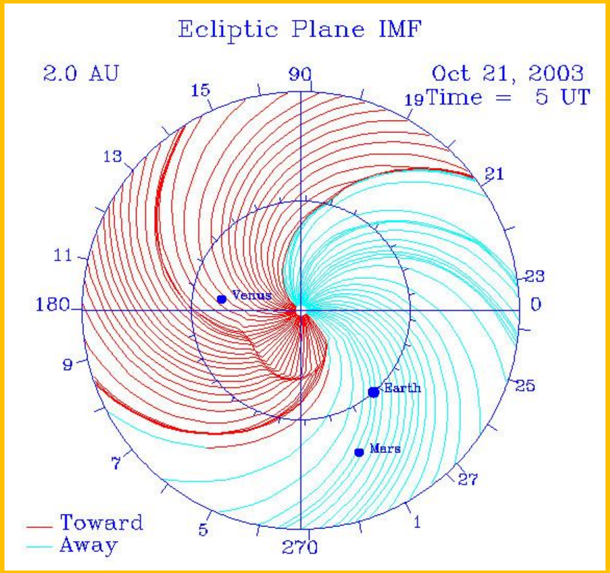
are interacting and escaping particles from the same population?

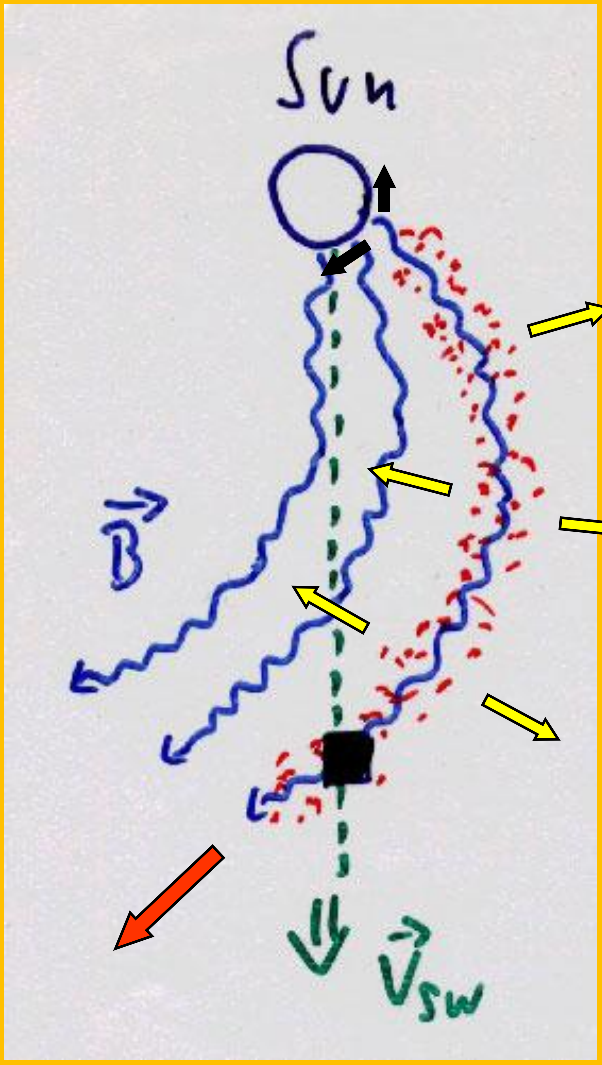


γ- ray imaging of solar flares, reconstruction of event geometry







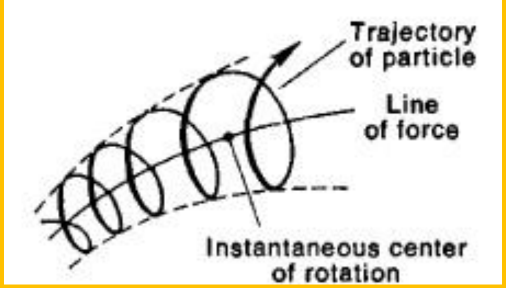


SOLAR PARTICLE PROPAGATION

COMBINATION OF:

- AZIMUTHAL TRANSPORT CLOSE TO THE SUN (CORONAL DIFFUSION)
- TRANSPORT PARALLEL TO *B*: PITCH ANGLE SCATTERING, FOCUSING
- CONVECTION WITH SOLAR WIND, ADIABATIC LOSSES
- POSSIBLE DIFFUSION ACROSS THE AVERAGE MAGNETIC FIELD
- DRIFTS

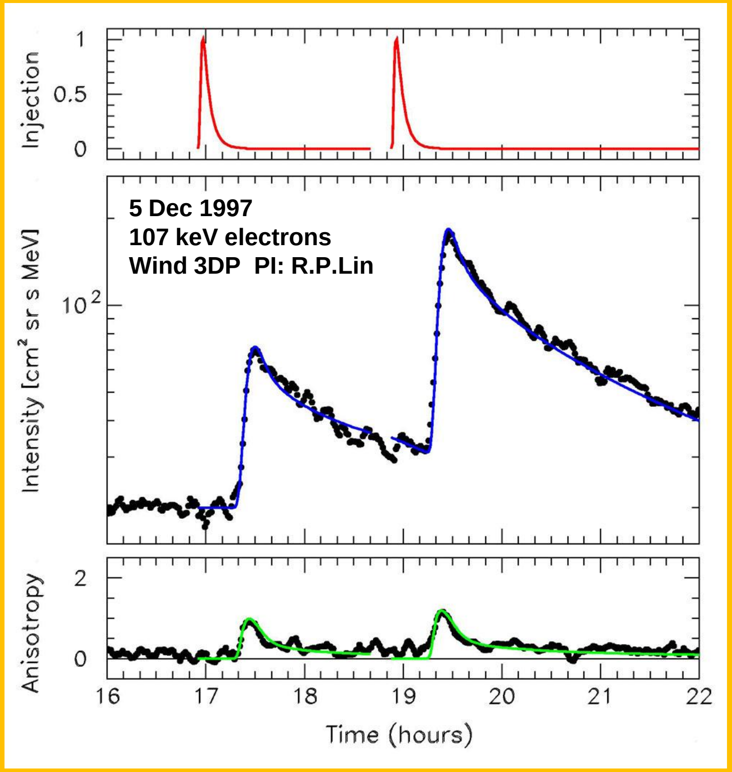
transport parallel to the average magnetic field



- **ballistic gyrocenter motion along the field**
- **adiabatic focusing**
- **pitch-angle diffusion**

transport equation for gyro-averaged phase space density ***f (z,μ,|p|,t)*** ***(focused transport)***

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



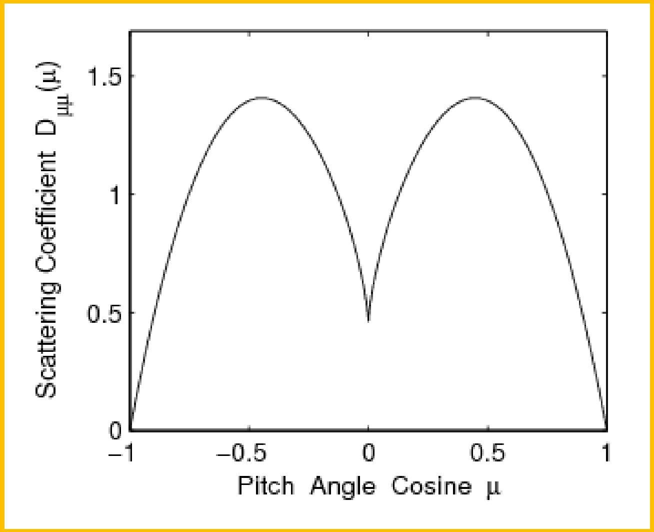
$$I(s,E,\mu,t) = \int_0^t d\tau\, I_0(s,E,\mu,t-\tau)\, q(s,E,\mu,\tau)$$

modeling parameters:

pitch-angle diffusion coefficient

$$D^s_{\mu\mu}(s,R,\mu) = \kappa_0(r,R)\cdot\{|\mu|^{q-1}+H\}\ (1-\mu^2)$$

injection function $q(s, E, \mu, \tau)$



$$\lambda_{\|} = \frac{3v}{8}\int_{-1}^{+1} d\mu\, \frac{(1-\mu^2)^2}{D_{\mu\mu}(\mu)}$$

parallel mean free path

determined by properties of magnetic fluctuations

$$\kappa = \begin{pmatrix} \kappa_\perp & \kappa_A & 0 \\ -\kappa_A & \kappa_\perp & 0 \\ 0 & 0 & \kappa_{\|} \end{pmatrix}$$

diffusion tensor

$$\frac{\partial f}{\partial t} + \mathbf{U}\cdot\nabla f = \nabla\cdot(\kappa\cdot\nabla f) + \frac{1}{3}\nabla\cdot\mathbf{U}p\frac{\partial f}{\partial p}$$

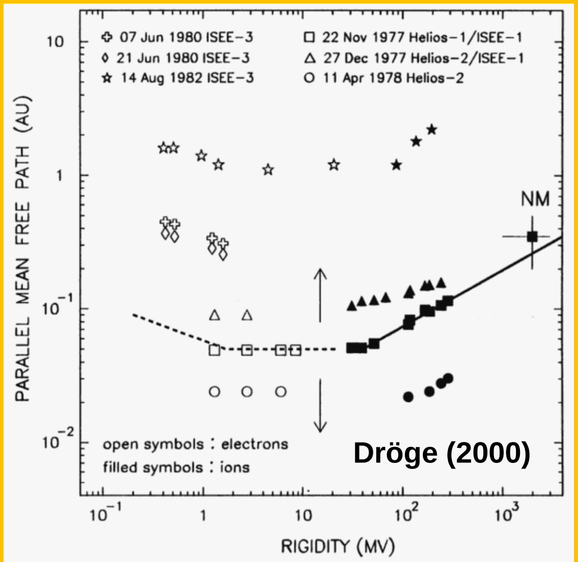
diffusion – convection equation

transport parameters are determined by properties of fluctuations (distribution of wave vectors, dynamical effects) <u>and</u> model used for wave-particle coupling

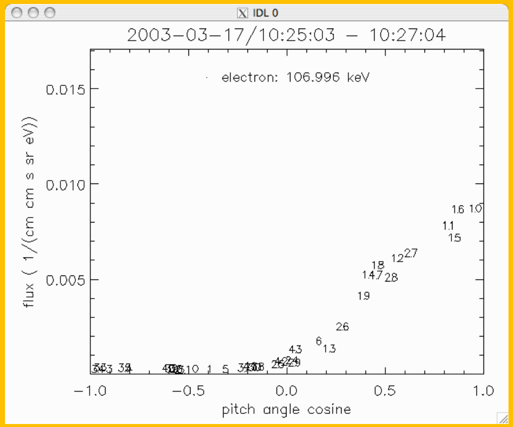
→ resonant QLT (Jokipii 1966) , non-resonant, non-linear extensions

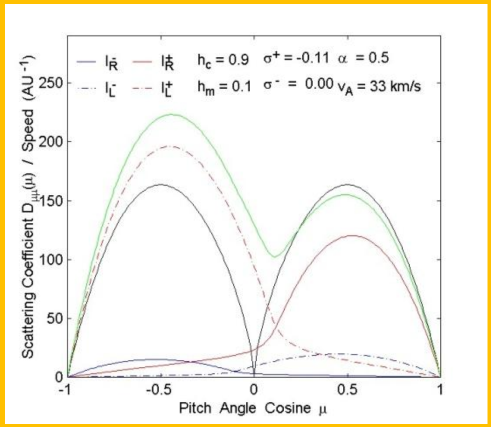
observational input to distinguish between different theories :

1. rigidity dependence of mfps



2. pitch angle distributions





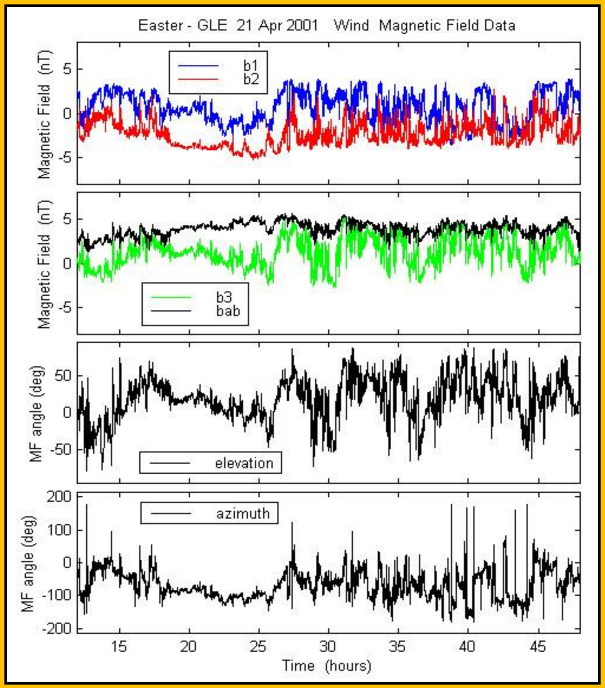
flat between 1–10 MV
increasing towards
lower rigidities } e^-

