Energetic Particles in the Heliosphere

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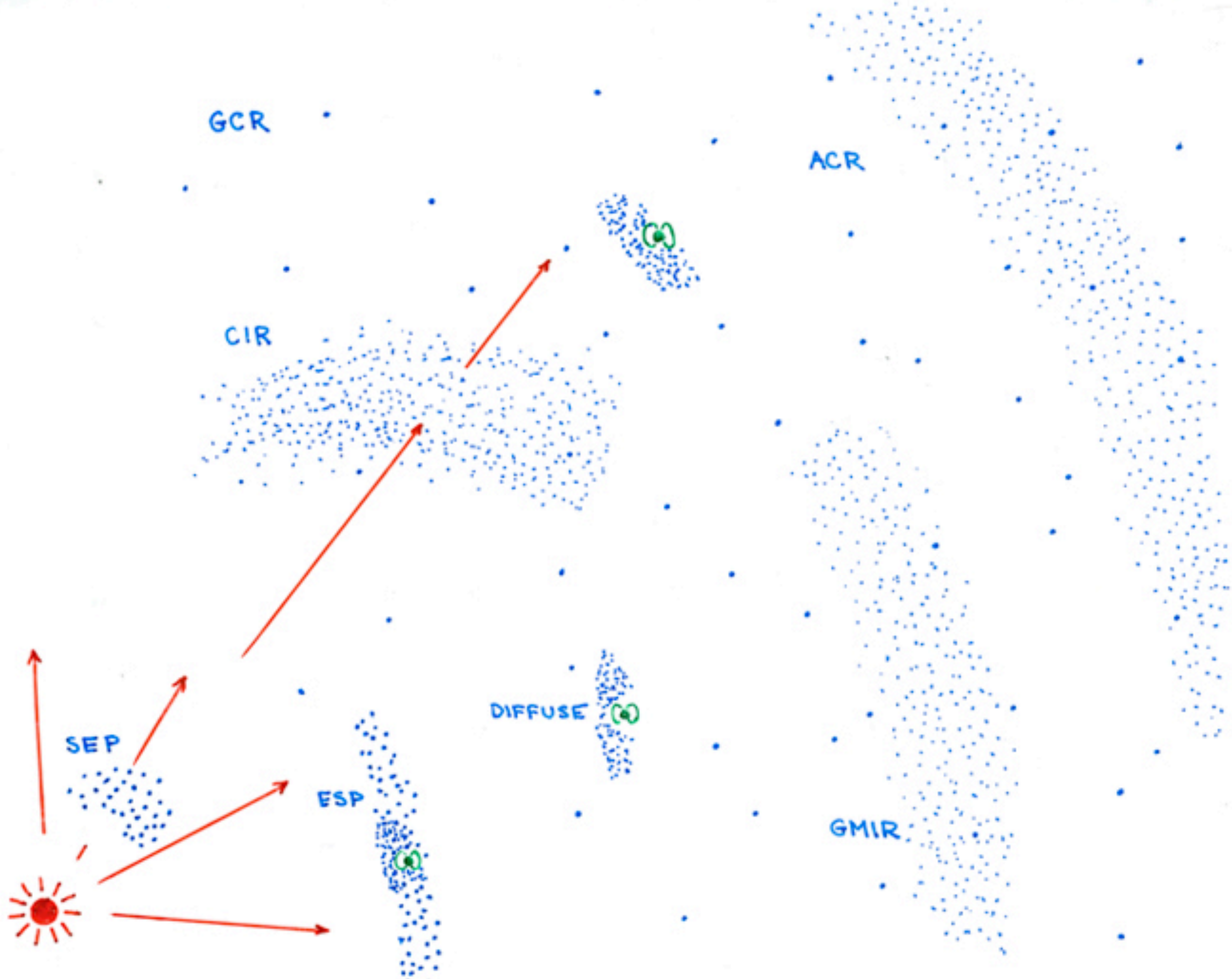
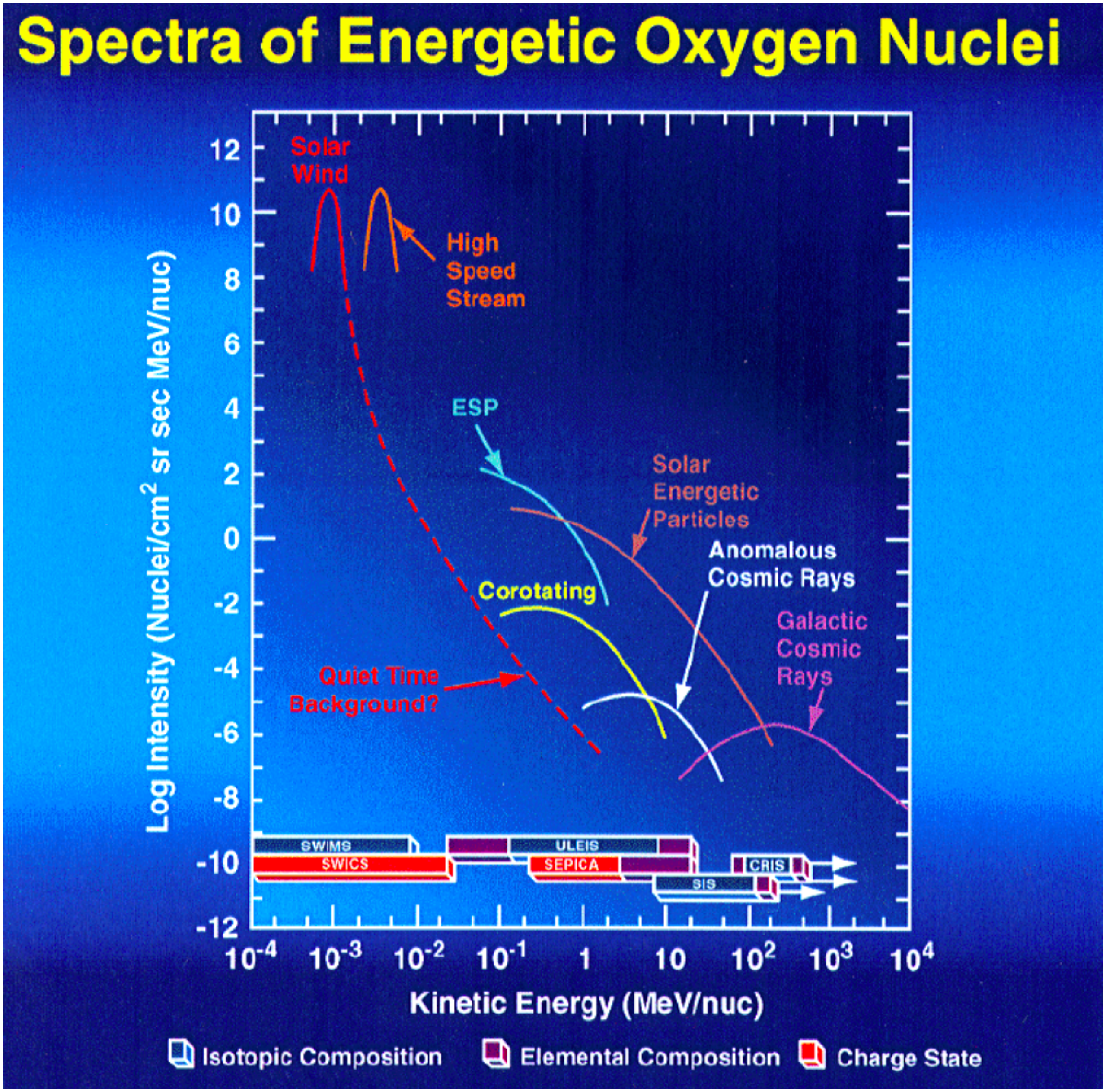
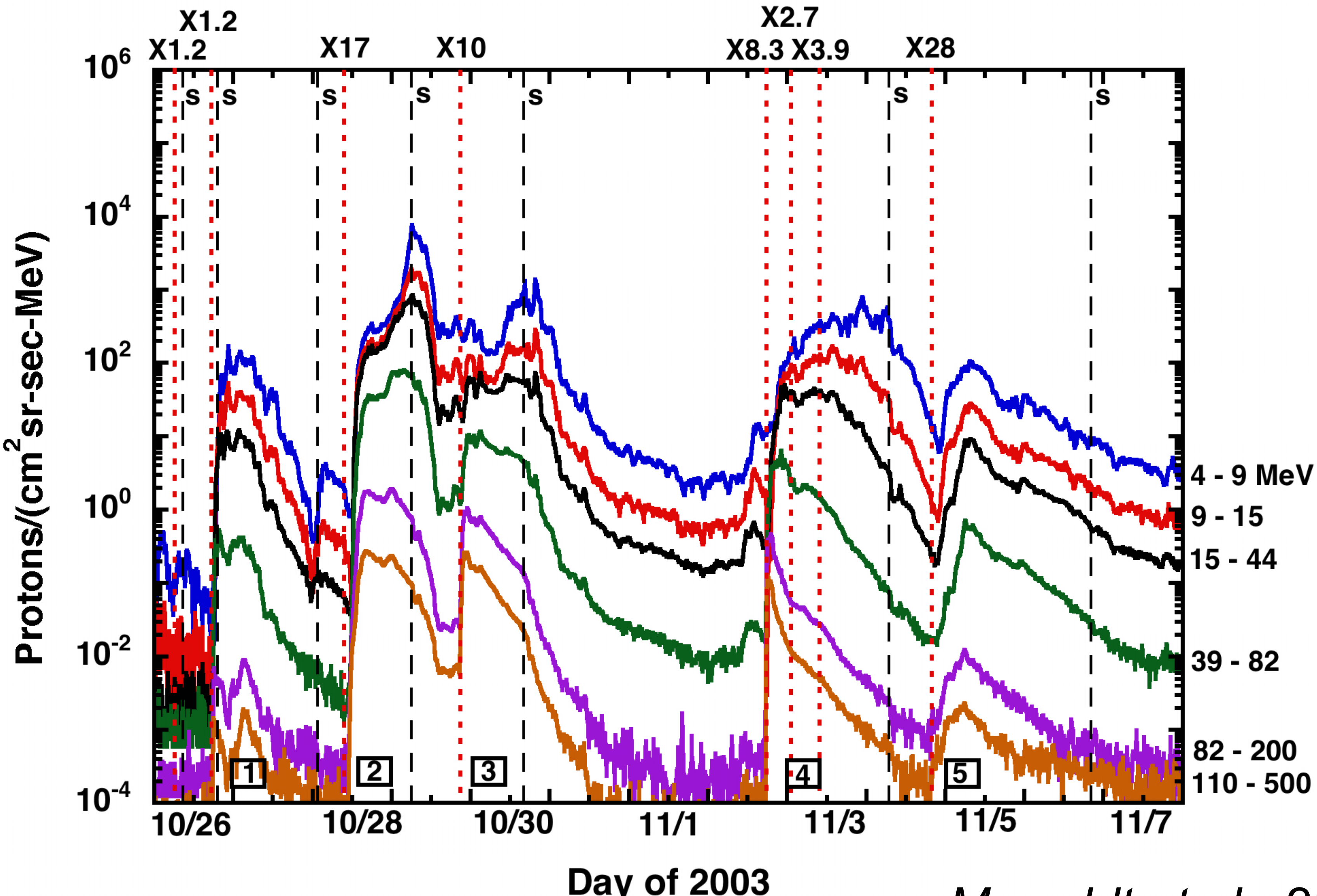

GCR
ACR
CIR
DIFFUSE
SEP
ESP
GMIR



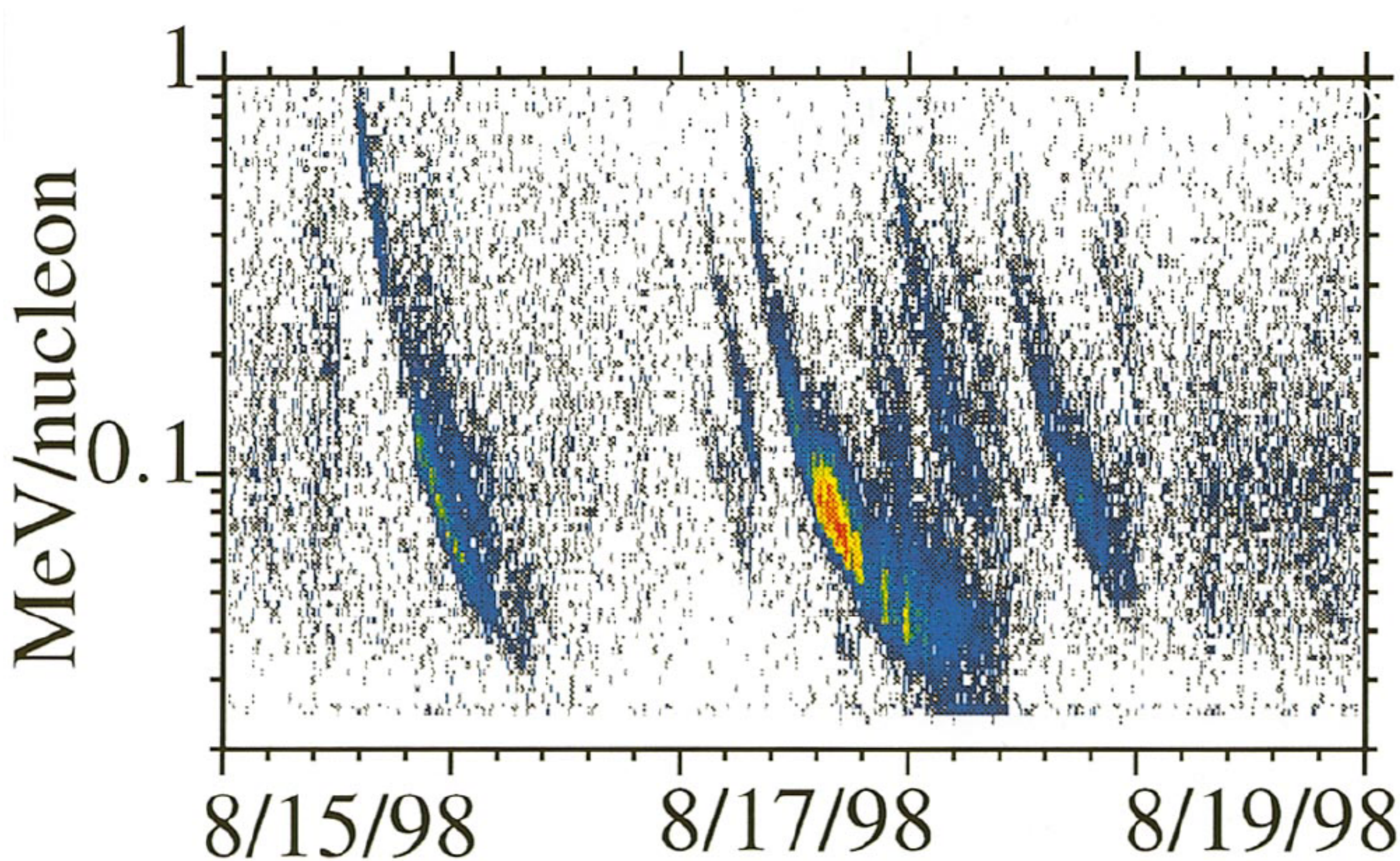
Stone et al., 1998

2003 Haloween Events



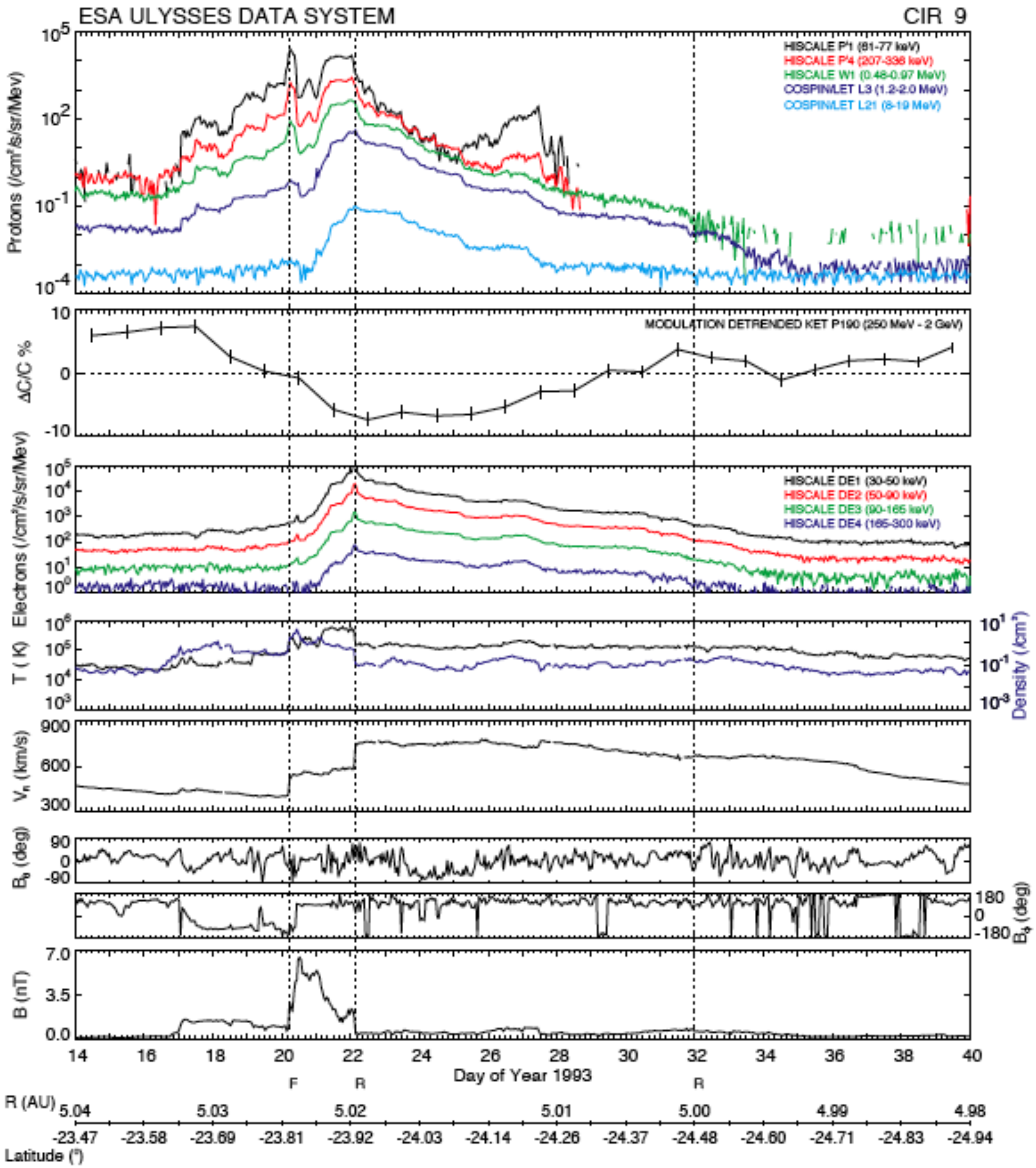
Mewaldt et al., 2005

Impulsive Events



Mason et al., 1999

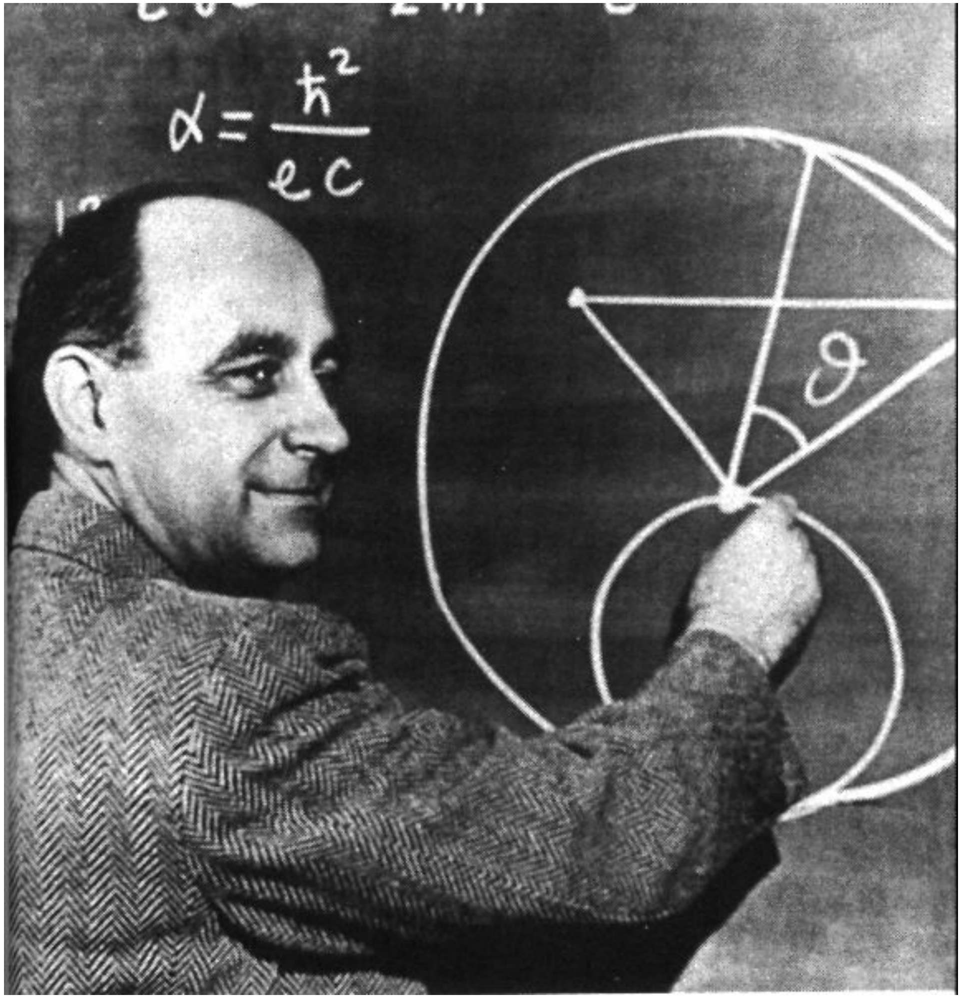
CIR Event: Ulysses



Kunow et al., 1999

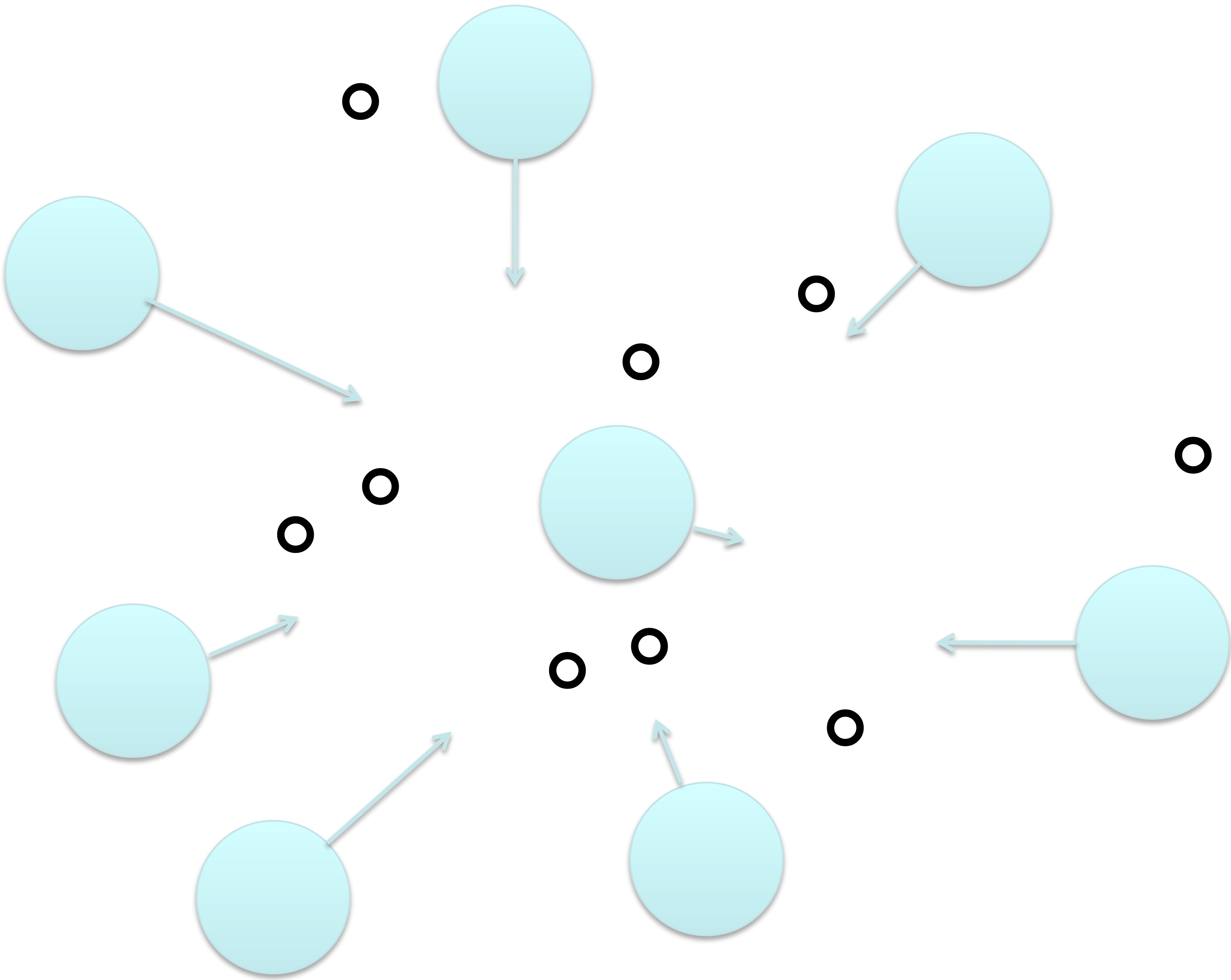
Particle Acceleration

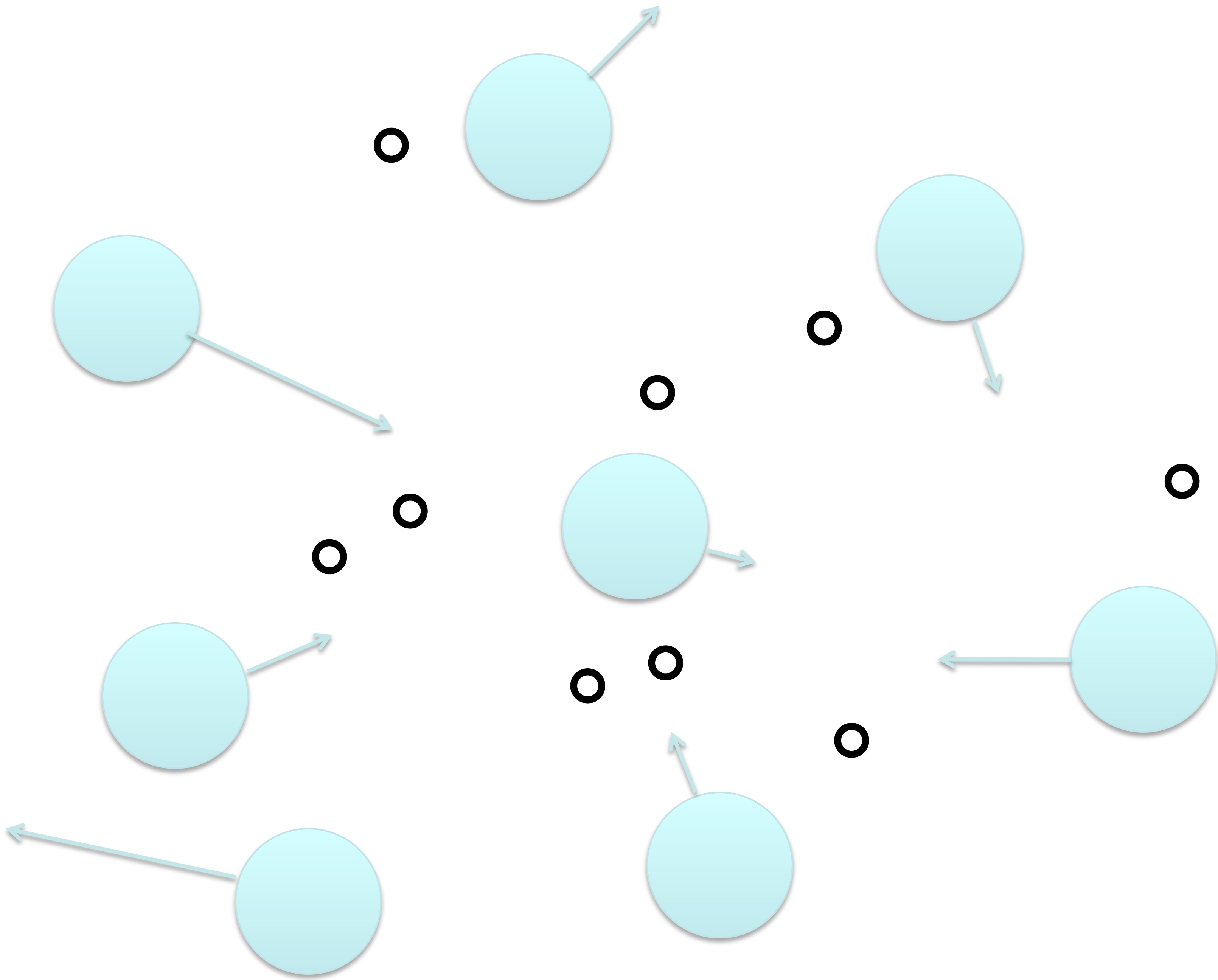
$$\mathbf{E} = -c^{-1}\mathbf{V} \times \mathbf{B}$$



Enrico Fermi (1949, 1954):

First-Order and Second-Order Fermi Acceleration



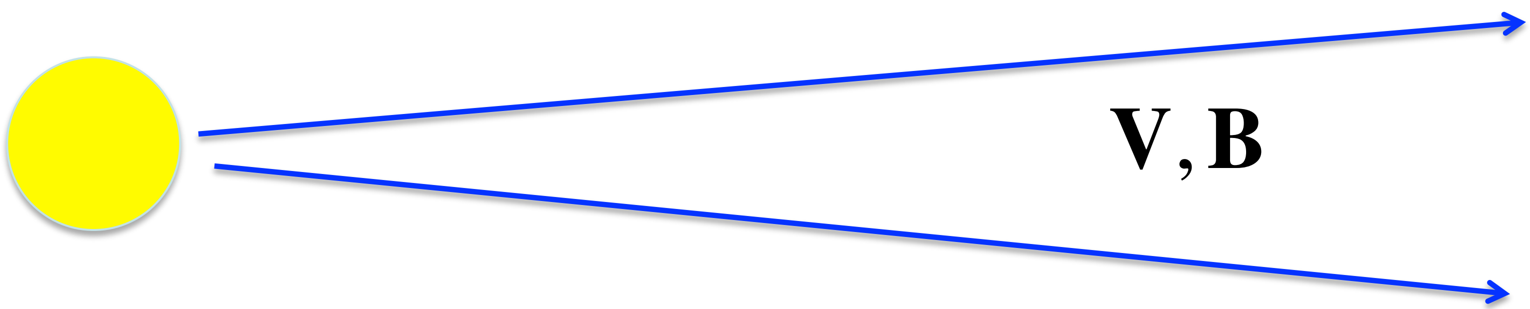


Transport Equations

Vlasov Equation

$$\frac{\partial F}{\partial t} + \mathbf{v} \cdot \frac{\partial F}{\partial \mathbf{x}} + q\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) \cdot \frac{\partial F}{\partial \mathbf{p}} = 0$$

Transport in Radial V and B in the Solar Wind Frame



$$\frac{dF[t, r(t), \mu(t), v(t)]}{dt} = \frac{\partial F}{\partial t} + \frac{\partial F}{\partial r}\frac{dr}{dt} + \frac{\partial F}{\partial \mu}\frac{d\mu}{dt} + \frac{\partial F}{\partial v}\frac{dv}{dt} = \left(\frac{dF}{dt}\right)_{\text{scat.}}$$

$$M = v_{\perp}^{2} / B \propto v^{2}(1 - \mu^{2})r^{2} \qquad E = v^{2} + 2v\mu V + V^{2}$$