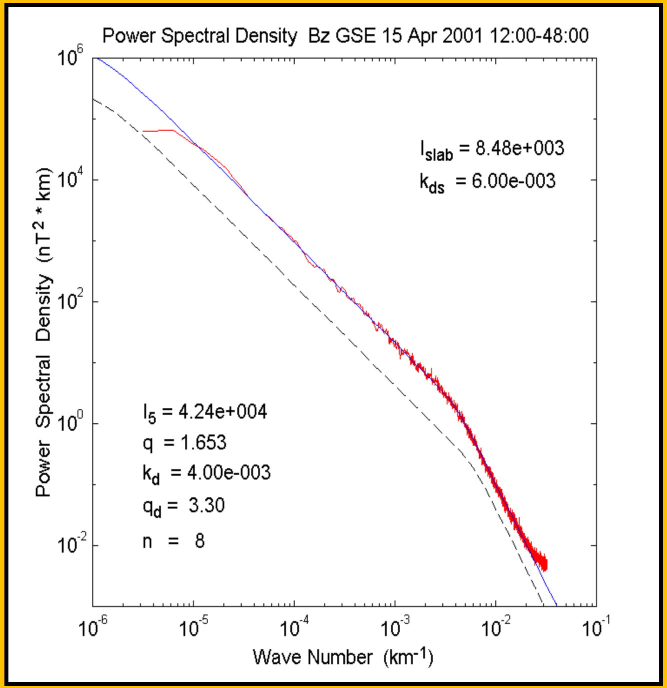
increasing towards
higher rigidities } ions

for mfps 0.02 – 2 AU

information about:
μ -dependence of $D_{\mu\mu}$
properties of fluctuations

information about the interaction of energetic particles with magnetic turbulence in the solar wind can be obtained from spectral densities of the fluctuations:

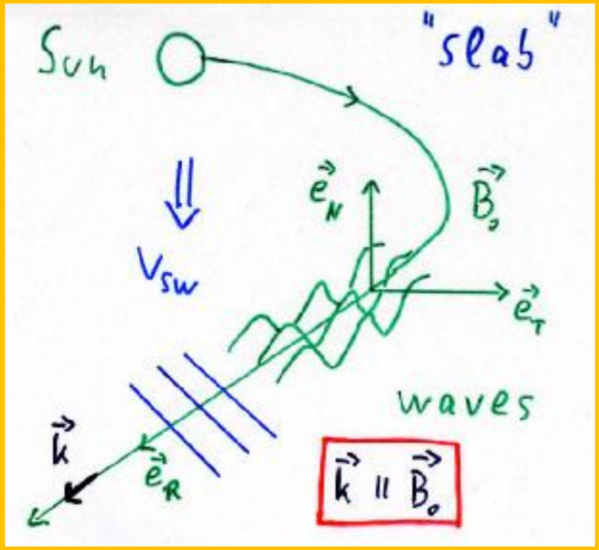


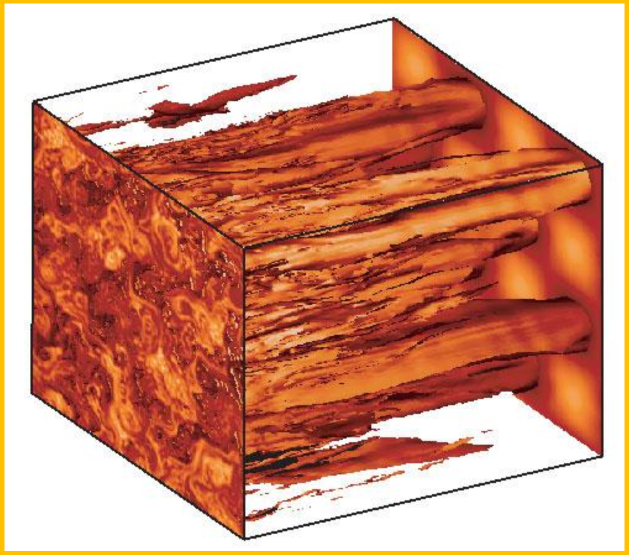


observations of magnetic fluctuations consistent with

~ X % slab content

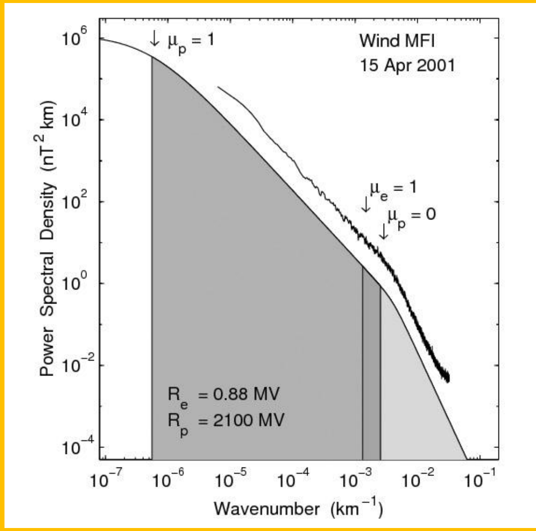
~ Y % 2-D content

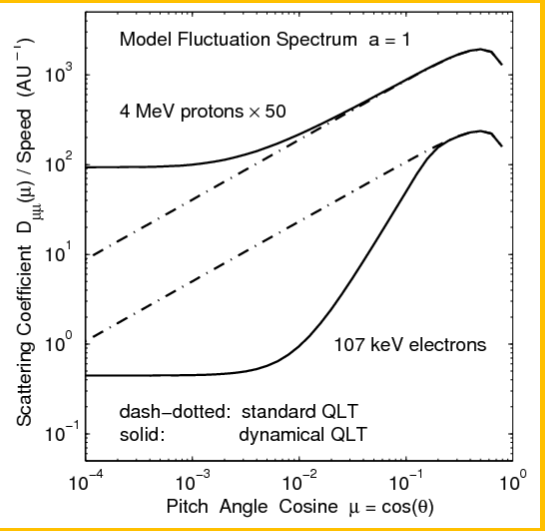


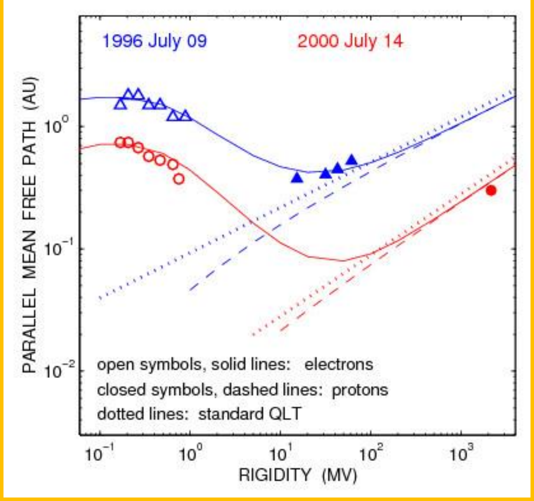


making certain assumptions about the slab/2D ratio (X ~ 20, Y ~ 80), dynamical effects and the dissipation range (reduced scattering through 90 for electrons) allows to reproduce observed rigidity dependence of mfp quite well …

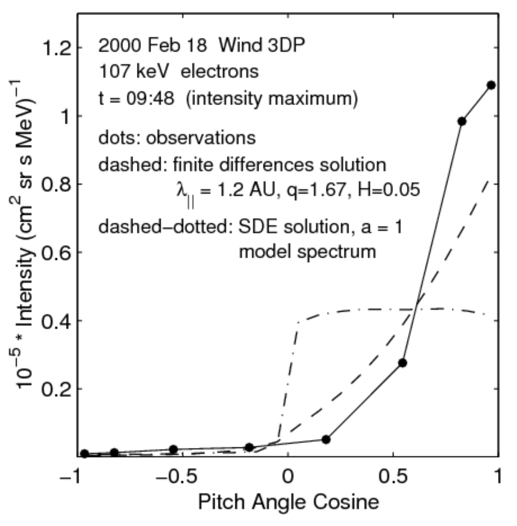
however, predicted pitch angle distributions are in clear contradiction with observations







observed



not observed

way out:

- **smaller slab content at large wave numbers, few %**
- **strong decorrelation (a>>1) or non-linear effects**

anisotropy of energy transfer – critical balance

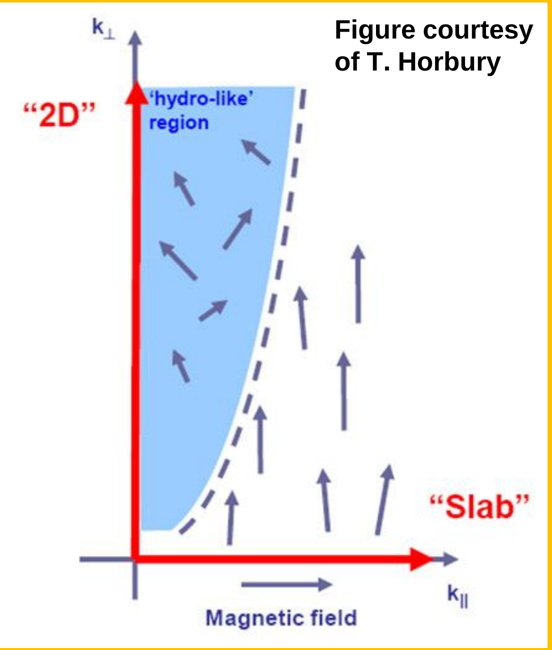
Goldreich & Sridhar (1995)

- **critical balance region close to $k_{||}$**
- **results in hydrodynamic-like caskade in wedge of wave vectors near $k_{||} \sim 0$**
- **expect Kolmogorov scaling inside this region**

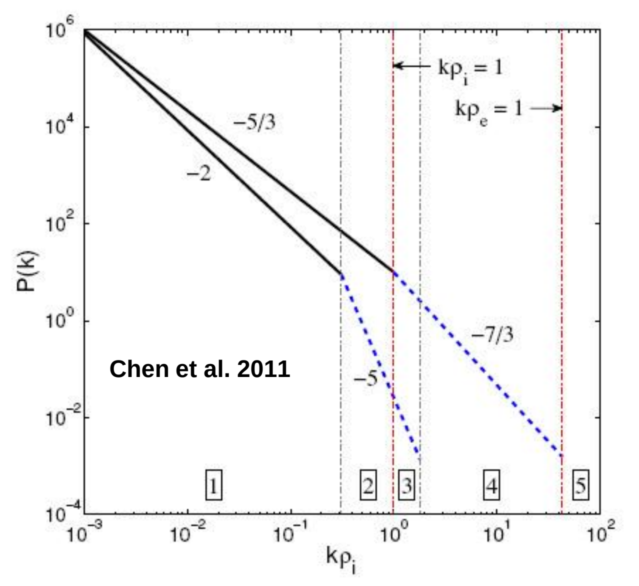
reduced power spectrum in inertial range *P(f, θ_B)* exhibits

$f^{-5/3}$ behaviour at θ_B near 90

f^{-2} behaviour at small θ_B

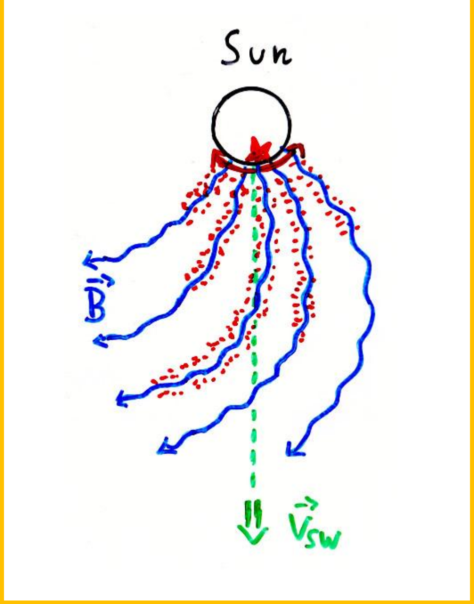


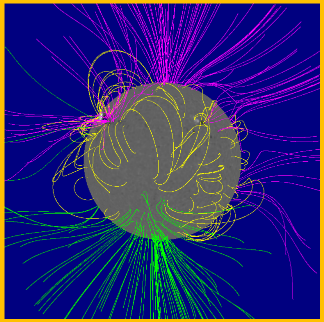
$$P(f, \theta_B) = \iiint d^3\mathbf{k} P(\mathbf{k}) \delta(2\pi f - \mathbf{k} \cdot \mathbf{V})$$
$$= \frac{1}{V} \iiint d^3\mathbf{k} P(\mathbf{k}) \delta\left(\frac{2\pi f}{V} - k_x \sin\theta_B - k_z \cos\theta_B\right)$$



lateral transport of solar energetic particles
undisturbed solar wind (no shocks/CMEs)

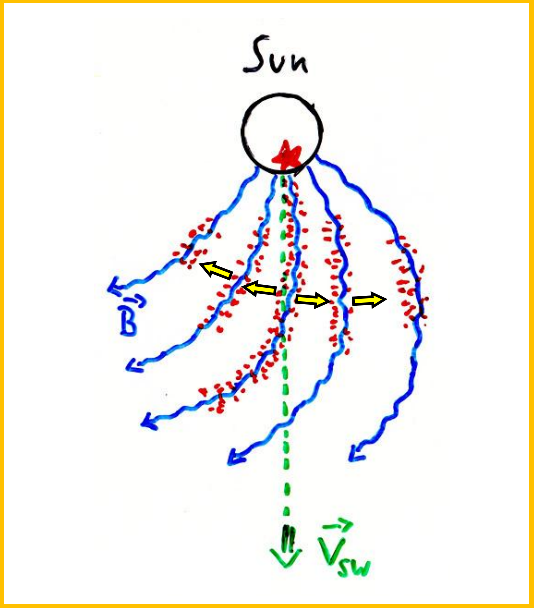
coronal transport



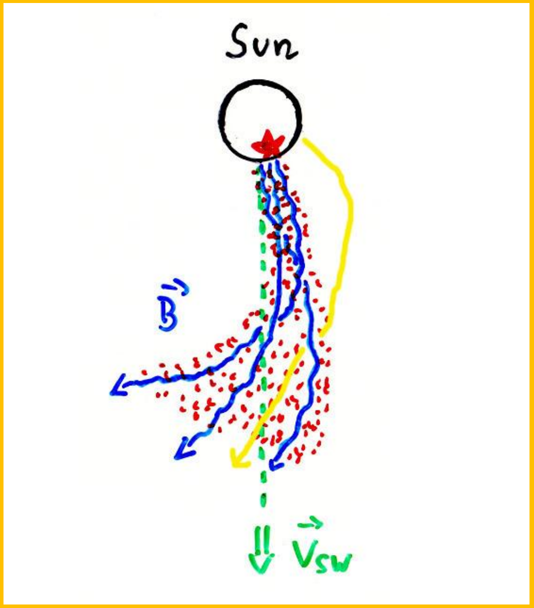


transport perpendicular to average magnetic field

diffusion across B



field line random walk



QLT + FLRW	$K_\perp / K_\parallel \sim 0.02 – 0.05$ needed for modulation of GCRs	(Ferreira 2002)
Drop-outs, Cut-offs	$K_\perp / K_\parallel \sim 10^{-4}$	(Droege et al 2010)
CIR particle events	$K_\perp / K_\parallel \sim 1$	(Dwyer et al 1997)

$$
\partial f/\partial t = \overbrace{\left[\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 K_{rr}) + \frac{1}{r\sin\theta}\frac{\partial K_{\phi r}}{\partial\phi}\right]\frac{\partial f}{\partial r} + \left[\frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}(K_{\theta\theta}\sin\theta)\right]\frac{\partial f}{\partial\theta}}^{diffusion}
$$

$$
\overbrace{+\left[\frac{1}{r^2\sin\theta}\frac{\partial}{\partial r}(rK_{r\phi}) + \frac{1}{r^2\sin^2\theta}\frac{\partial K_{\phi\phi}}{\partial\phi} + \Omega\right]\frac{\partial f}{\partial\phi}}^{diffusion}
$$

$$
\overbrace{+K_{rr}\frac{\partial^2 f}{\partial r^2} + \frac{K_{\theta\theta}}{r^2}\frac{\partial^2 f}{\partial\theta^2} + \frac{K_{\phi\phi}}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial\phi^2} + \frac{2K_{r\phi}}{r\sin\theta}\frac{\partial^2 f}{\partial r\partial\phi}}^{diffusion}
$$

$$
\overbrace{+\left[-\langle\mathbf{v}_d\rangle_r\right]\frac{\partial f}{\partial r} + \left[-\frac{1}{r}\langle\mathbf{v}_d\rangle_\theta\right]\frac{\partial f}{\partial\theta} + \left[-\frac{1}{r\sin\theta}\langle\mathbf{v}_d\rangle_\phi\right]\frac{\partial f}{\partial\phi}}^{drift}
$$

$$
\overbrace{-V\frac{\partial f}{\partial r}}^{convection}
$$

$$
\overbrace{+\frac{1}{3r^2}\frac{\partial}{\partial r}(r^2 V)\frac{\partial f}{\partial\ln p}}^{adiabatic\ energy\ change}
$$

$$
\overbrace{+Q}^{sources} .
$$

3-dimensional spatial diffusion in a Parker field (Ferreira, PhD thesis 2002)

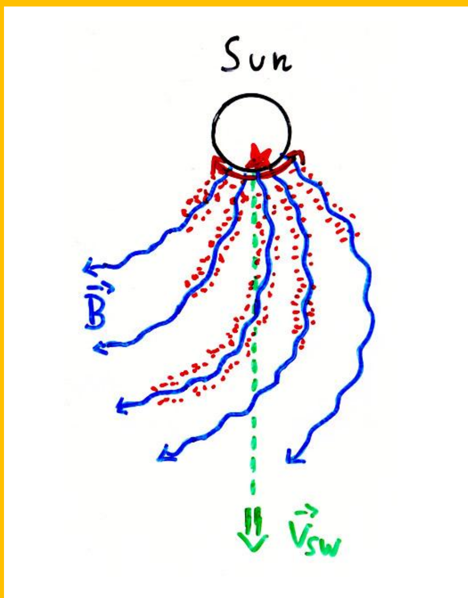
lateral transport of solar energetic particles
undisturbed solar wind (no shocks/CMEs)

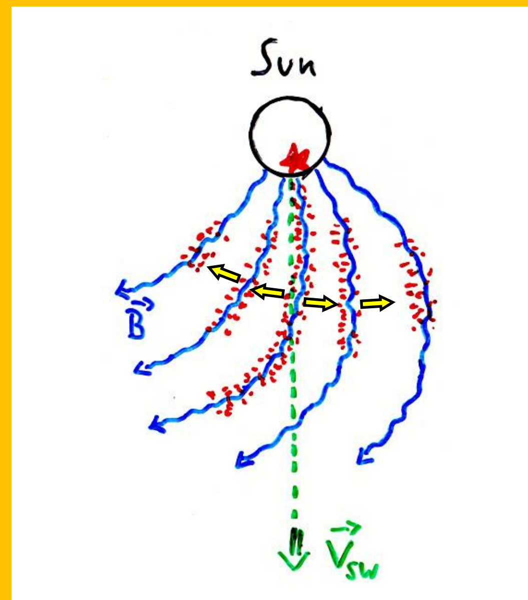
coronal transport

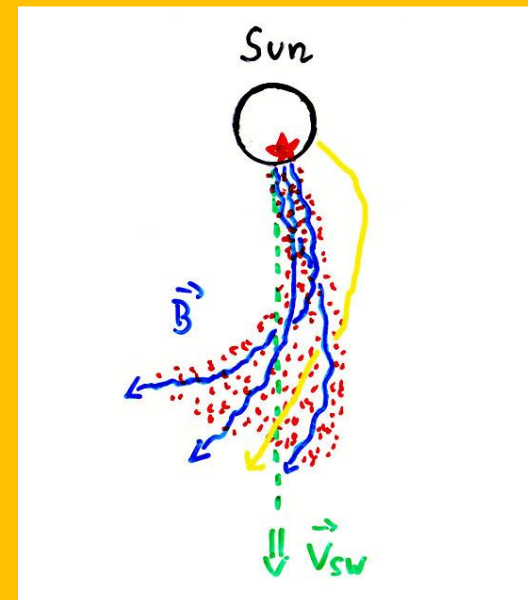
transport perpendicular to average magnetic field

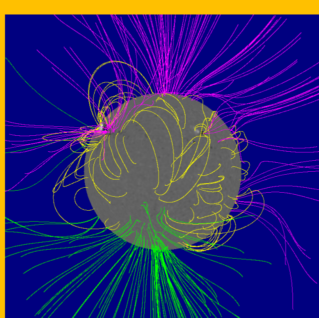
diffusion across B

field line random walk









QLT + FLRW	$K_\perp / K_\parallel \sim 0.02 – 0.05$ needed for modulation of GCRs	(Ferreira 2002)
Drop-outs, Cut-offs	$K_\perp / K_\parallel \sim 10^{-4}$	(Dröge et al 2010)
CIR particle events	$K_\perp / K_\parallel \sim 1$	(Dwyer et al 1997)

transport equation for solar energetic particles with large anisotropies (Skilling 1975, Ruffolo 1995, Isenberg 1997, Dröge et al 2010)

$$\frac{\partial f}{\partial t} = -\mu v \boldsymbol{b}\cdot\nabla f - \frac{1-\mu^2}{2L} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}(\mu)\frac{\partial f}{\partial \mu}\right) + q(\boldsymbol{r},\mu,p,t)$$

$$- (\boldsymbol{V}_{sw} + \boldsymbol{V}_d)\cdot\nabla f - \left[\frac{\mu(1-\mu^2)}{2}(\nabla\cdot\boldsymbol{V}_{sw} - 3\boldsymbol{bb}:\nabla\boldsymbol{V}_{sw}) + \frac{2}{v}\boldsymbol{b}\boldsymbol{V}_{sw}:\nabla\boldsymbol{V}_{sw}\right]\frac{\partial f}{\partial \mu}$$

$$+ \left[\frac{1-\mu^2}{2}(\nabla\cdot\boldsymbol{V}_{sw} - \boldsymbol{bb}:\nabla\boldsymbol{V}_{sw}) + \mu^2\boldsymbol{bb}:\nabla\boldsymbol{V}_{sw} + \frac{\mu}{v}\boldsymbol{b}\boldsymbol{V}_{sw}:\nabla\boldsymbol{V}_{sw}\right] p\frac{\partial f}{\partial p}$$

$$+ \nabla\cdot(\boldsymbol{K}_\perp\nabla f)$$

stochastic differential equation solver:

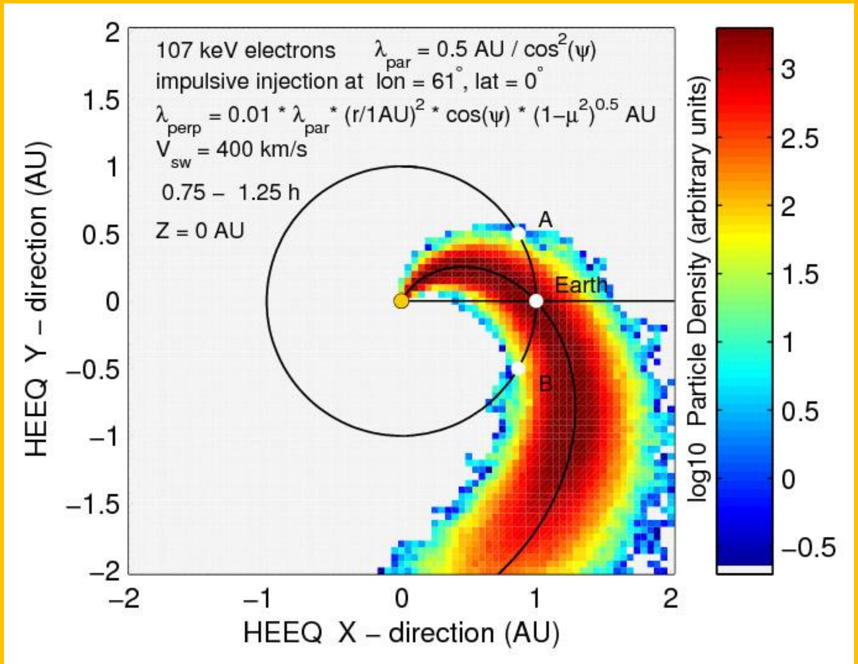
$$d\boldsymbol{r}(t) = \mu v dt\, \boldsymbol{e}_B + \sqrt{2\boldsymbol{K}_\perp}\, d\boldsymbol{W}_\perp(t) + \nabla\boldsymbol{K}_\perp dt$$