Focused Transport Equation I

$$\frac{\partial F}{\partial t} + (V + v\mu)\frac{\partial F}{\partial r} - \frac{(1-\mu^2)}{r} V v \frac{\partial F}{\partial v}$$

$$+ \frac{(1-\mu^2)}{r}(v + \mu V)\frac{\partial F}{\partial \mu} = \left(\frac{dF}{dt}\right)_{\text{scatt.}}$$

Particle Scattering I

Parker, 1964

$$\mathbf{B} = B_0\left(\frac{dF}{dz}\mathbf{i} + \frac{dG}{dz}\mathbf{j} + \mathbf{k}\right)$$

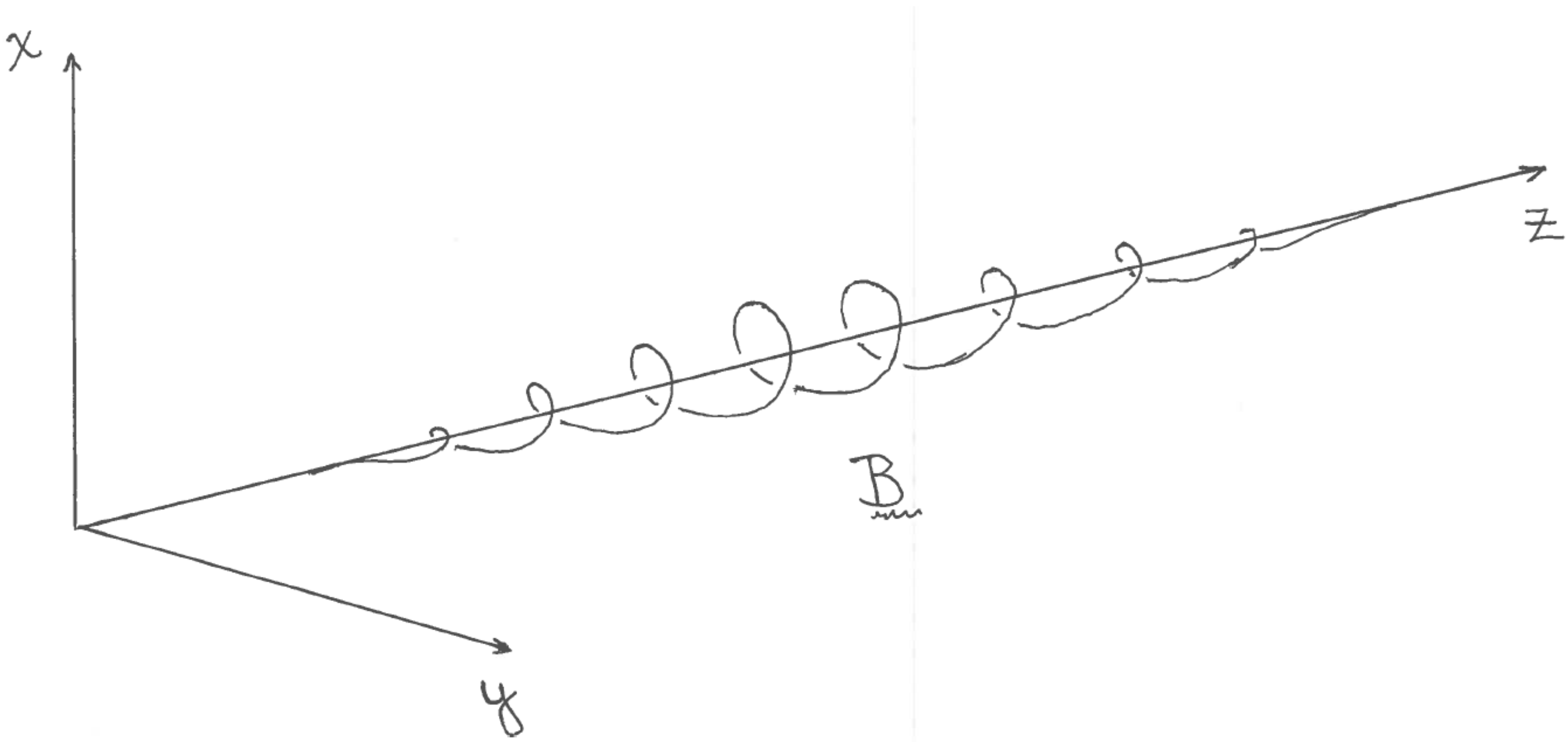
Fieldlines: $x = F(z) + x_0;\ y = G(z) + y_0$

If $F, G \to F_\pm, G_\pm$ as $z \to \pm\infty$, particle remains on original fieldline!

$$F(z) = \varepsilon \sin(2\pi z / L)\exp\left(-z^2 / l^2\right)$$

$$G(z) = \varepsilon \cos(2\pi z / L)\exp\left(-z^2 / l^2\right)$$

Particle Scattering II



Particle Scattering III

$$\Delta v_z = -\Omega^2 \frac{v_{\perp 0}}{v_{z0}^2} \alpha l (\cos\phi) \pi^{1/2} \exp\left[-\frac{l^2 \Omega^2}{4 v_{z0}^2} \left(1 - \frac{2\pi v_{z0}}{\Omega L} \right)^2 \right]$$

$$\tau_g = \frac{L}{v_{z0}}$$

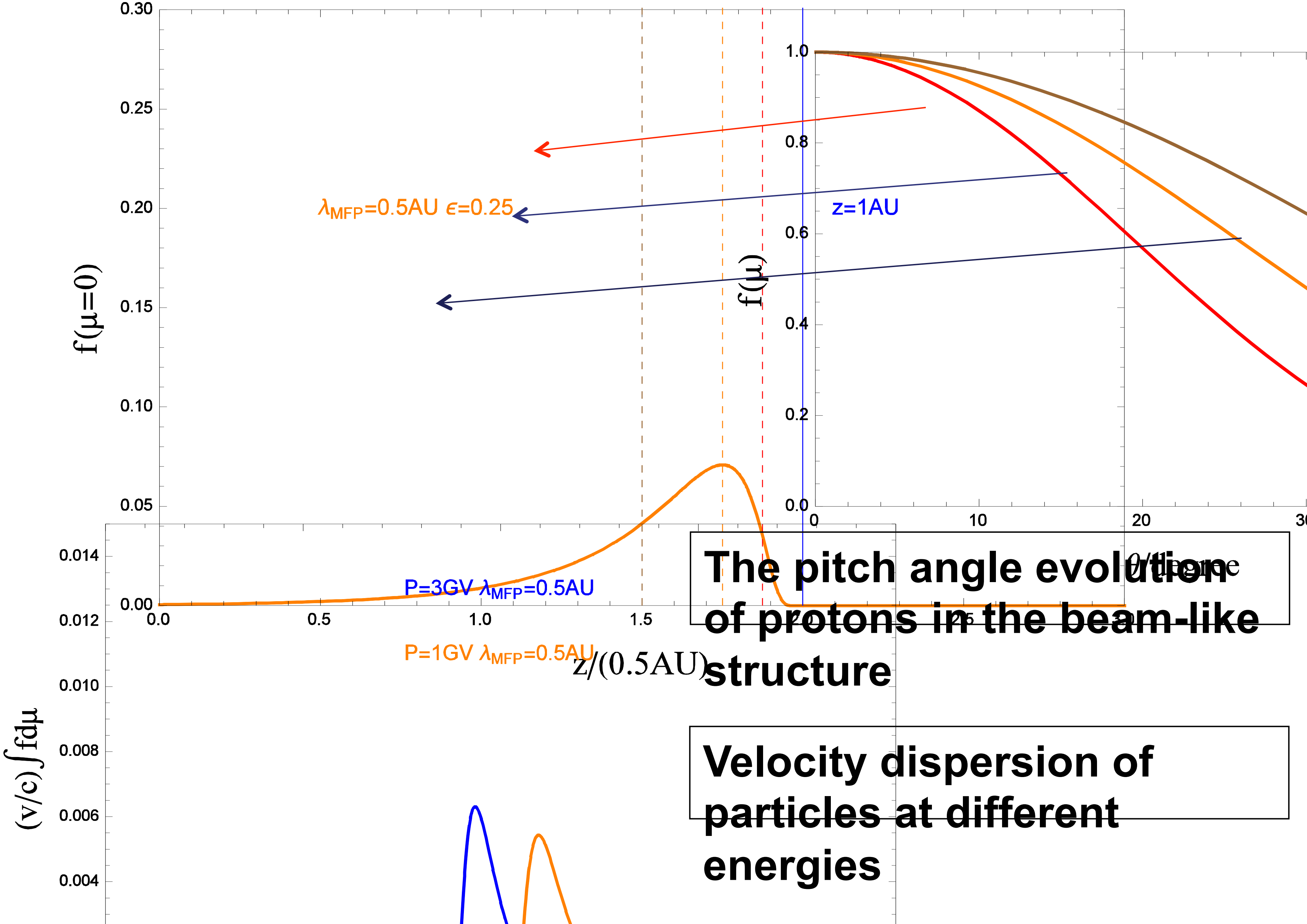
$\Rightarrow$ pitch-angle diffusion!

Exercise 8 in Heliospheric Problems (M. Lee)

Focused Transport Equation II

$$\frac{\partial F}{\partial t} + (V + v\mu)\frac{\partial F}{\partial r} - \frac{(1-\mu^2)}{r} Vv \frac{\partial F}{\partial v}$$

$$+ \frac{(1-\mu^2)}{r}(v + \mu V)\frac{\partial F}{\partial \mu} = \frac{\partial}{\partial \mu}\left[(1-\mu^2) D_{\mu\mu} \frac{\partial F}{\partial \mu}\right]$$



The pitch angle evolution of protons in the beam-like structure

Velocity dispersion of particles at different energies

Parker Transport Equation I

$$f = \frac{1}{2}\int_{-1}^{1} d\mu F$$

$$\frac{\partial f}{\partial t} + V\frac{\partial f}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 S_r\right) - \frac{2V}{3r}v\frac{\partial f}{\partial v} = 0$$

Generalize:

$$\frac{\partial f}{\partial t} + \mathbf{V}\cdot\nabla f + \nabla\cdot\mathbf{S} - \frac{1}{3}\nabla\cdot\mathbf{V}v\frac{\partial f}{\partial v} = 0$$

Parker, 1965

Parker Transport Equation II

$\mathbf{S}$?

$$v\mu\frac{\partial f}{\partial z} = \frac{\partial}{\partial \mu}\left[(1-\mu^2)D_{\mu\mu}\frac{\partial g}{\partial \mu}\right]$$

$$g = -\frac{1}{2}v\frac{\partial f}{\partial z}\int_0^{\mu}\frac{d\mu'}{D_{\mu\mu}}$$

$$S_z = \frac{1}{2}\int_{-1}^{1} d\mu v\mu g(\mu) = -K_{zz}\frac{\partial f}{\partial z}$$

$$K_{zz} = \frac{1}{8}v^2\int_{-1}^{1} d\mu\frac{1-\mu^2}{D_{\mu\mu}}$$

$$\mathbf{S} = -K_{\perp}\frac{\partial f}{\partial x} - K_{\perp}\frac{\partial f}{\partial y} - K_{zz}\frac{\partial f}{\partial z} + ?$$

Parker Transport Equation III

$$v_i v_j \frac{\partial F}{\partial x_j} + \frac{qB}{mc} v_i \left[\left(\mathbf{v} \times \mathbf{k} \right) \cdot \frac{\partial F}{\partial \mathbf{v}} \right] \simeq 0$$

$$\frac{\partial}{\partial x_j} \frac{1}{4\pi} \int d\phi \, d\mu v_z^2 \delta_{ij} f - \Omega \frac{1}{4\pi} \int d\phi \, d\mu v_i \frac{\partial F}{\partial \phi} = 0$$

$$\frac{1}{3} v^2 \nabla f = \Omega \left(\mathbf{S} \times \mathbf{k} \right)$$

$$\frac{1}{3} v^2 \mathbf{k} \times \nabla f = \Omega \left[\mathbf{k} \times \left(\mathbf{S} \times \mathbf{k} \right) \right] = \Omega \mathbf{S}_\perp$$

$$\mathbf{S}_\perp = \frac{v^2}{3\Omega} \mathbf{k} \times \nabla f$$

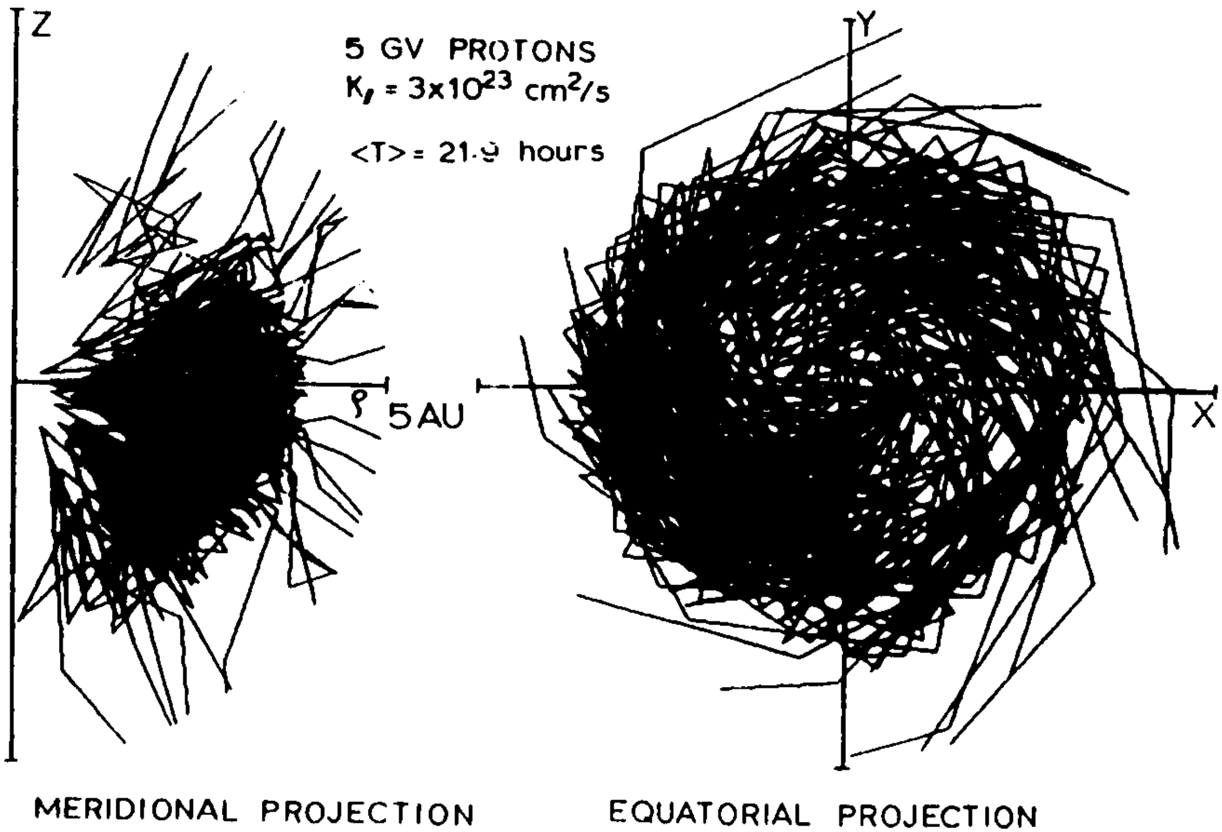
$$\nabla \cdot \mathbf{S}_\perp = \nabla f \cdot \left(\frac{v^2 mc}{3q} \nabla \times \frac{\mathbf{B}}{B^2} \right) \equiv \nabla f \cdot \mathbf{V}_D$$

Parker Transport Equation IV

$$\frac{\partial f}{\partial t} + (\mathbf{V} + \mathbf{V}_D) \cdot \nabla f - \nabla \cdot (\mathbf{K} \cdot \nabla f) - \frac{1}{3} \nabla \cdot \mathbf{V} v \frac{\partial f}{\partial v} = 0$$

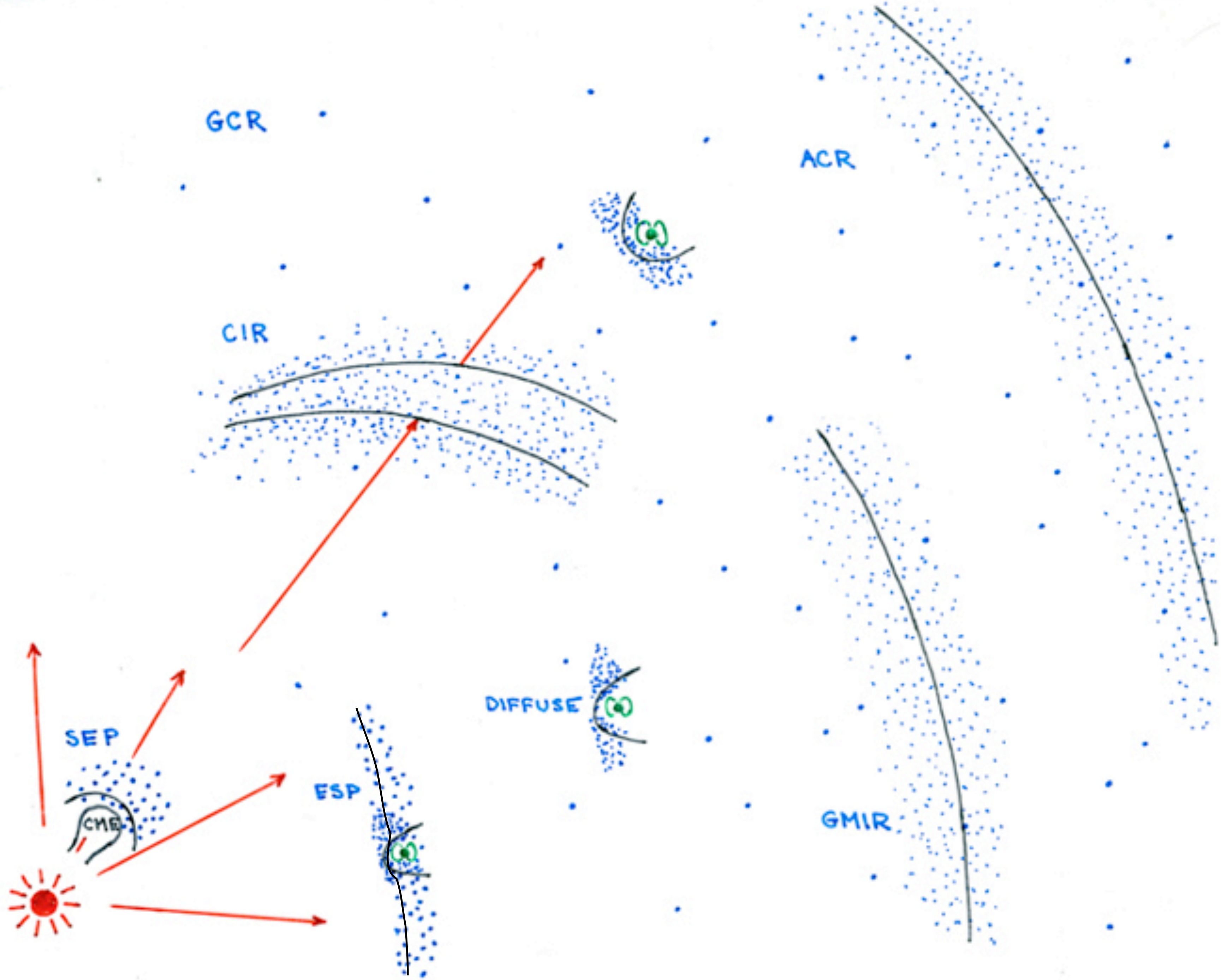
$$\frac{\partial f}{\partial t} + \nabla \cdot \left[-\mathbf{K} \cdot \nabla f - \frac{1}{3} \mathbf{V} v \frac{\partial f}{\partial v} + \frac{v^2}{3\Omega} \left(\mathbf{k} \times \nabla f \right) \right] + \frac{1}{3v^2} \frac{\partial}{\partial v} \left(v^3 \mathbf{V} \cdot \nabla f \right) = 0$$

The Hairy Ball?



Thomas and Gall, 1984

Shocks & Energetic Particles


GCR
ACR
CIR
DIFFUSE
SEP
CME
ESP
GMIR

Diffusive Shock Acceleration

$$V_z \frac{df}{dz} - \frac{d}{dz}\left(K_{zz}\frac{df}{dz}\right) - \frac{1}{3}\frac{dV_z}{dz} p \frac{df}{dp} = Q\delta(z)\delta(p-p_0)$$

$$f(z<0) = \frac{3Q}{(V_u - V_d)p_0}\left(\frac{p}{p_0}\right)^{-\beta} \exp\left(\frac{Vz}{K}\right)$$

$$f(z>0) = \frac{3Q}{(V_u - V_d)p_0}\left(\frac{p}{p_0}\right)^{-\beta}$$

$$\beta = 3X/(X-1)$$

Exercise 5 in Heliospheric Problems (M. Lee)

Fisk, 1971;………………...

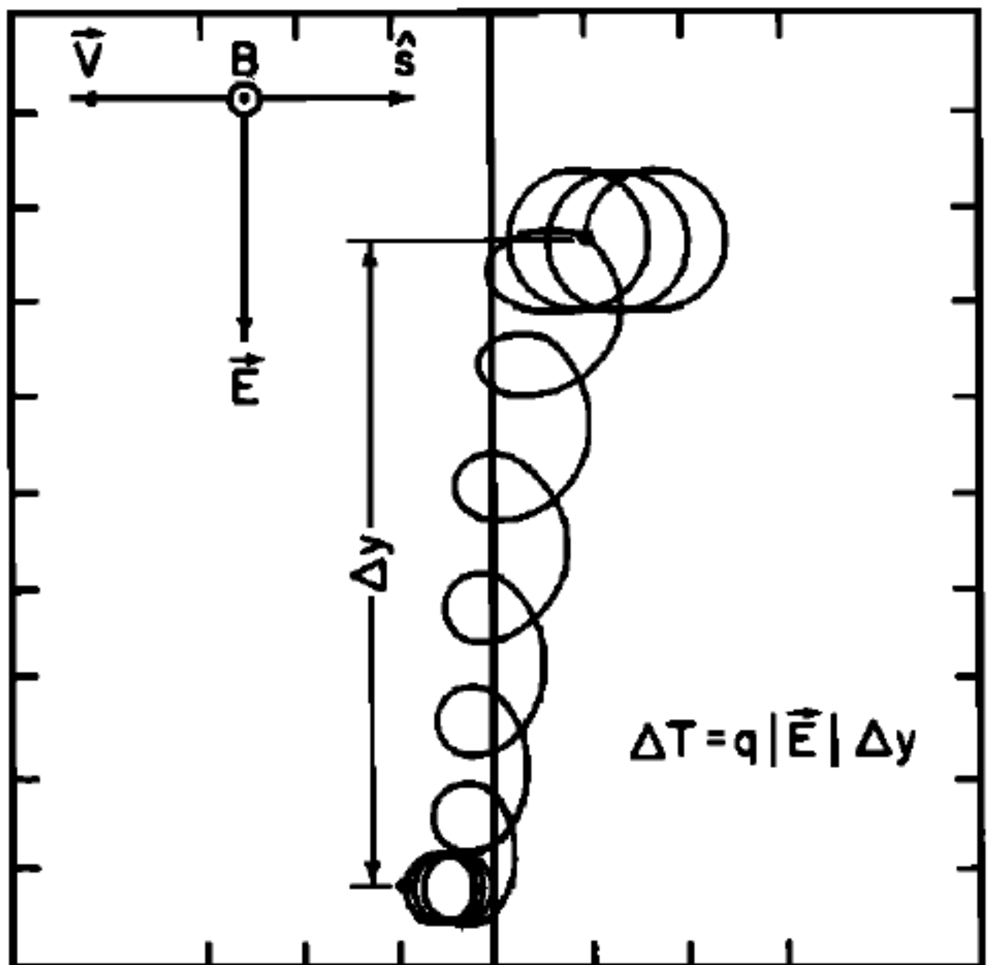
Axford, Leer & Skadron, 1977

Krymsky, 1977

Blandford & Ostriker, 1978

Bell, 1978

“Shock Drift” Acceleration

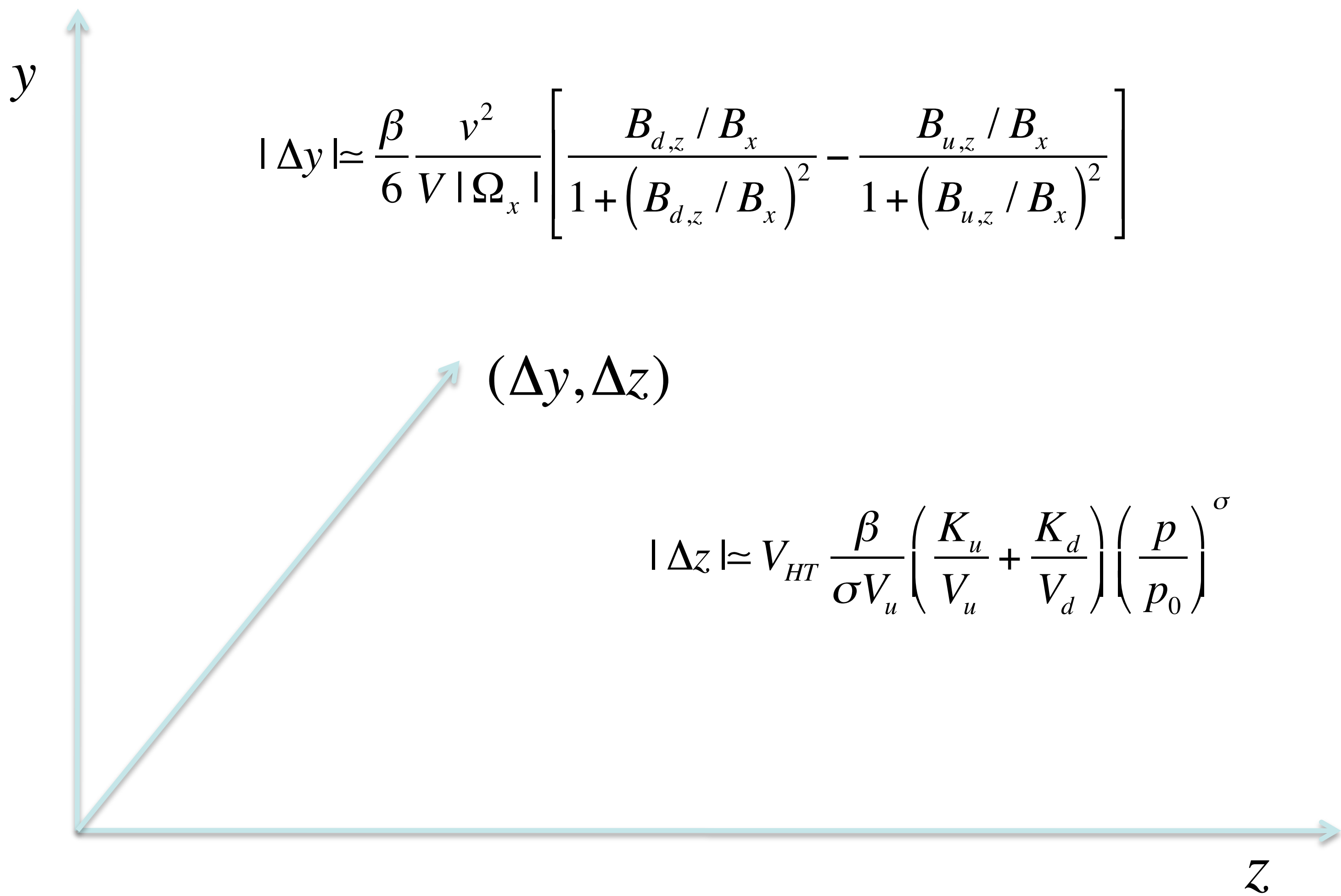


Jokipii, 1982

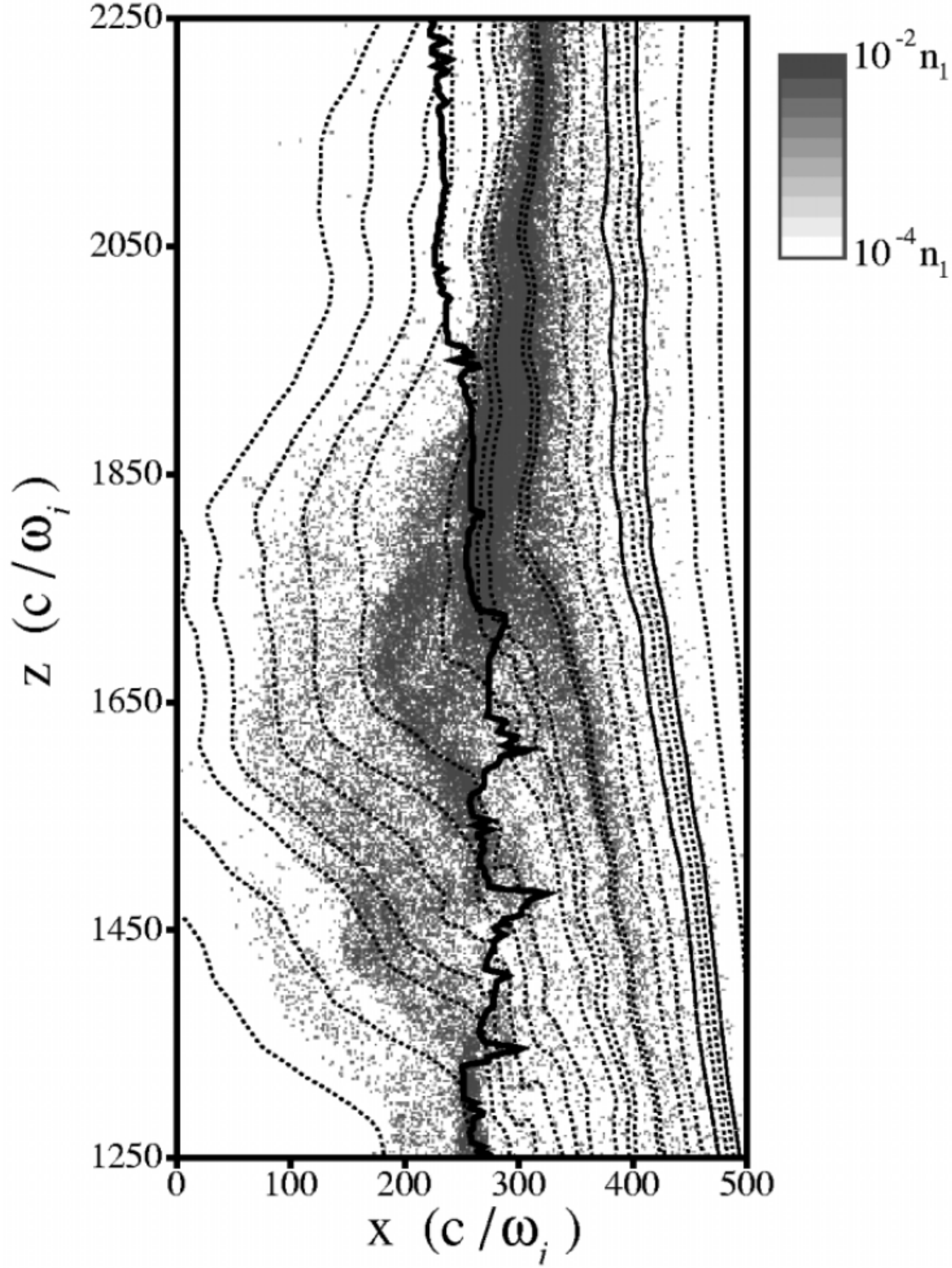
Pesses, 1981

Particle Drift Along Shock

$$|\Delta y| \simeq \frac{\beta}{6}\frac{v^2}{V\,|\Omega_x|}\left[\frac{B_{d,z}/B_x}{1+\left(B_{d,z}/B_x\right)^2}-\frac{B_{u,z}/B_x}{1+\left(B_{u,z}/B_x\right)^2}\right]$$