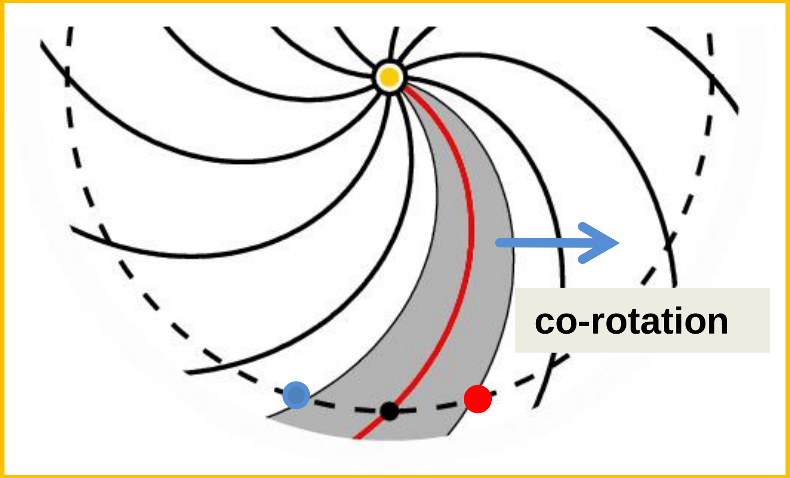
$$d\mu(t) = \sqrt{2D_{\mu\mu}}\, dW_\mu(t) + \left[\frac{v}{2L}(1-\mu^2) + \frac{\partial D_{\mu\mu}}{\partial \mu}\right]dt$$

convection, adiabatic deceleration and drift taken into account by transformations between (Kocharov et al, 1998, Dröge et al 2010):

1) **Heliocentric Inertial system**
2) **co-rotating system**
3) **co-moving system**

estimate amount of perpendicular diffusion through observations of azimuthal intensity gradients





- **relate intensity time profile to a longitudinal variation swept past single spacecraft by co-rotation**
- **simultaneous multi-spacecraft observations**

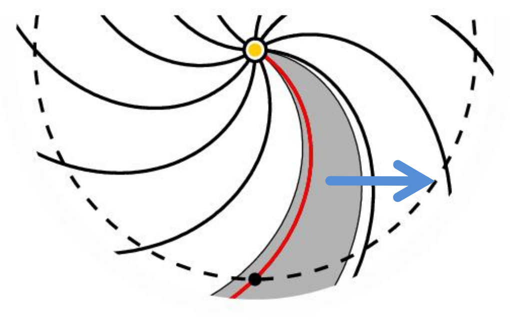
look for events which exhibit

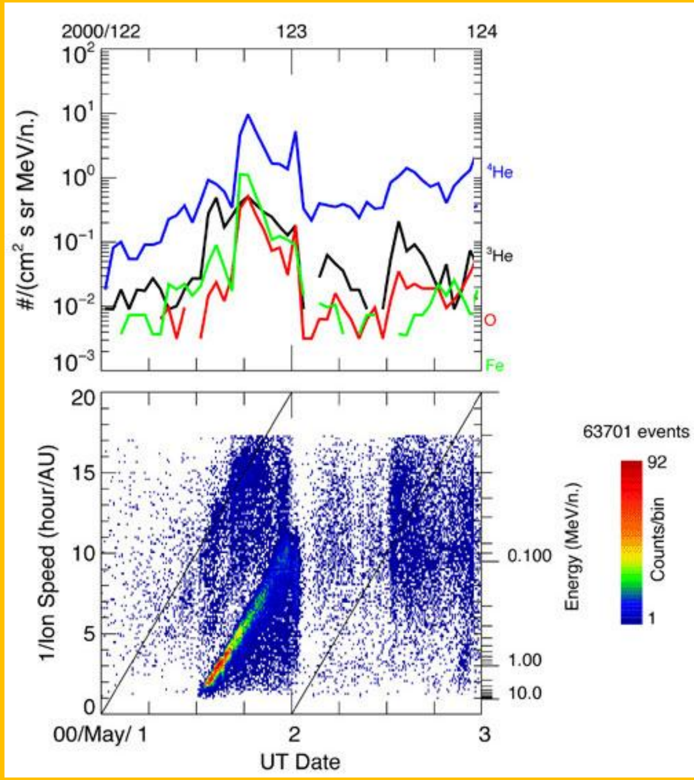
- **time variations corresponding to spatial gradients perpendicular to B which are convected past the spacecraft**
- **no velocity dispersion**

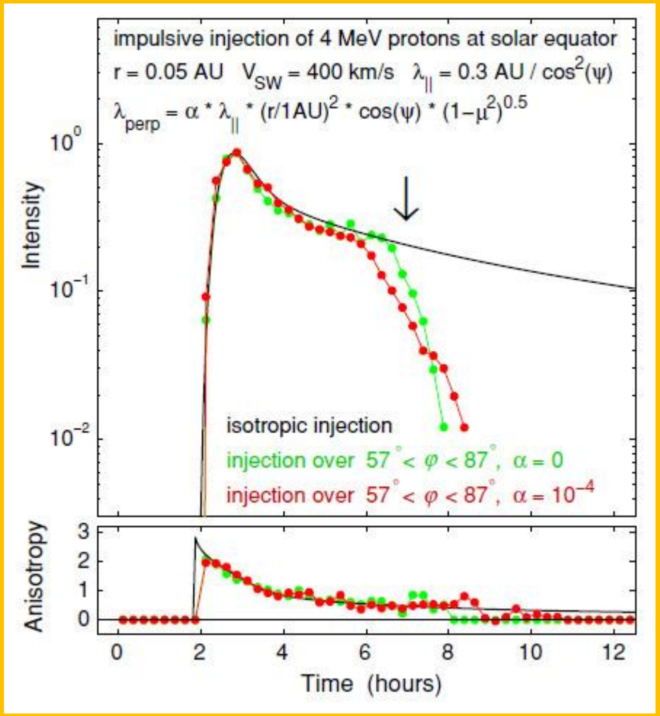
→ **dropouts, cutoffs**

observer 4 deg inside of connection region exits after ~ 7 h due to co-rotation

$$\lambda_\perp = (r/1\ AU)^2 \times \cos(\psi) \times (1-\mu^2)^{0.5} \times 5E\text{-}4\ \lambda_\parallel$$



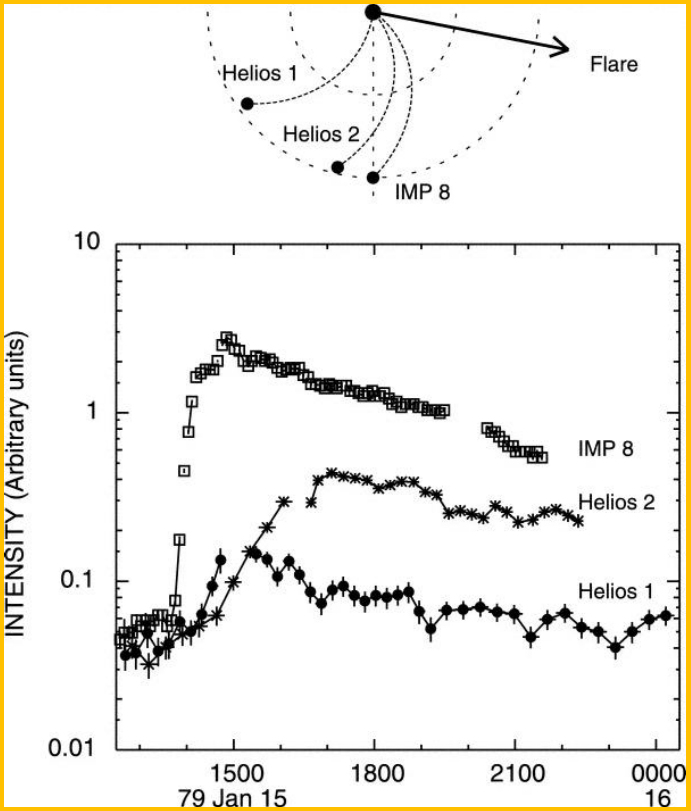


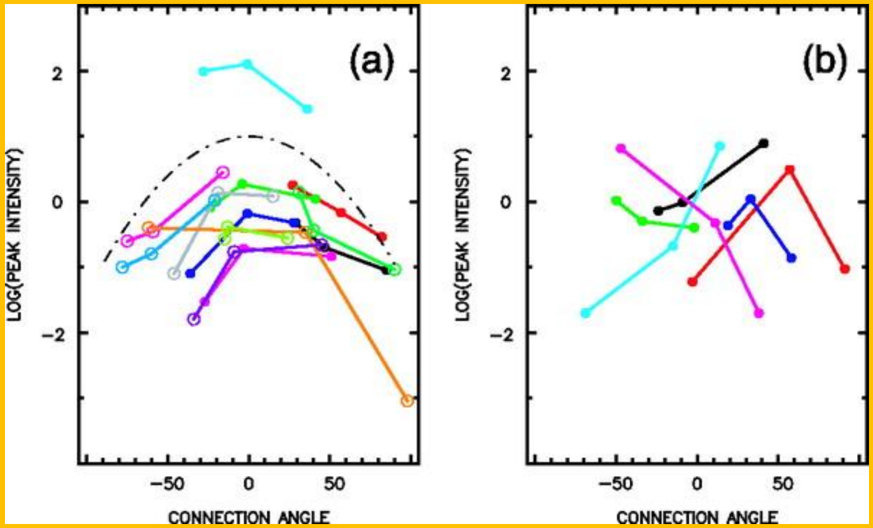


Multi-Spacecraft Observations of Impulsive Solar Events
Wibberenz & Cane (2006)

electrons in the MeV range can be detected more than 80 from the flare longitude

evidence for lateral transport

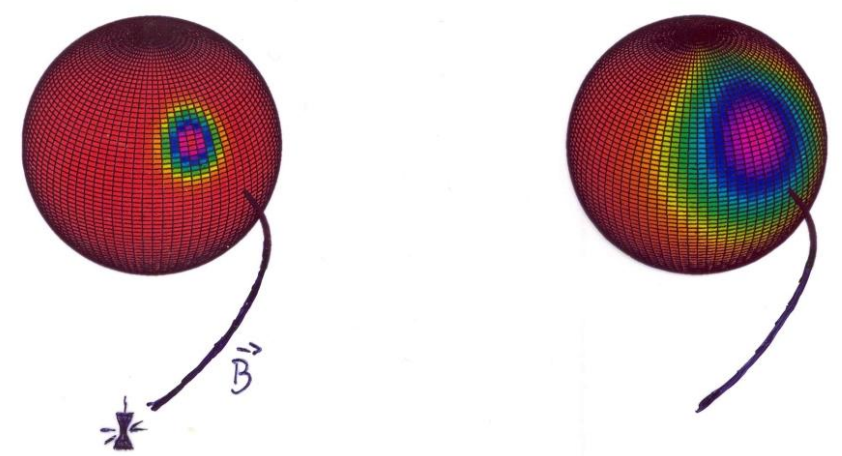




Connection plot and electron time profiles for the flare event of 1979 January 15.

Variation of peak intensities I_m with connection angle

lateral transport in the solar corona

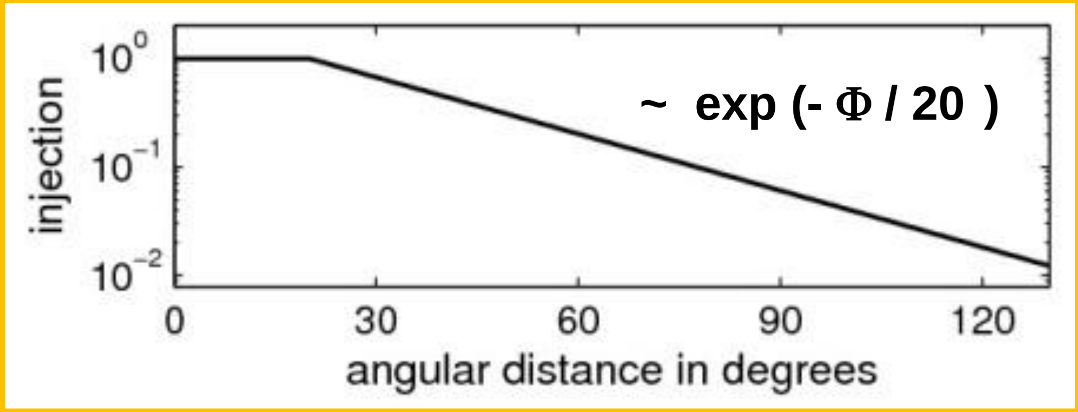


$$Q_R(r_c, \phi, \tau) = \frac{N_0 k}{4\pi \kappa_c \tau} \exp\left\{-\frac{\phi^2 r_c^2}{4\kappa_c \tau} - k\tau\right\}$$

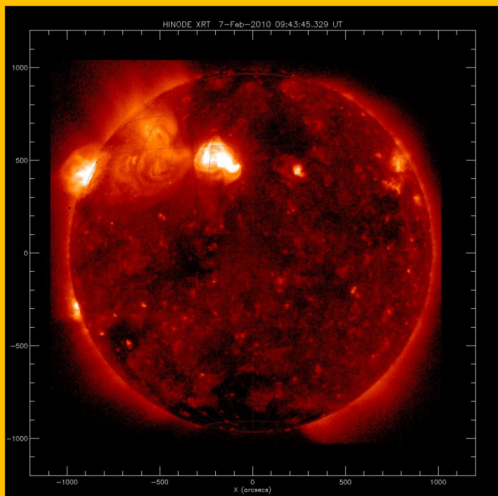
diffusion on a sphere
and
escape from the sphere

Reid 1964

used here:



modeling of electron event observed simultaneously on STEREO-A, STEREO-B, and ACE / Wind on 7 February 2010



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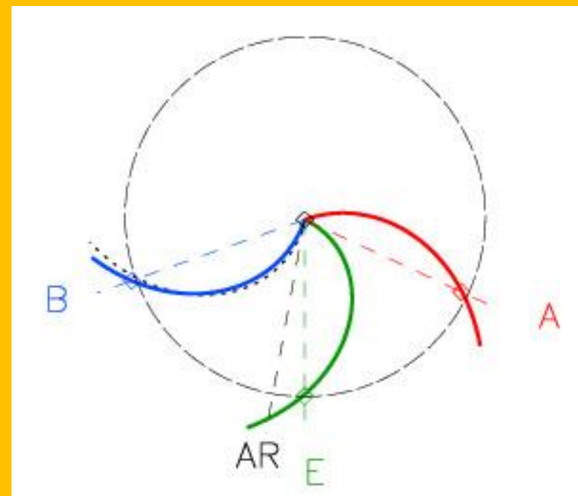
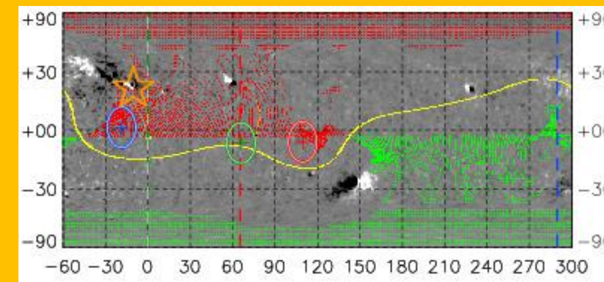
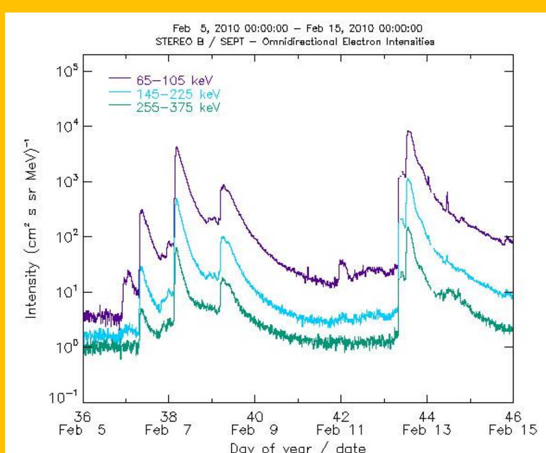
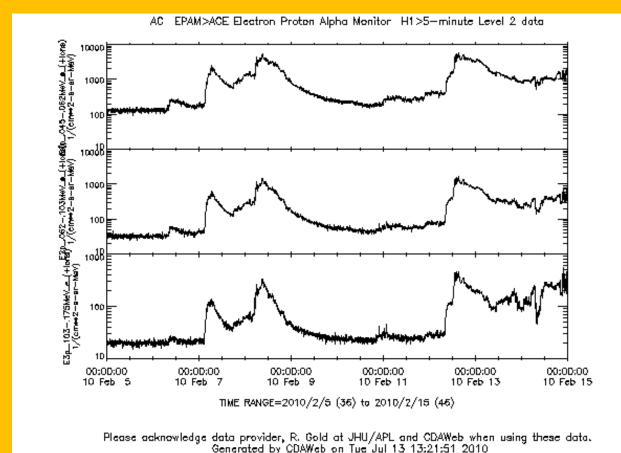




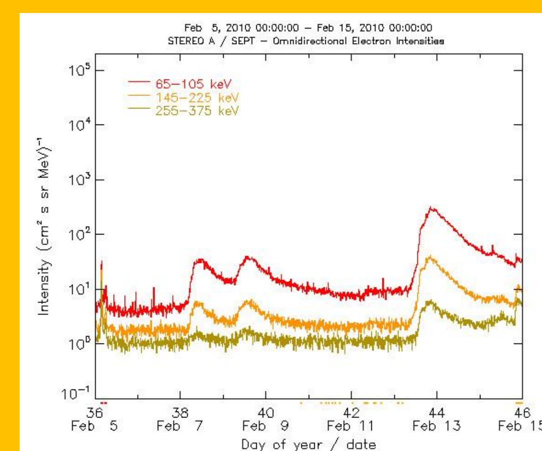
STB	ACE	STA
-15.9°	52.7°	116.8°



STEREO-B



ACE

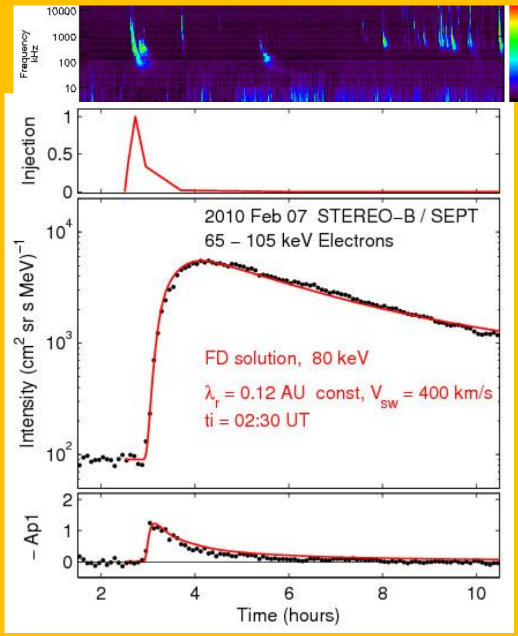


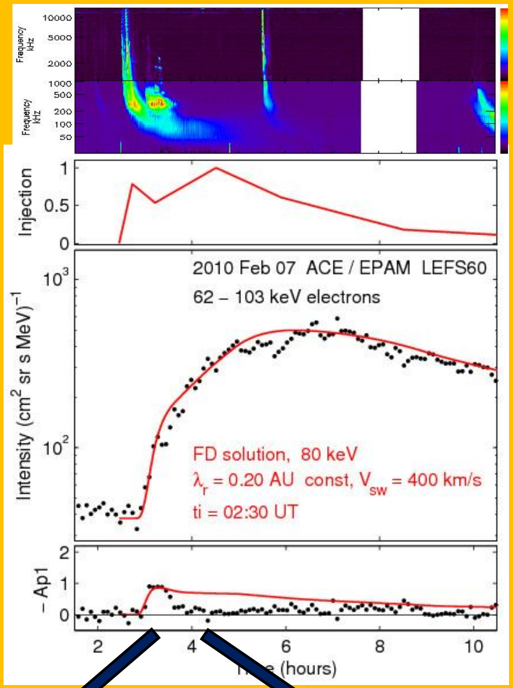
STEREO-A

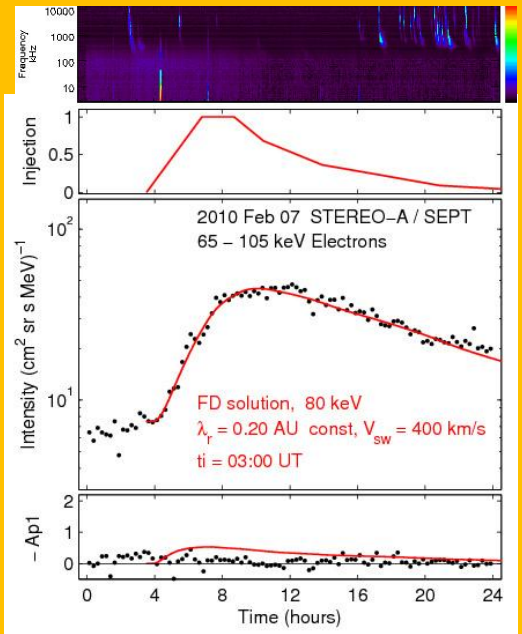
transport modeling of STEREO-A/B and ACE electron observations on 7 Feb 2010:

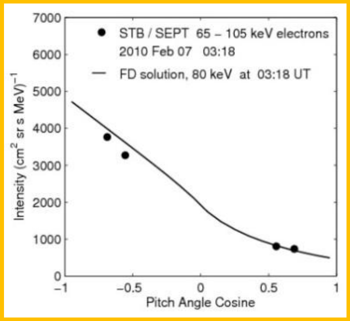
1. only time-dependent injection close to Sun and parallel tranport considered ⟶ red curves

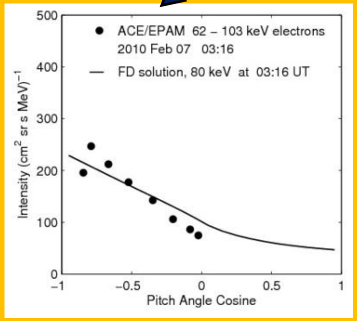
WAVES data by M. Kaiser GSFC/CDAWeb

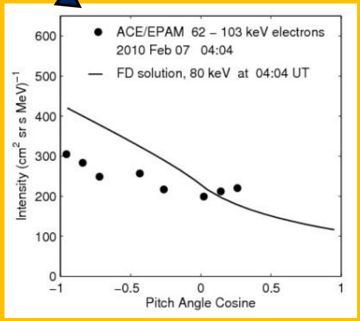


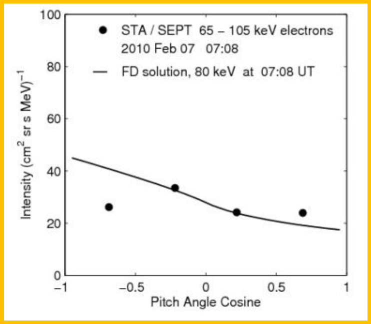






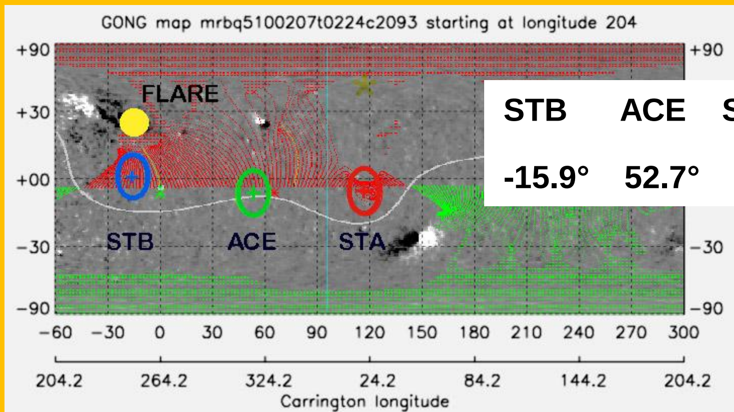






assumption of coronal transport and propagation parallel to IMF only does not explain observations ➔ also perpendicular diffusion required !

transport modeling of STEREO-A/B and ACE electron observations on 7 Feb 2010:
2. combination of extended injection at the Sun and 3-D interplanetary tranport