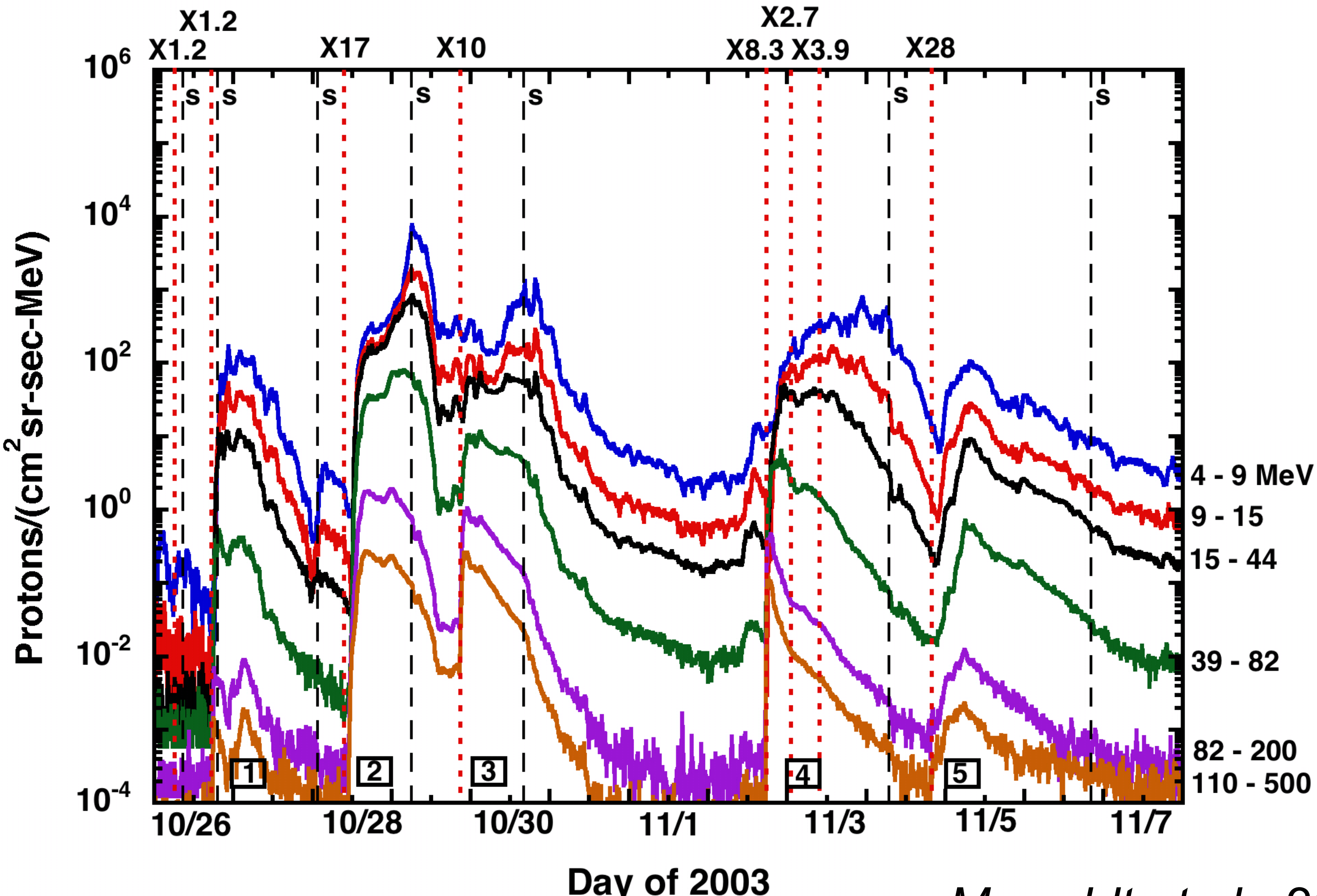
$$|\Delta z| \simeq V_{HT}\,\frac{\beta}{\sigma V_u}\left(\frac{K_u}{V_u}+\frac{K_d}{V_d}\right)\left(\frac{p}{p_0}\right)^{\sigma}$$



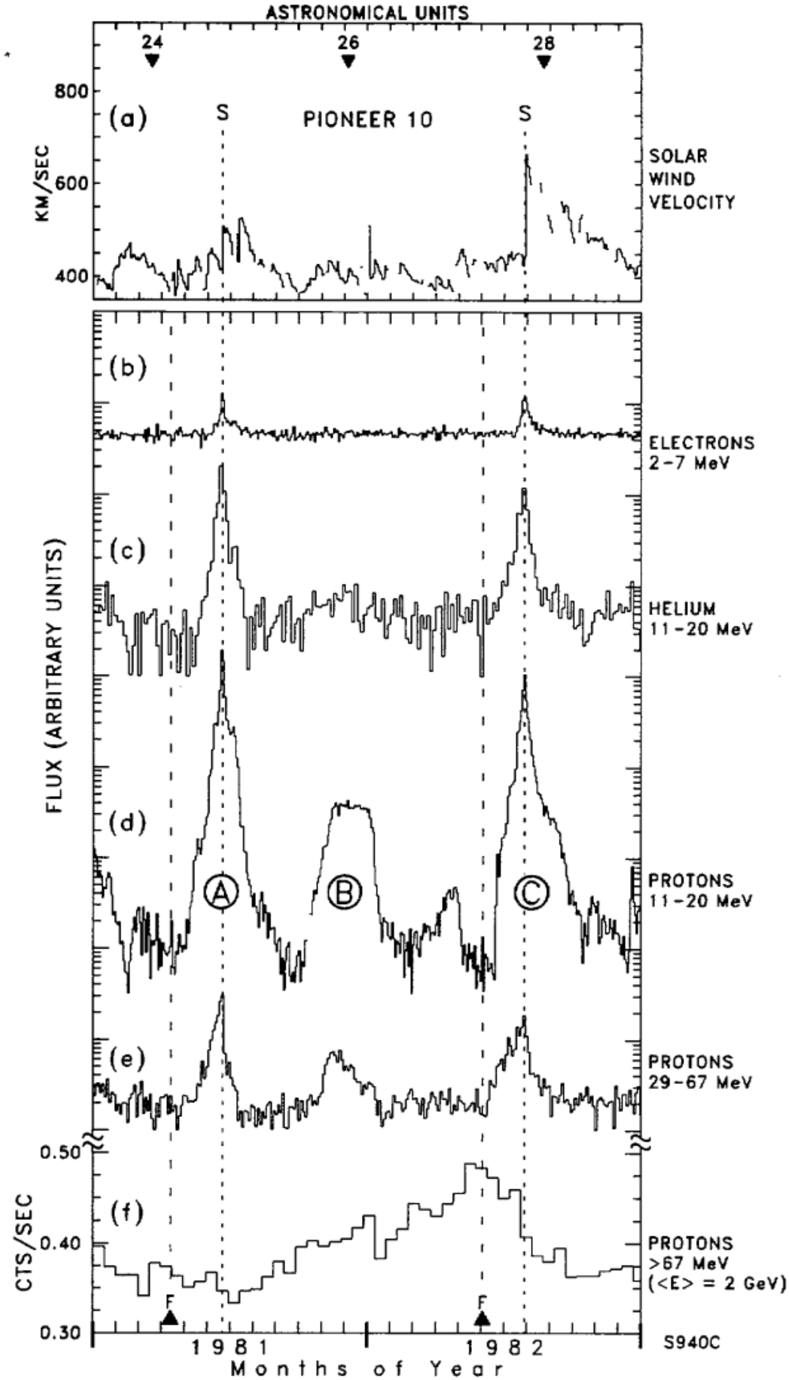
Quasi-Perpendicular Shock Simulation: Be Careful!