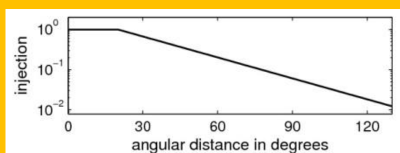


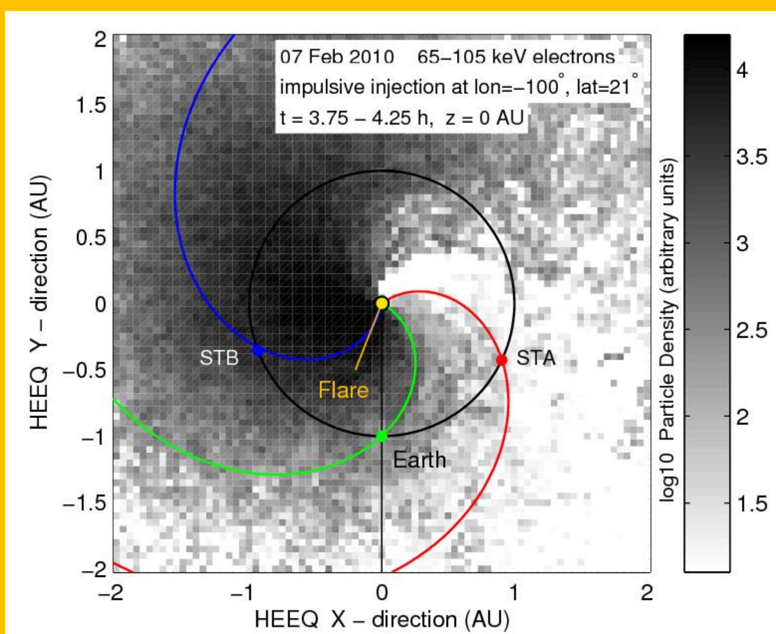
STB	ACE	STA
-15.9°	52.7°	116.8°

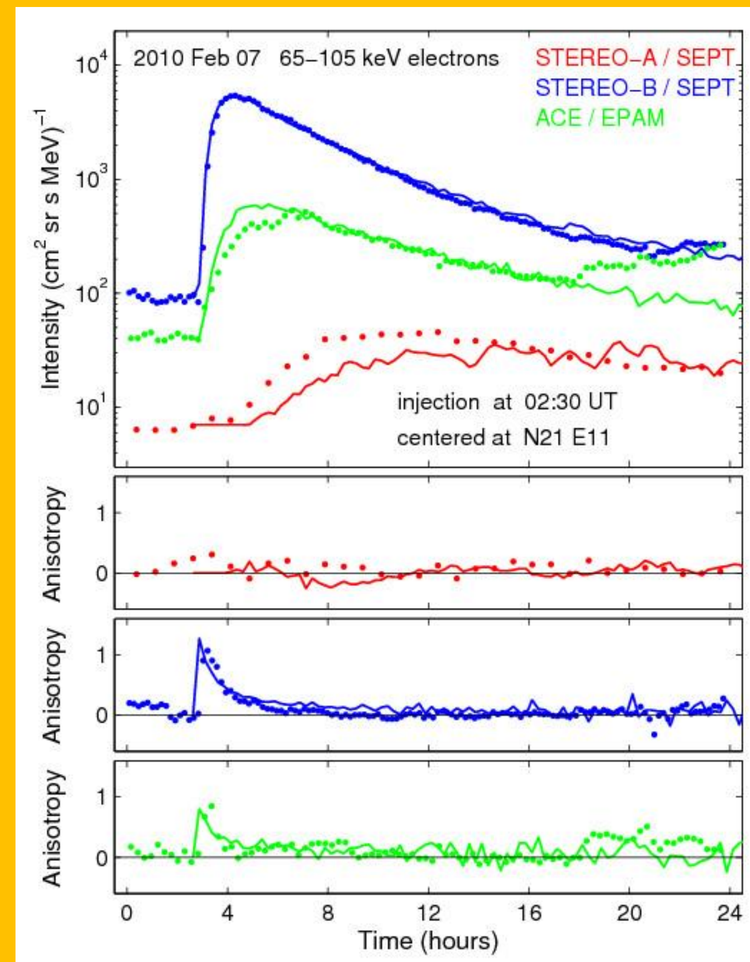
$\lambda_{\parallel}$ = 0.07 / $\cos^2(\psi)$ AU

$\lambda_{\perp}$ = 0.15 * $\lambda_{\parallel}$ * $(r/1\ AU)^2$ * $\cos(\psi)$ * $(1-\mu^2)^{0.5}$

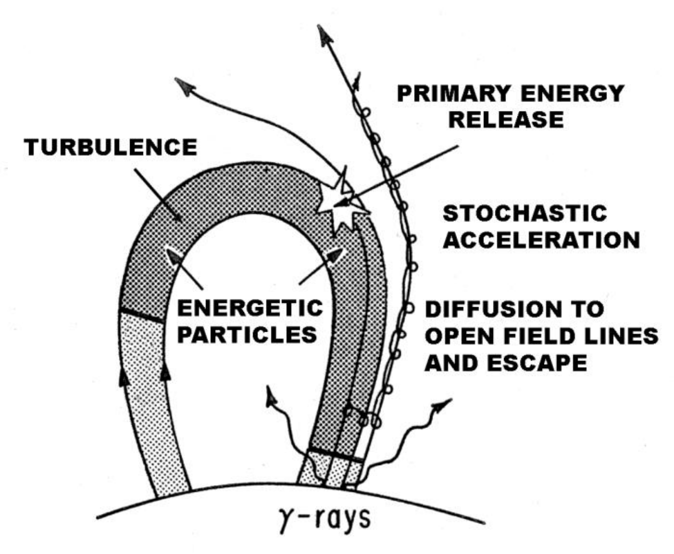
scales with gyroradius (B and $\sin(\theta)$)







Application I: Reconstruction of acceleration parameters and plasma properties in impulsive solar flares (e.g., Kartavykh et al. 2007)



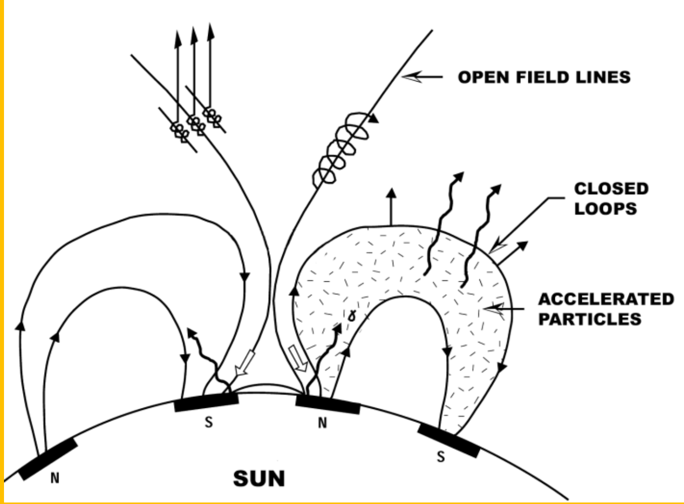
1. HOMOGENEOUS MODEL

ACCELERATION REGION OF LENGTH *L*

➡ VOLUME AT THE TOP OF A CORONAL LOOP

IONS COLLIDE WITH ELECTRONS, PROTONS, HE^{++}, LEADING TO ENERGY LOSS AND CHARGE EXCHANGE PROCESSES

MEAN ESCAPE RATE PROPORTIONAL TO SPATIAL DIFFUSION COEFFICIENT



2. INHOMOGENEOUS MODEL

ACCELERATION VOLUME CONSISTS OF 2 DISTINCT REGIONS WHERE PARAMETERS ARE DIFFERENT BUT CONSTANT IN EACH OF THEM

TOTAL CHARGE AND ENERGY SPECTR OBTAINED AS WEIGHTED SUM OF PARTICLE POPULATION FROM THE 2 REGIONS

PROPAGATION IN SOLAR WIND SUBSEQUENTLY APPLIED TO TOTAL PARTICLE DISTRIBUTION

SYSTEM OF COUPLED FOKKER-PLANCK EQUATIONS FOR NUMBER DENSITY OF FE IONS OF CHARGE STATE *I*, $F_I(E,t)$

SOLVED BY METHOD OF STOCHASTIC DIFFERENTIAL EQUATIONS

$$\frac{\partial F_I}{\partial t} - \frac{\partial^2}{\partial E^2}(\varphi F_I) + \frac{\partial}{\partial E}(\psi F_I) - K\frac{\partial^2 F_I}{\partial x^2} + \frac{\partial}{\partial E}(\frac{dE}{dt}F_I) + \frac{F_I}{\tau_{I,I+1}}$$
$$-\frac{F_{I-1}}{\tau_{I-1,I}} - \frac{F_{I+1}}{\tau_{I+1,I}} + \frac{F_I}{\tau_{I,I-1}} = X_I(T)\ \delta(t)\,\delta(E-E_0)/L$$

$$\varphi = D_p(\frac{dp}{dE})^{-2}, \qquad \psi = (p^2\frac{dp}{dE})^{-1}\frac{\partial}{\partial E}(\frac{p^2 D_p}{dp/dE})$$

$$K = K_0\,(Q/A)^{S-2}\,E^{(3-S)/2}$$

$$D_p = D_0\,(Q/A)^{2-S}\,E^{(S-1)/2}$$

SPATIAL AND MOMENTUM DIFFUSION

$$\tau_A = p^2/D_p \propto (Q/A)^{S-2}E^{(3-S)/2)}$$

$$\tau_C = E/|(dE/dt)_{Coul}| \propto E^{3/2}A/(Q^2N)$$

$$\tau_D = L^2/K \propto (Q/A)^{S-2}E^{(S-3)/2)}$$

$\tau_{I,J}$: Ostryakov et al. 2000

TIME SCALES FOR:

ACCELERATION

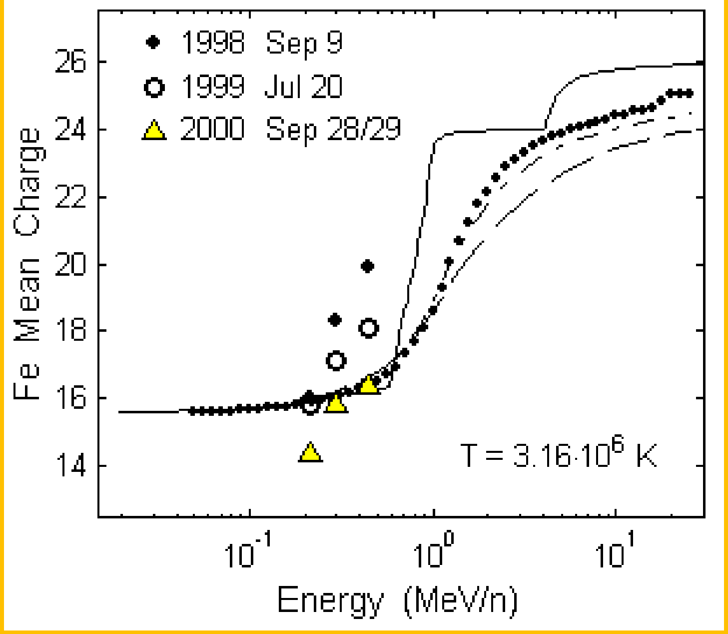
COULOMB LOSSES

ESCAPE

CHARGE EXCHANGE

for low-energy (< 1 MeV/n) ions effects adiabatic deceleration are important

→ reconstruction of charge spectra of Fe ions in impulsive solar events



mean charge of accelerated iron for $T = 3.16\times10^6$ K, τ_A/τ_D = 0.1 and

$\tau_A N = 5\times10^{10}$ s cm^{-3} (dashed),

$\tau_A N = 10^{11}$ s cm^{-3} (dashed-dotted),

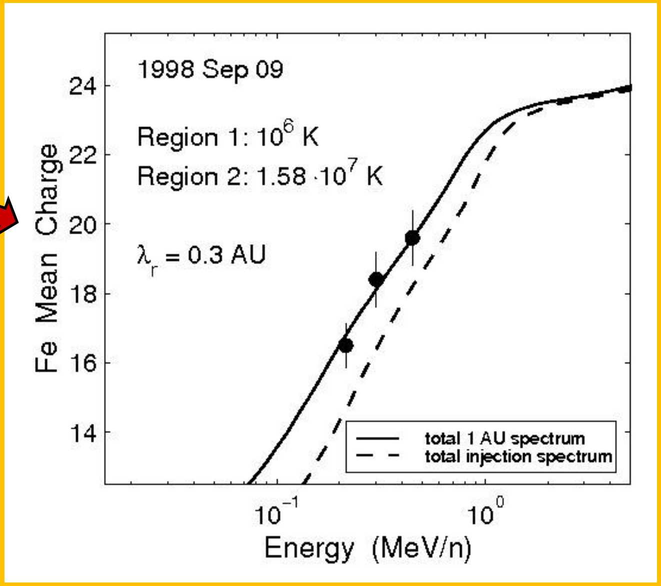
$\tau_A N = 2\times10^{11}$ s cm^{-3} (dotted curve).

solid curve is equilibrium mean charge of iron for $T = 3.16\times10^6$ K

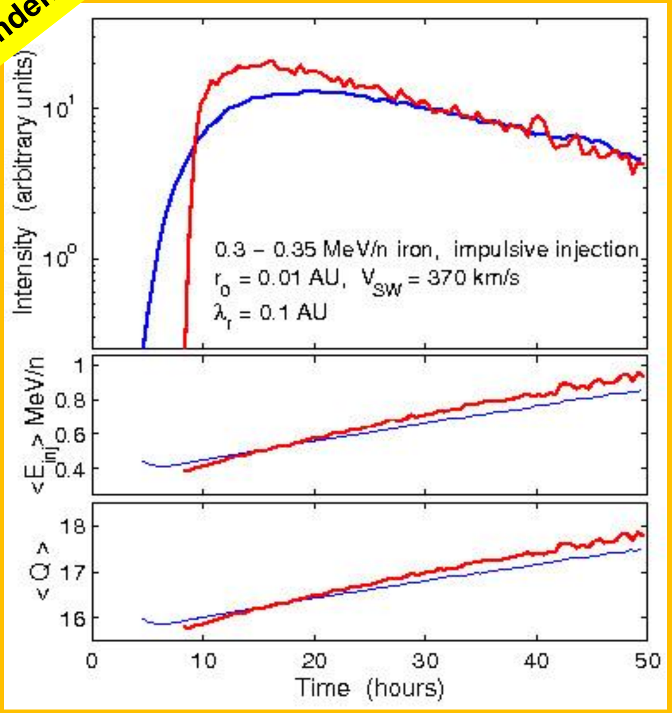
- recent observations of the iron mean charge in impulsive SEP events (Moebius et al., 2003) have shown a strong energy dependence in the range 0.18-0.55 MeV/nucleon
- data points typically lie to the left of the equilibrium spectra
- energy dependence can not easily be explained within the framework of current acceleration models