Giacalone, 1999

2003 Haloween Events



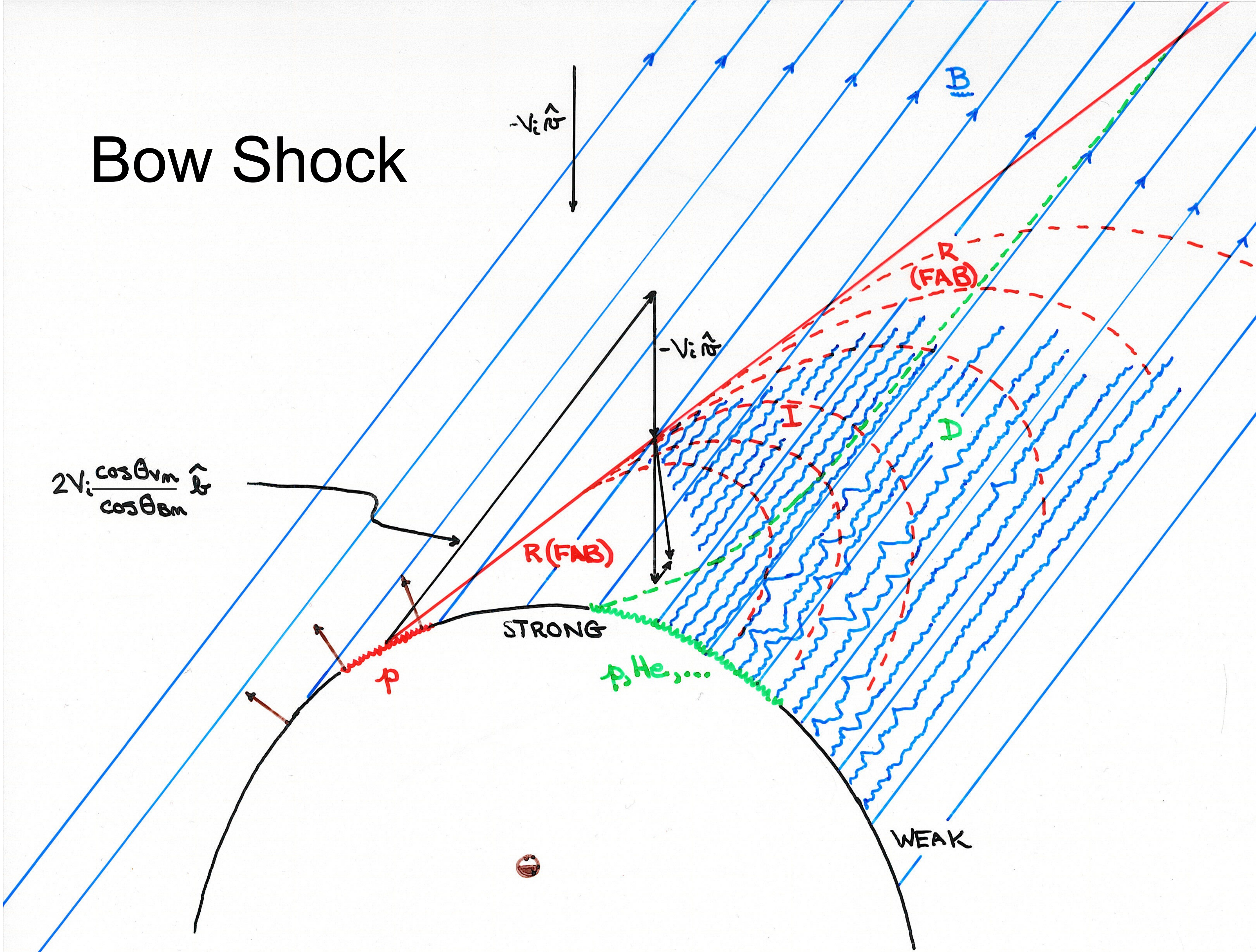
Mewaldt et al., 2005



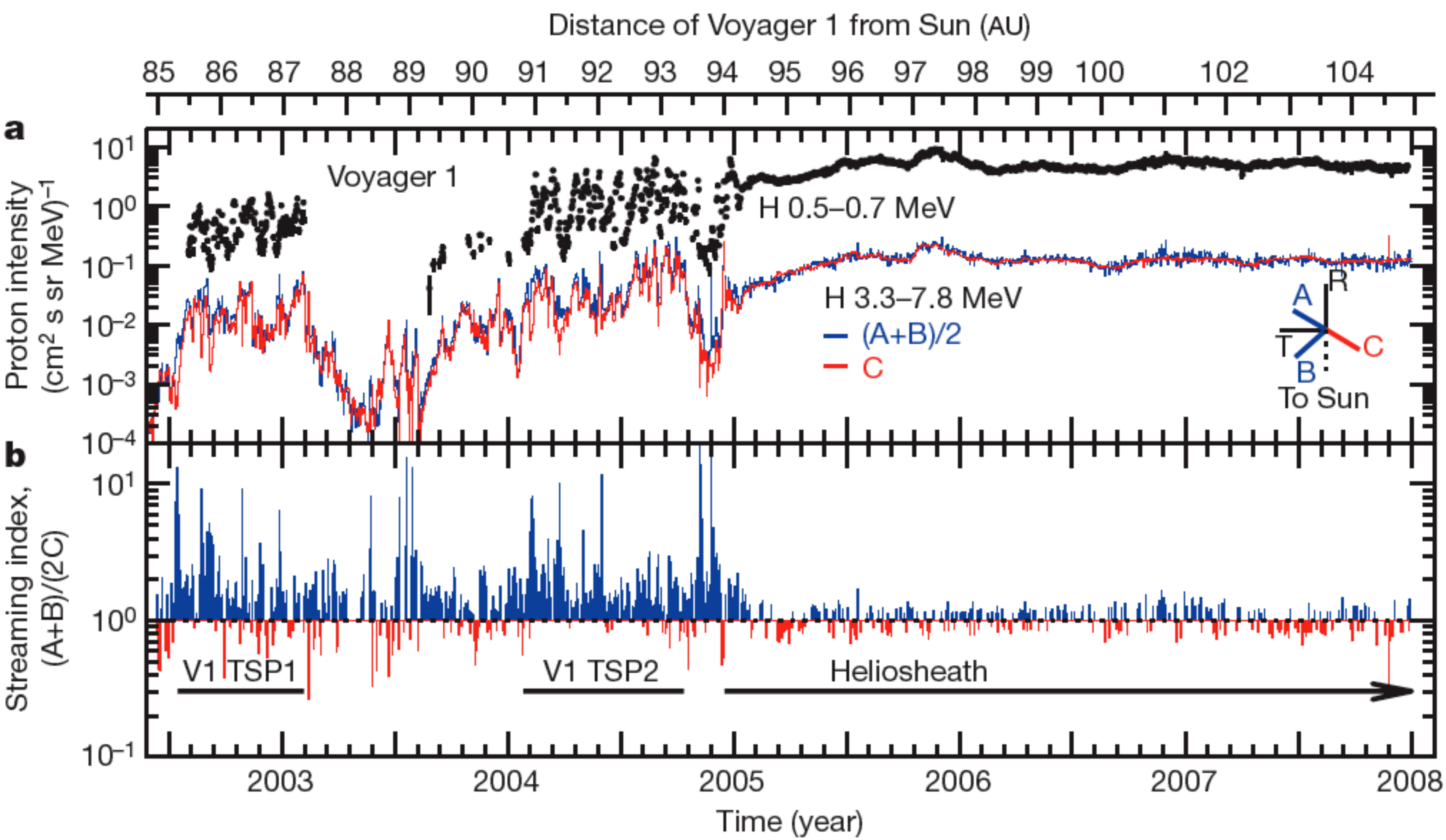
Pioneer Super Events

Pyle et al., 1984

Bow Shock

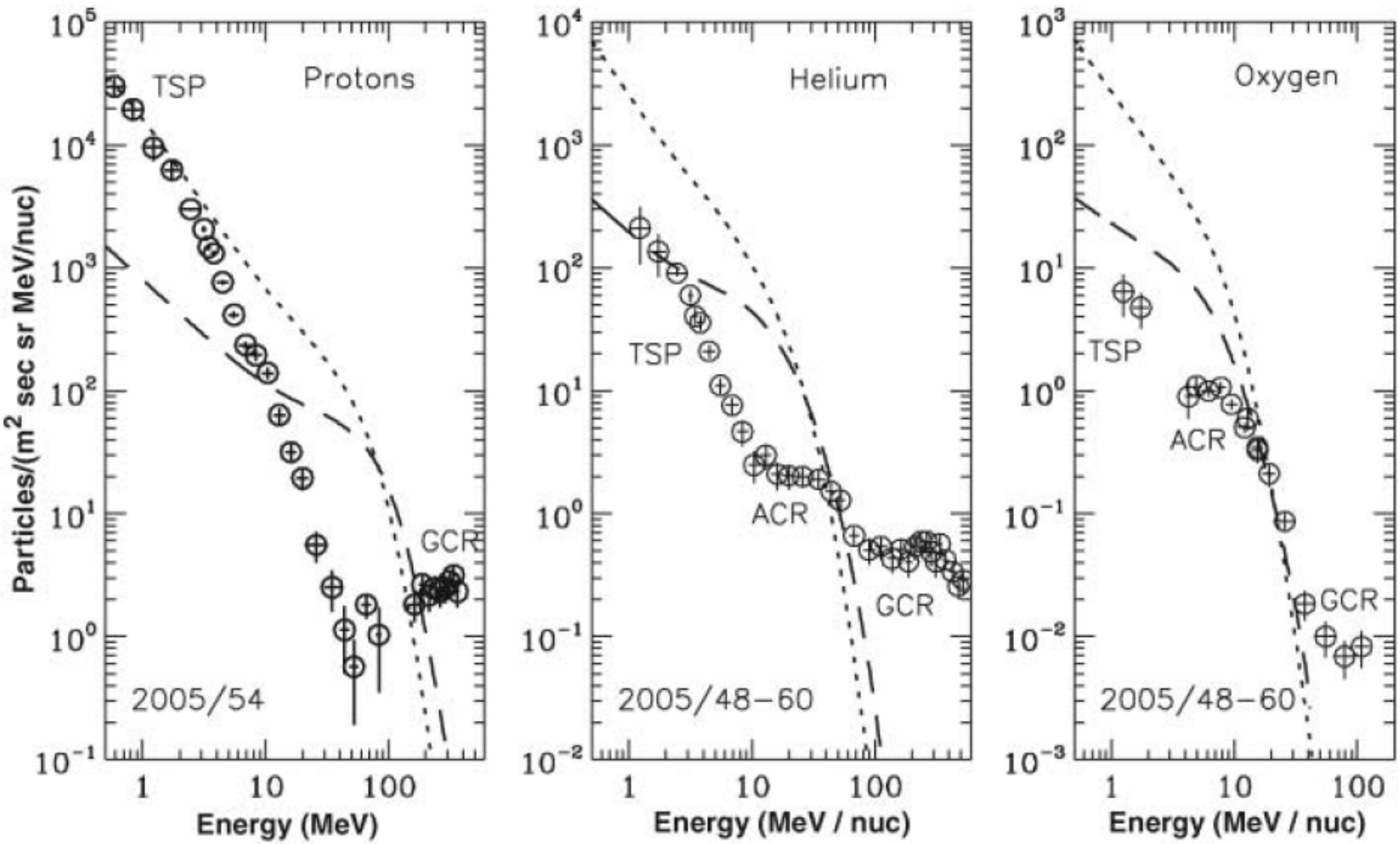


$-V_i \hat{v}$
B
R
(FAB)
$-V_i \hat{v}$
I
D
$2V_i \frac{\cos\theta_{vn}}{\cos\theta_{Bn}} \hat{b}$
R(FAB)
STRONG
p
p, He, ...
WEAK



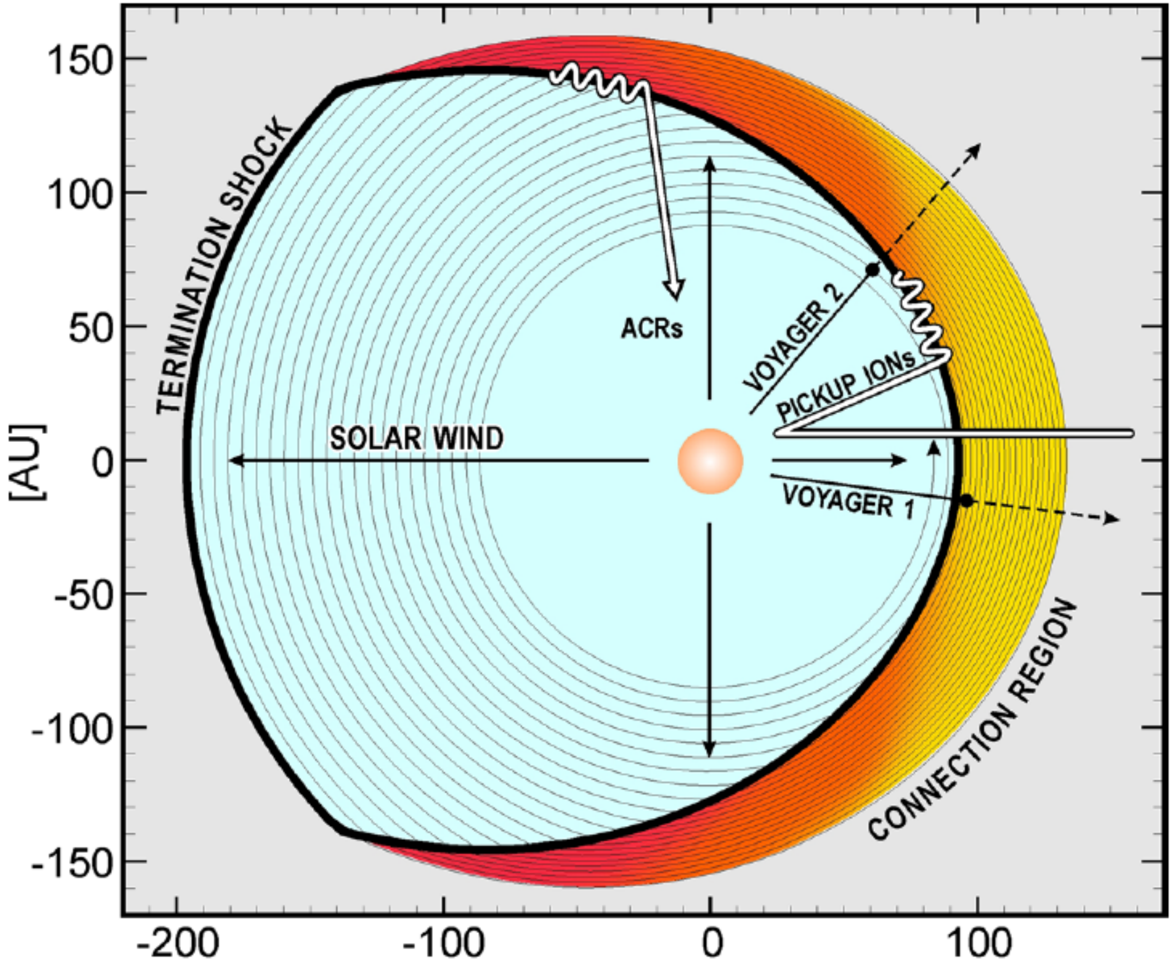
Stone et al., 2008

Voyager 1 Energy Spectra



Stone et al., 2005

The Blunt Termination Shock



McComas and Schwadron, 2006

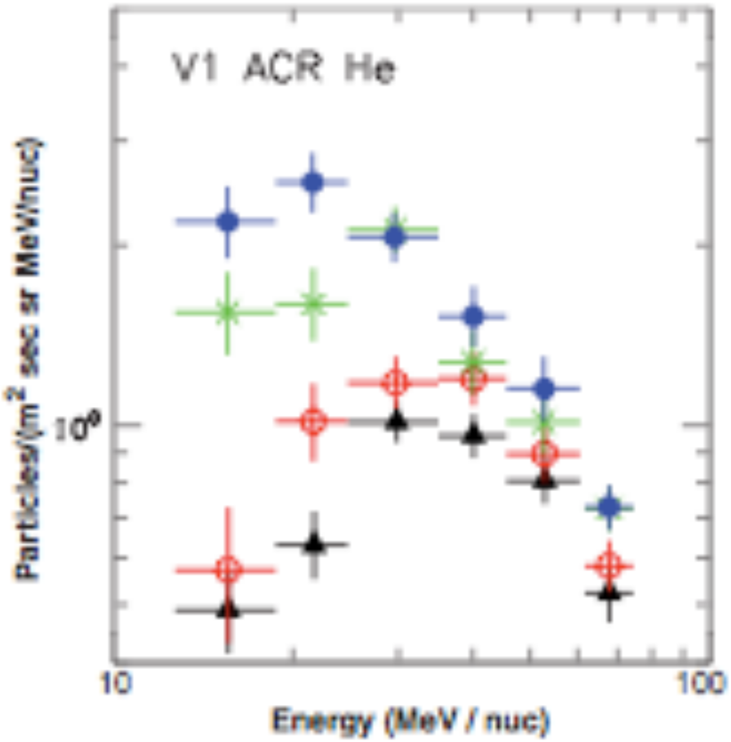
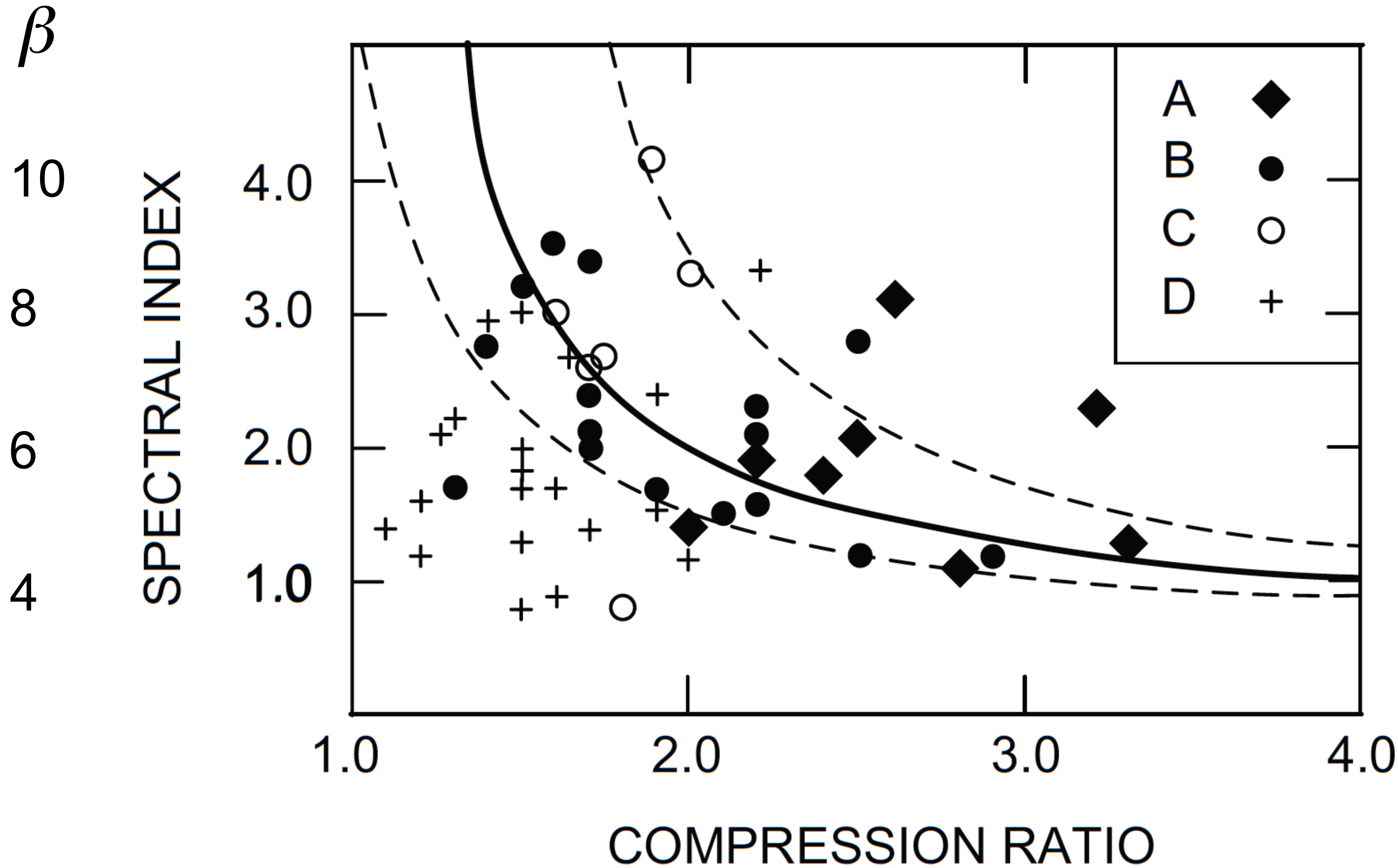


Fig. 3. ACR helium spectra just upstream of the shock (▲) (2004/313 to 350) and in the heliosheath [(○) 2004/352 to 2005/052, (×) 2005/053 to 104, (●) 2005/105 to 156]. The TSP, ACR, and GCR spectra overlap in the observed spectra in Fig. 2. Estimates of the TSP and GCR components have been subtracted in the regions of overlap to determine the ACR He spectra. The ACR He intensity did not reach a maximum at the shock, but continued to rapidly increase at lower energies in the heliosheath, indicating increasingly easy propagation from the ACR source to V1.

Stone et al., 2005

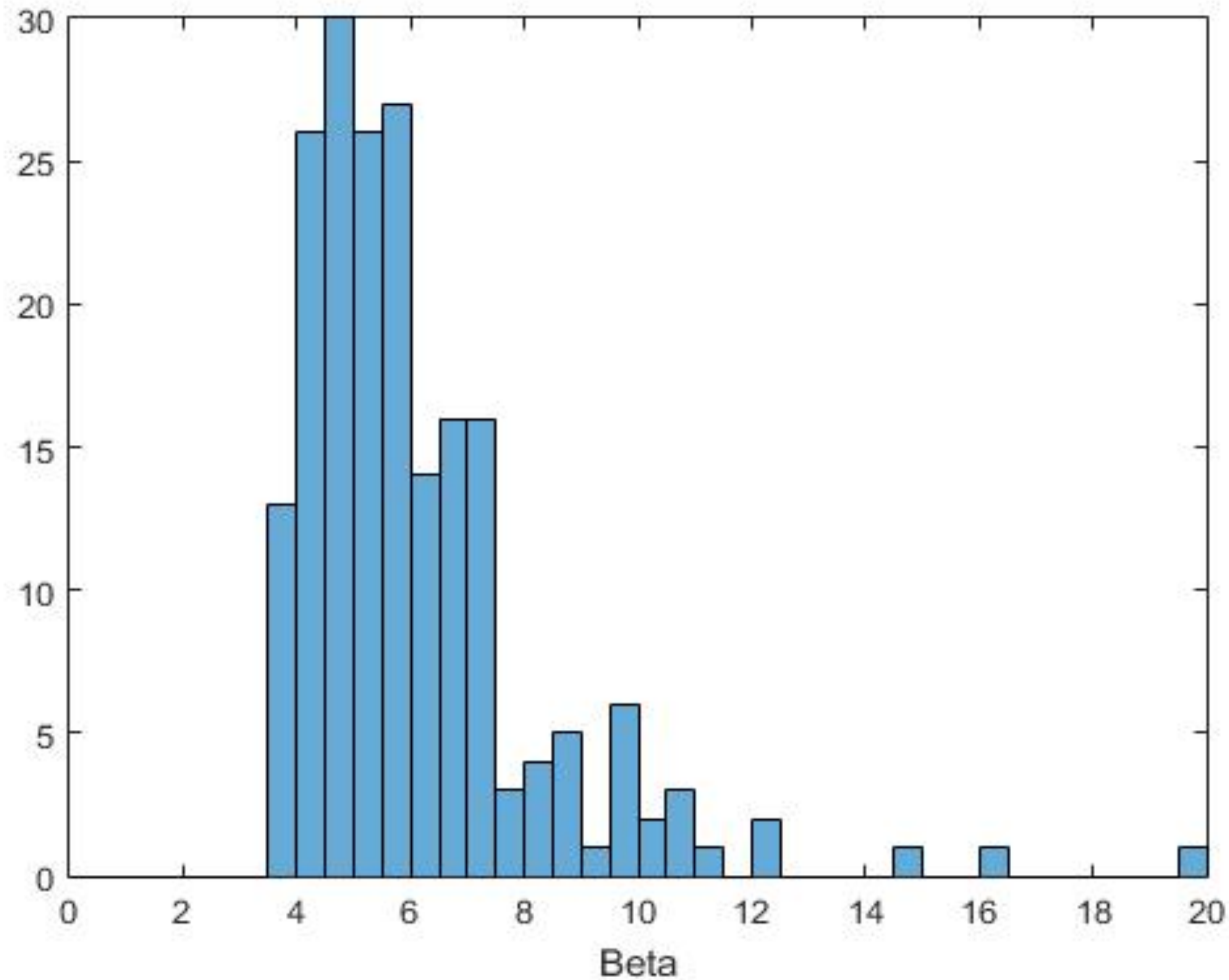
Power Law Index

$$\beta = 3X/(X-1)?$$

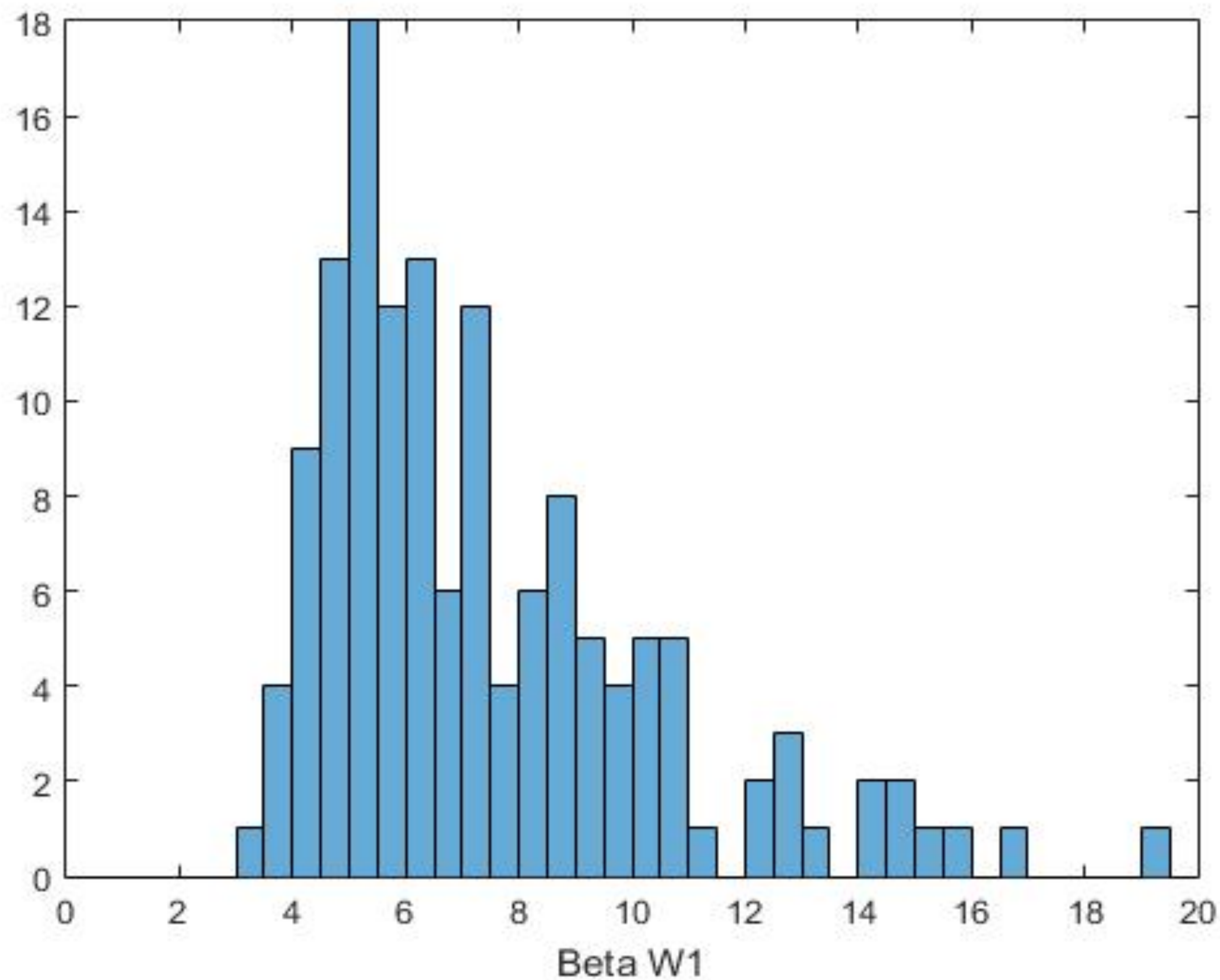


Van Nes et al., 1984

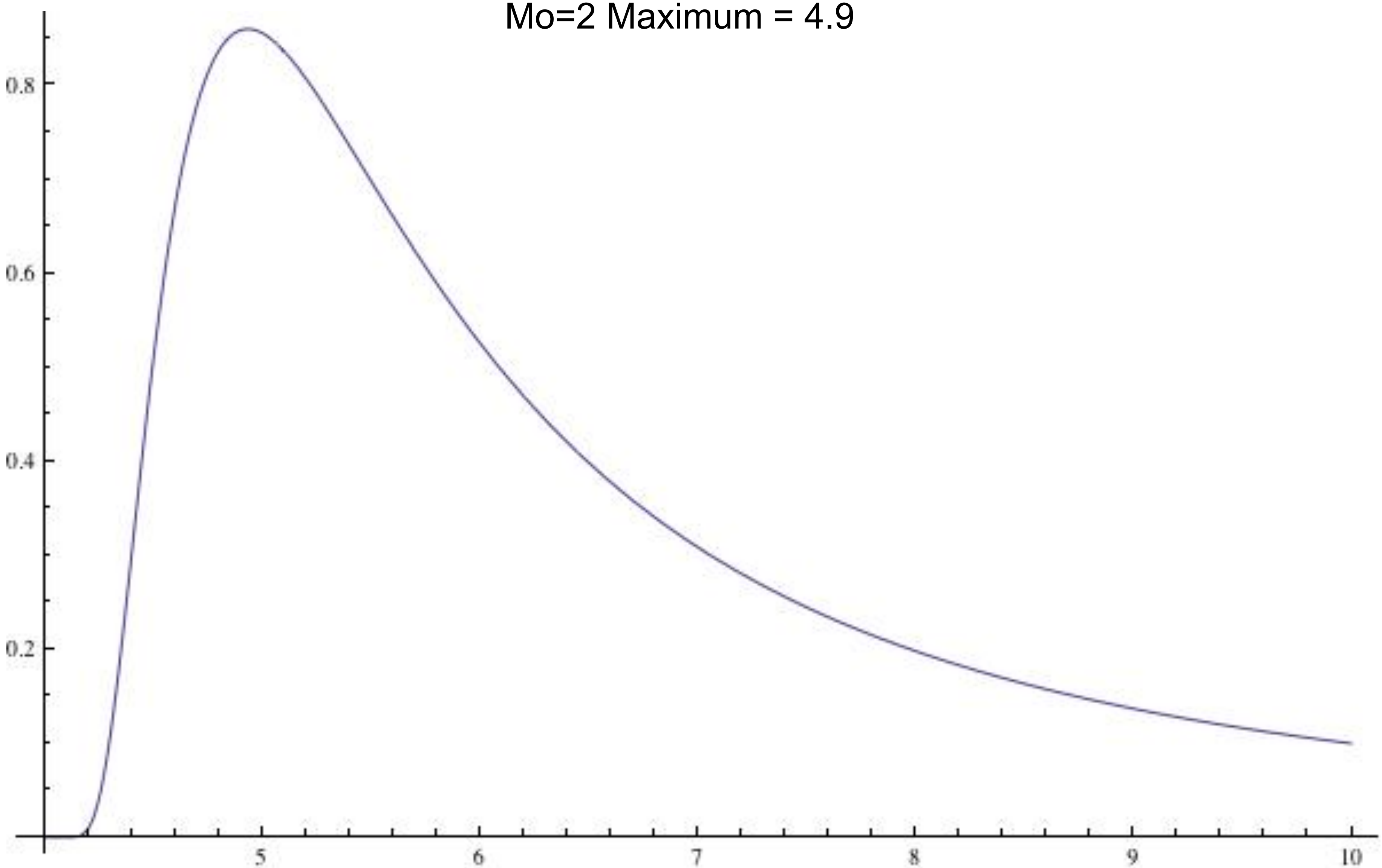
Beta(X) for X>1

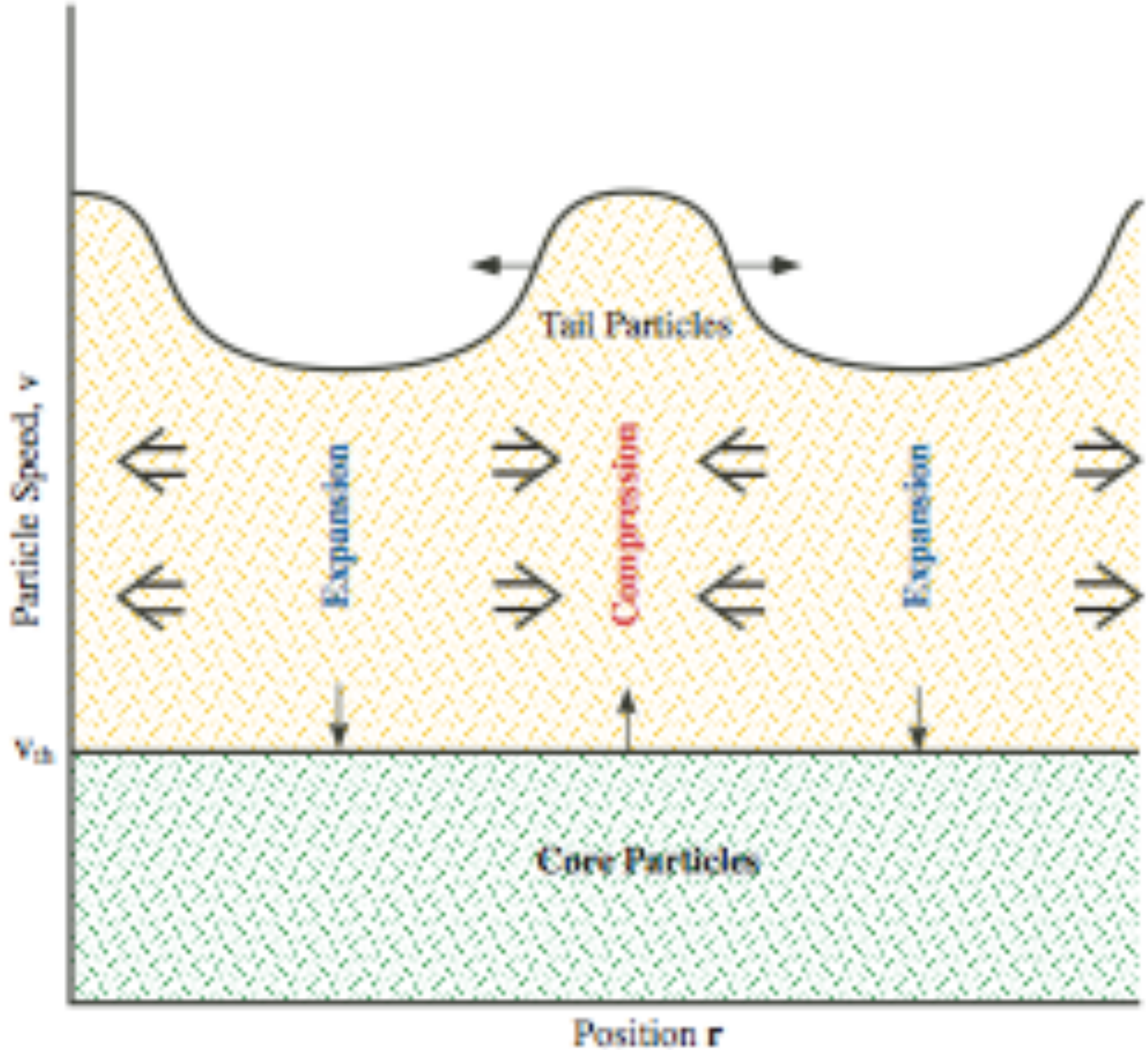


Beta(X) for upstream Alfven waves only



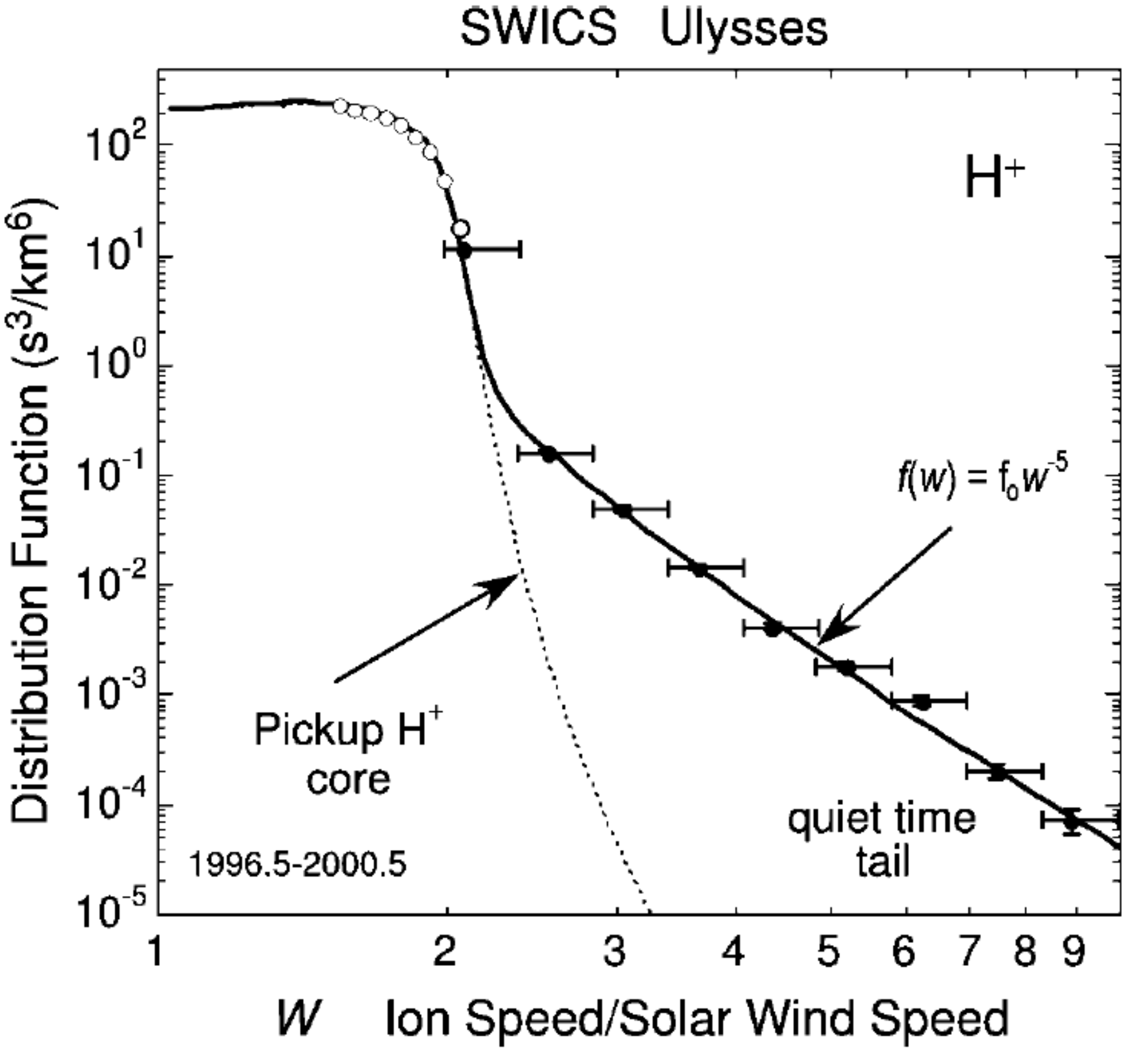
Mo=2 Maximum = 4.9





Fisk et al., 2010

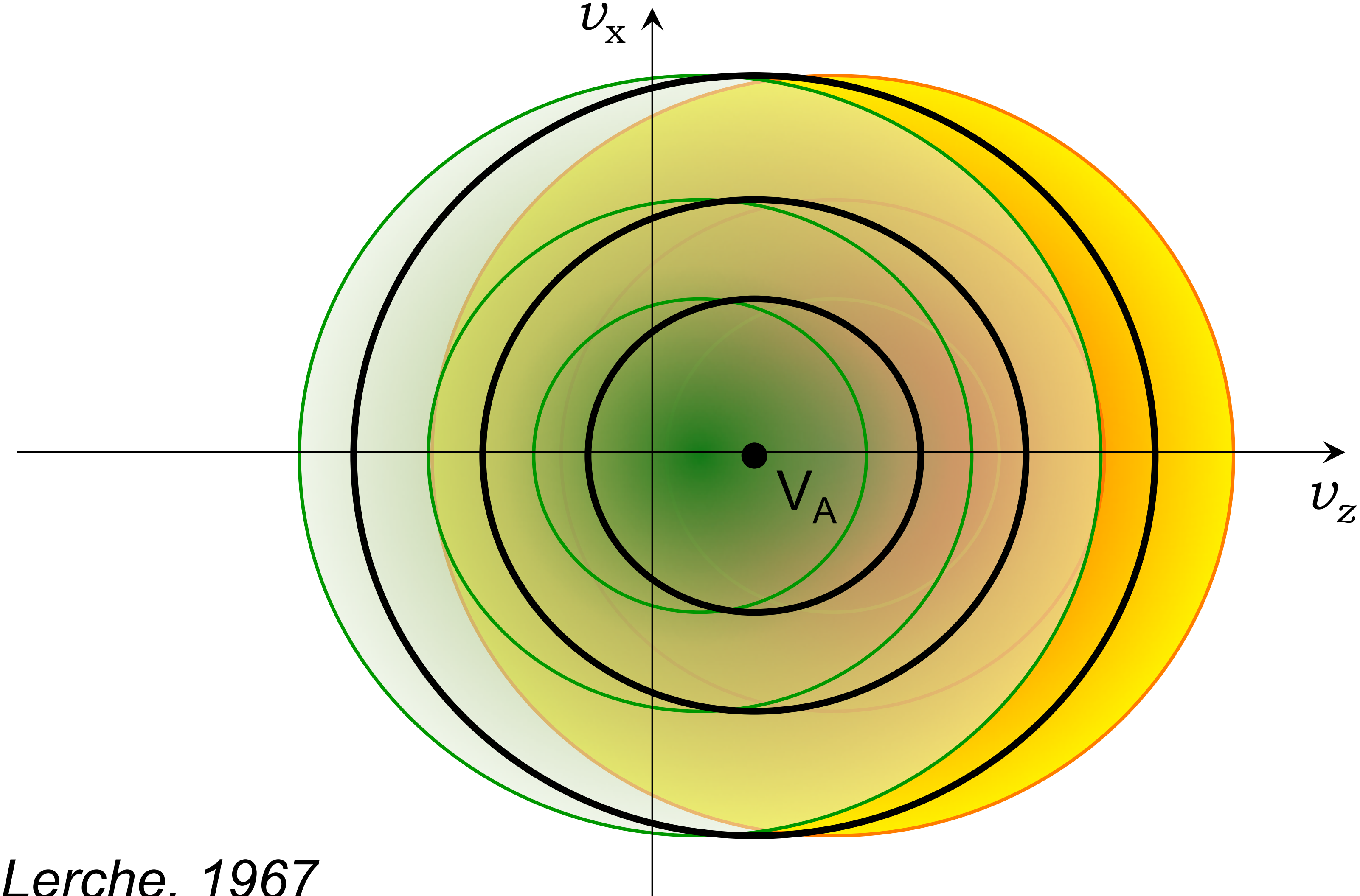
Ubiquitous Suprathermals



Fisk and Gloeckler, 2006

Wave Excitation

Instability Mechanism



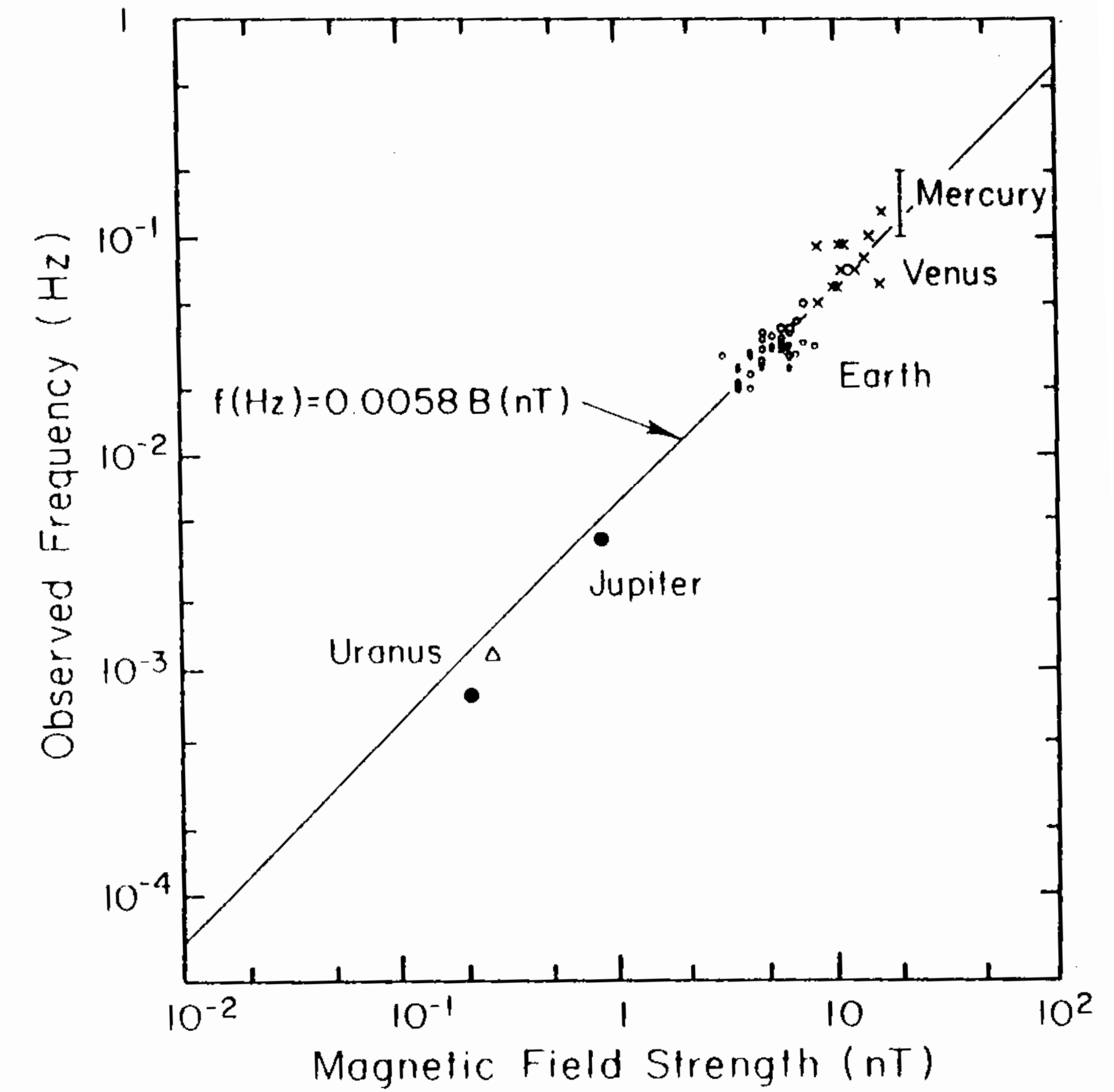
Lerche, 1967

Cyclotron Resonance Condition

$$\omega - kv_z + \Omega = 0$$

$$kv_z \approx \Omega$$

$$\omega_s \sim kV_{sw} \sim \Omega(V_{sw} / v_z) \propto B$$



Upstream Waves at Planetary Shocks

Russell et al., 1990

Wave Excitation - I

$$-V\partial I_{\pm} / \partial z = 2\gamma_{\pm} I_{\pm}$$

$$I \cong I_{+} = I_{+}^{\circ}(k) + \frac{4\pi^2}{k^2}\frac{V_A}{V}|\Omega_p| m_p \cos\psi \int_{|\Omega_p/k|}^{\infty} dv v^3 (1 - \frac{\Omega_p^2}{k^2 v^2})(f_p - f_{p,\infty})$$