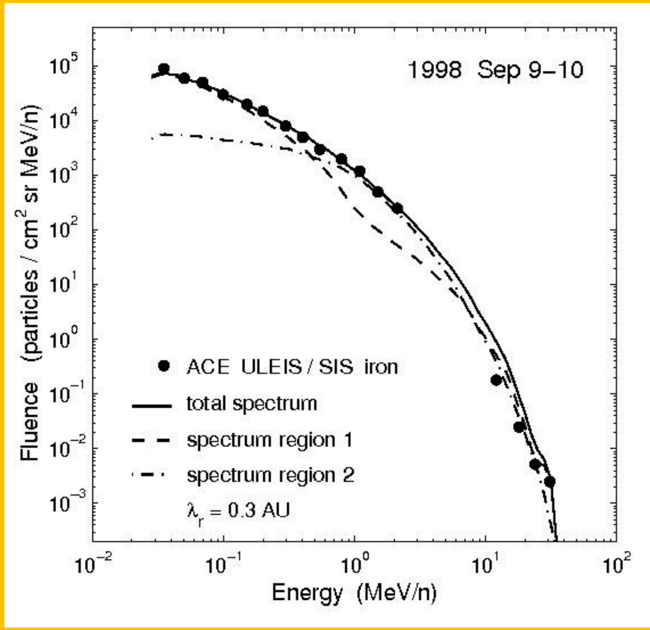
effect of adiabatic deceleration results in a shift of charge spectra:

Fe ions start at sun with ~ twice the energy they are observed at 1 AU after one day



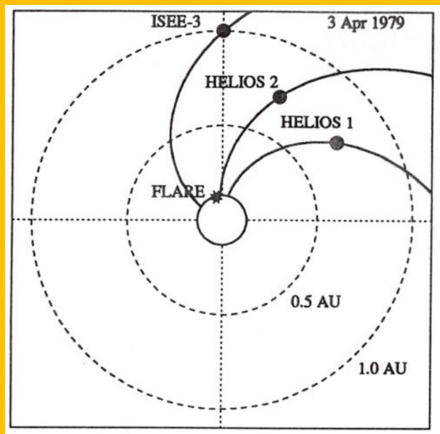
blue: spatial diffusion
red: pitch-angle dependent transport





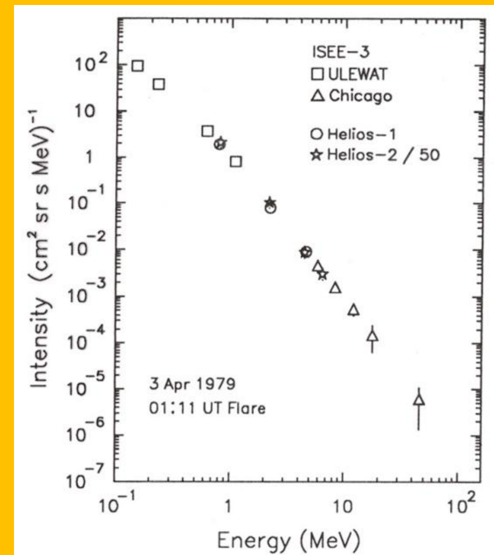
inclusion of above effect allows meaningful interpretation of charge and energy spectra

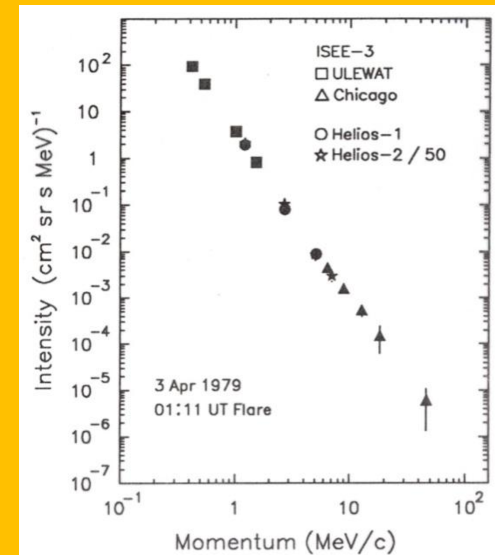
reconstruction of electron spectra from multi-spacecraft observations

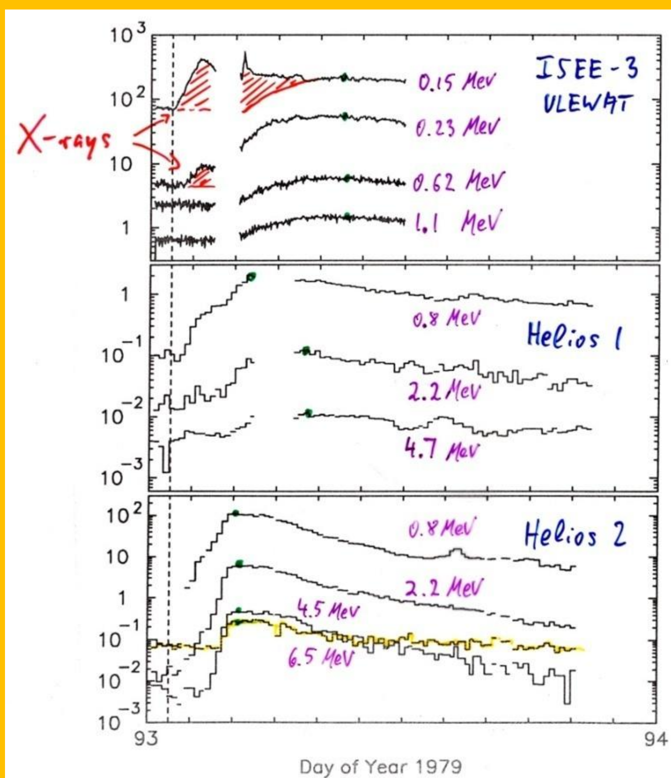


3 April 1979 01:11 UT
S25 W14

ISEE-3 r=1.0 AU N04 W63
Helios 1 r=0.75 AU S05 E14
Helios 2 r=0.68 AU S07 E14





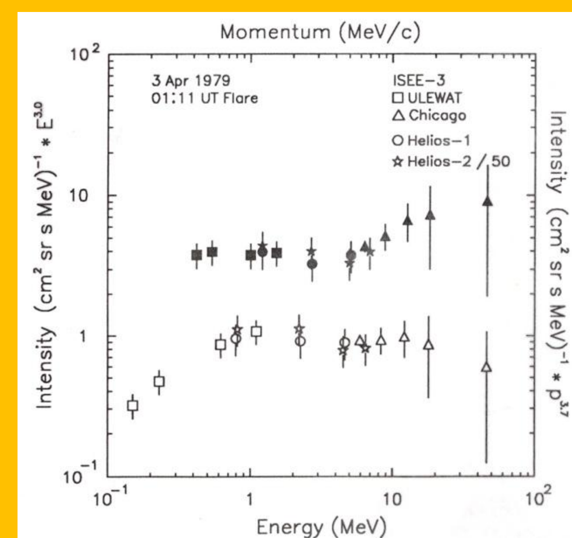


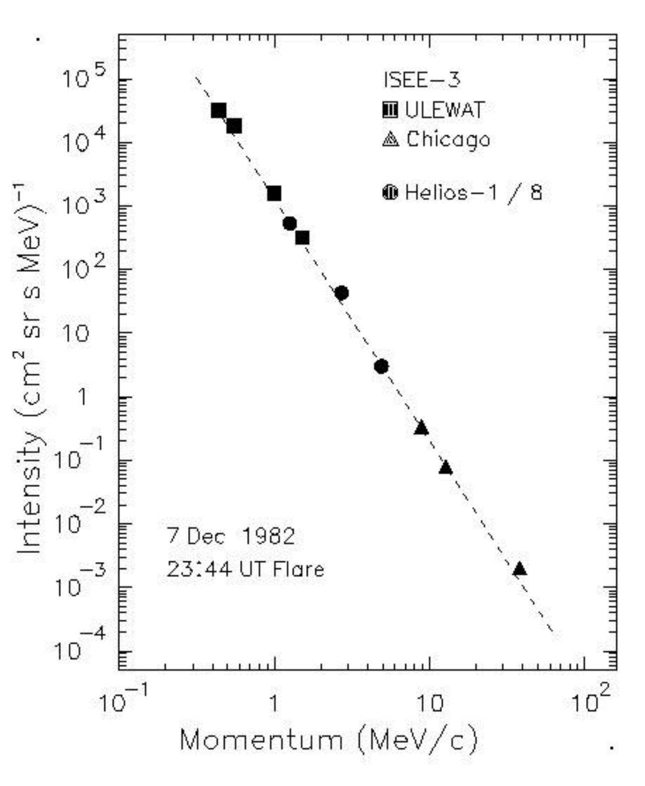
characteristics of solar flare electron spectra

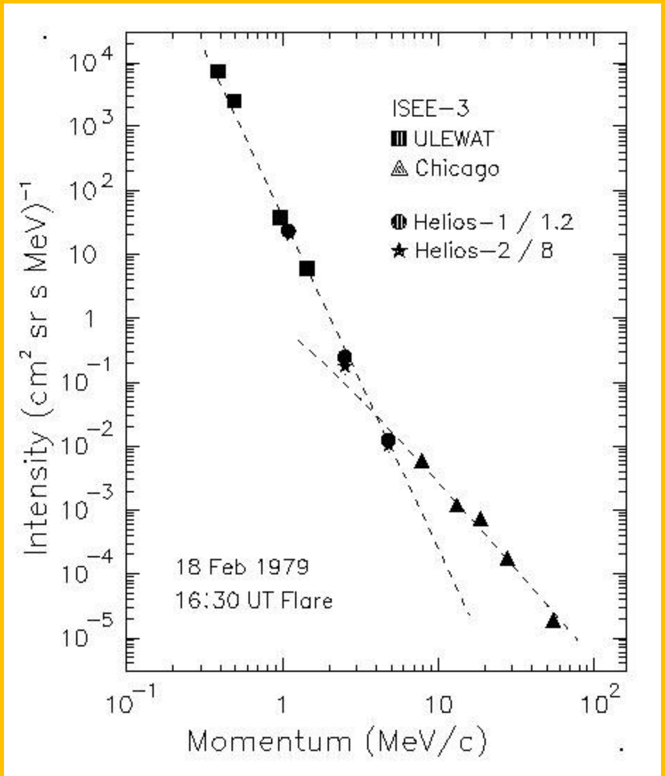
plot (N(E), J(E) vs. E, p

flux spectra multiplied by power laws in

energy (open symbols)
momentum (filled symbols)







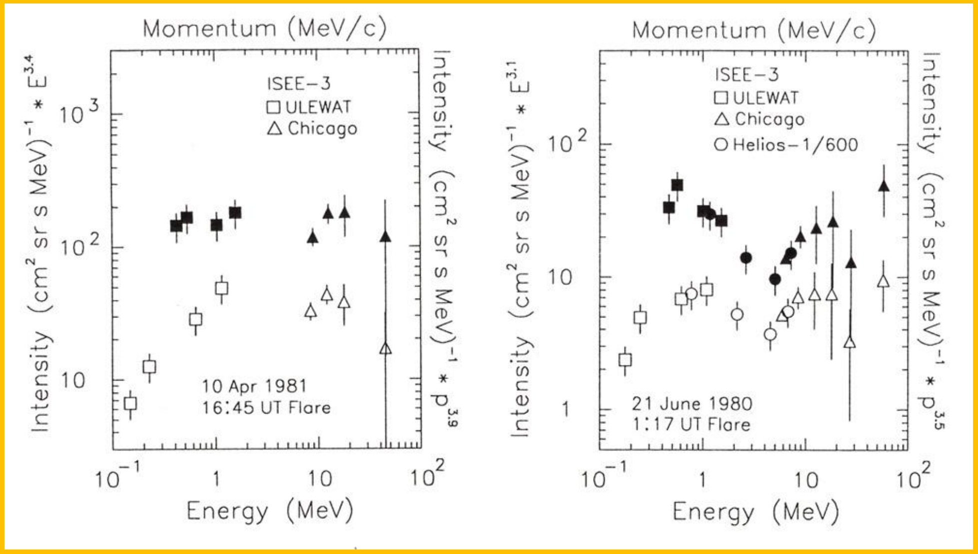
``gradual, long-duration´´ event (LDE)

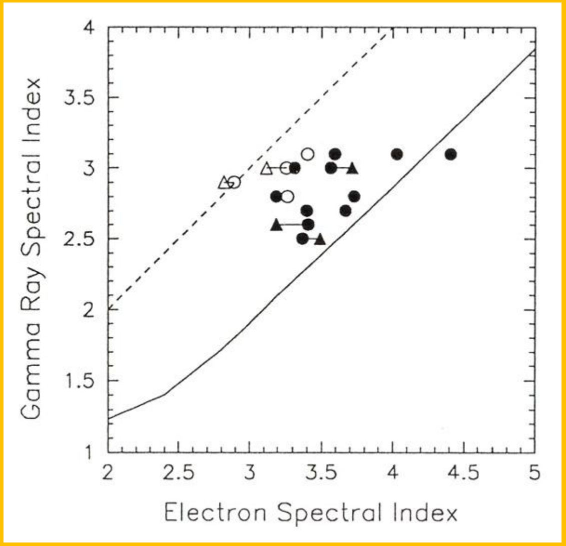
single power law in momentum

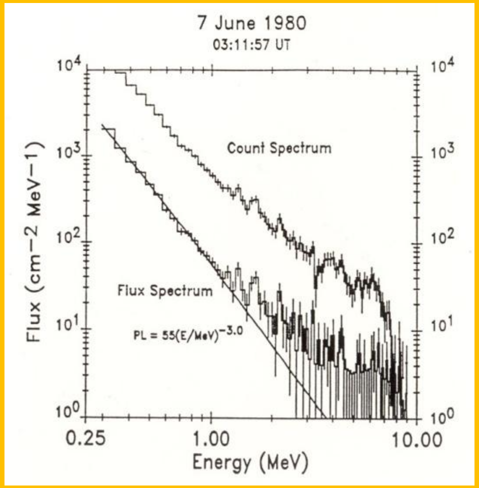
`impulsive, short duration´´ event (SDE)

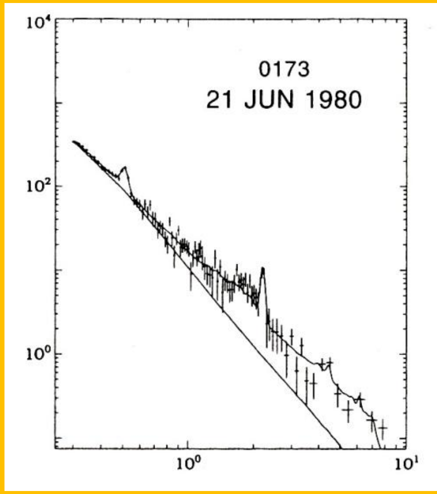
double power law in momentum

comparison of electron (~ 1 MeV) and gamma-ray (~ 0.3) spectral indices









dots:	**ISEE-3**
triangles:	**Helios**
open symbols:	**LDEs**
filled symbols:	**SDEs**
dashed line:	**thin target**
solid line:	**thick target**

observation of particles from the decay of solar neutrons

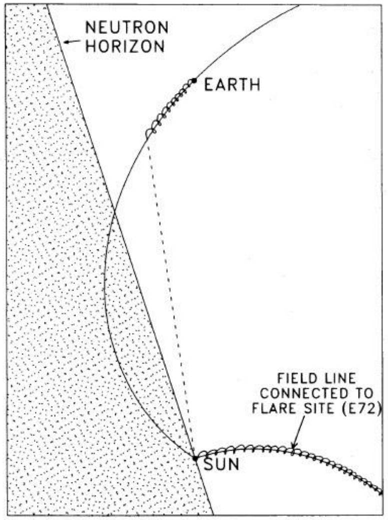


FIG. 2.—Solar system geometry at the time of the 1982 June 3 solar flare in a view perpendicular to the ecliptic plane. Protons from the flare are initially confined to field lines far from the Earth, while neutrons cross the field freely until they decay.

protons
Evenson et al. 1983
ApJ 274, 875

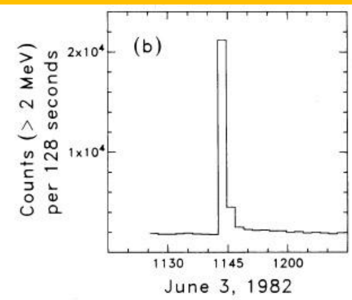


FIG. 1.—128 s accumulations of the counting rate of > 2 MeV gamma-rays at the *ISEE 3* spacecraft (Fig. 1*a*: 1980 June 21; Fig. 1*b*: 1982 June 3). The detector is a 1.4 kg CsI crystal enclosed in active anticoincidence shielding.

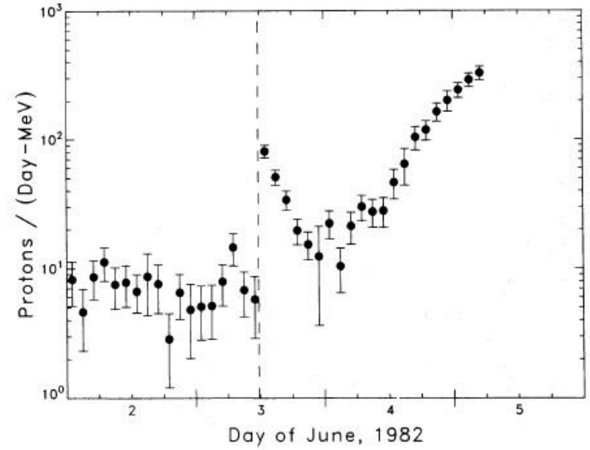
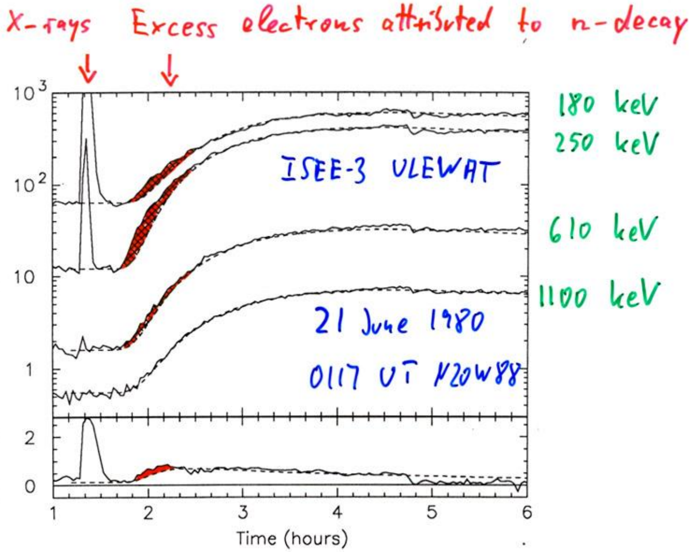


FIG. 3.—The flux of 25–45 MeV protons observed at *ISEE 3*. Two-hour averages are plotted. The gamma-ray arrival time is indicated by a dashed line.

electrons
Dröge et al. 1996
ApJ 464, L87



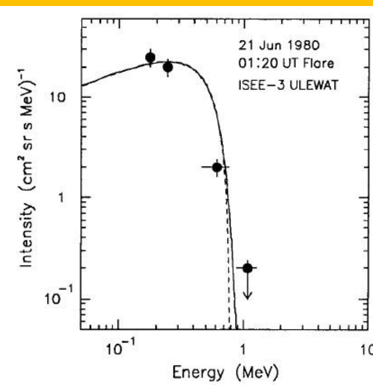


FIG. 2.—Energy spectrum of the excess electrons (*filled circles*) and theoretical prediction for decay electrons in the rest frame of the parent neutron (*dashed line*) and for the estimated neutron spectrum for the 1980 June 21 flare (*solid line*).

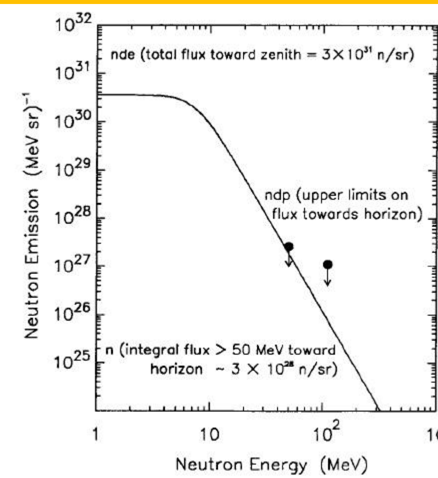
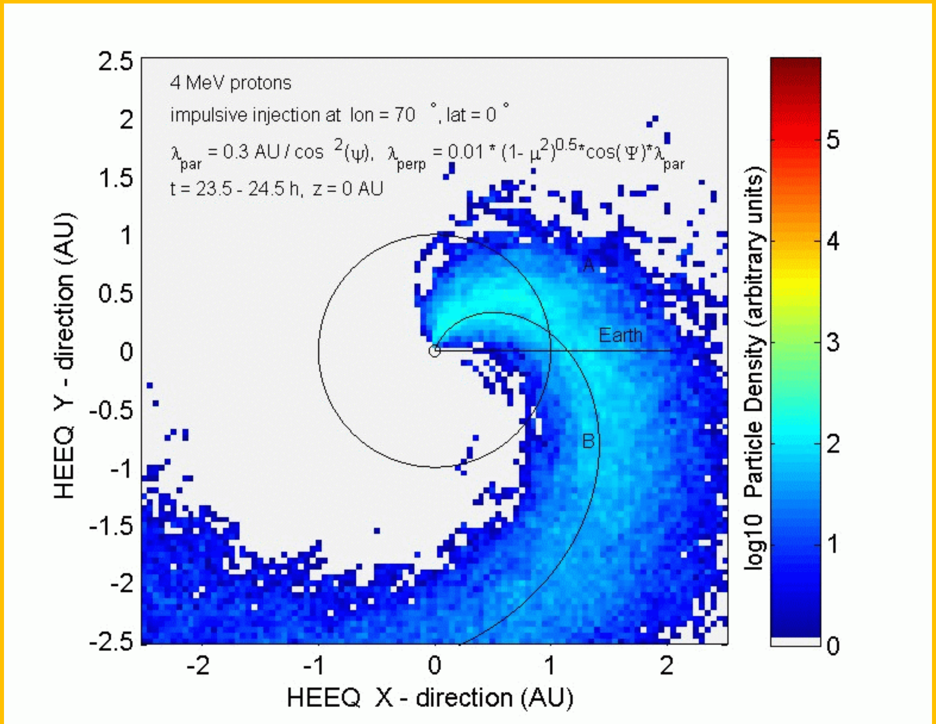
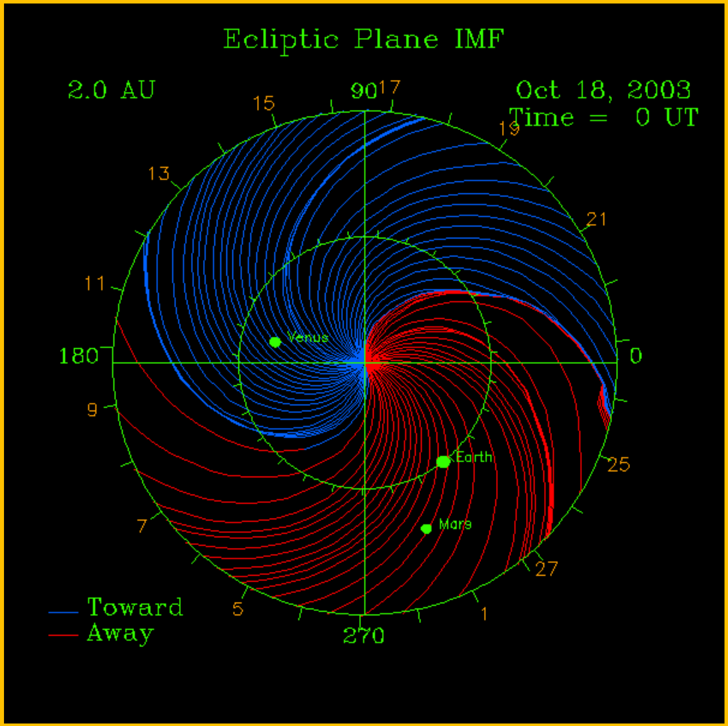


FIG. 4.—Neutron source spectrum of the 1980 June 21 flare compiled from various observations (see text for details).

evolution of particle distributions in the inner heliosphere





impulsive injection

Fearless Forecasts

University of Alaska and
Exploration Physics International, Inc.
http://gse.gi.alaska.edu/index.html

realistic configurations of interplanetary magnetic field

SUMMARY

- good phenomenological description of parallel transport of solar particles in impulsive events
- electron pitch angle distributions not consistent with form of $D_{\mu\mu}$ predicted by dynamical QLT
- reconstruction of timing, energy and charge spectra of particles injected on field line connected to spacecraft, acceleration processes, correlation with electromagnetic emission
- tools for modeling anisotropic 3D transport are being developed
- evidence for significant perpendicular transport ($\lambda_\perp / \lambda_\parallel \sim 10^{-4} - 10^{-1}$) in the events studied so far

  ⟹ indication for anticorrelation between $\lambda_\perp$ and $\lambda_\parallel$

<u>possibilities to explore:</u>

- ratio of accelerated to escaping particles
- nature of acceleration process
- transport of energetic particles and magnetic structures in the solar corona
- science goals for future missions (Solar Orbiter, Solar Probe …)