$$f_{p,\infty} = \overline{n}_p (4\pi v_{p,0}^2)^{-1} \delta(v - v_{p,0}) + \overline{C} v^{-\gamma} S(v - \overline{v}_{p,0})$$

Wave Excitation - II

$$I = I_{+}^{\circ} + \frac{4\pi^2}{k^2}\frac{V_A}{V}|\Omega_p| m_p \cos\psi \int_{|\Omega_p/k|}^{\infty} dv v^3 (1 - \frac{\Omega_p^2}{k^2 v^2}) \cdot$$

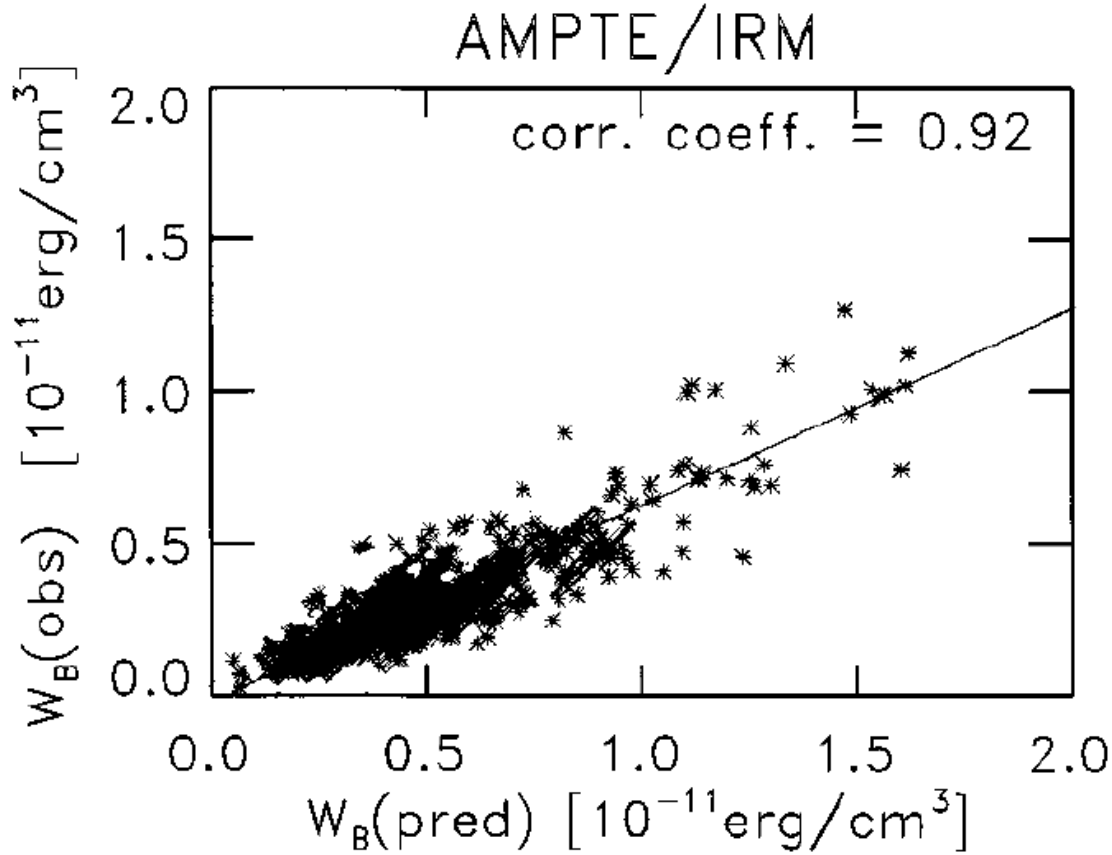
$$\cdot \left\{ \frac{\beta \bar{n}}{4\pi v_{0,p}^3} (\frac{v}{v_{0,p}})^{-\beta} S(v - v_{0,p}) - \frac{\bar{n}}{4\pi v_{0,p}^2} \delta(v - v_{0,p}) \right.$$

$$\left. + \frac{\bar{C}\bar{v}_{0,p}^{-\gamma}}{\beta - \gamma} \left[\gamma (\frac{v}{\bar{v}_{0,p}})^{-\gamma} - \beta (\frac{v}{\bar{v}_{0,p}})^{-\beta} \right] S(v - \bar{v}_{0,p}) \right\} \cdot$$

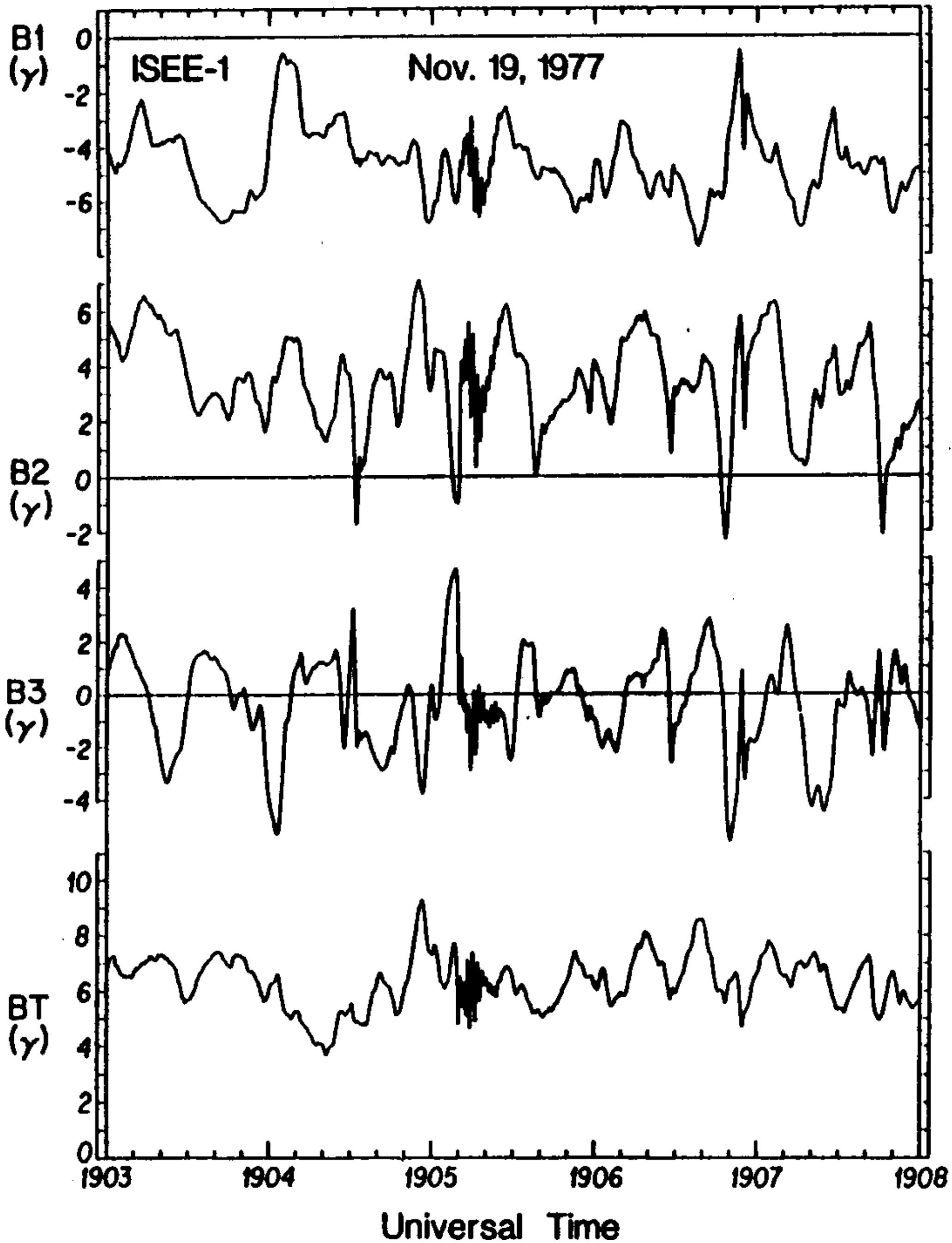
$$\cdot \exp\left\{ -V \int_0^z dz' \left[\cos^2\psi \frac{v^3}{4\pi} \frac{B_0^2}{\Omega_p^2} \int_{-1}^{1} d\mu \frac{|\mu|(1-\mu^2)}{I(\Omega_p \mu^{-1} v^{-1})} + \sin^2\psi \, K_\perp \right]^{-1} \right\}$$

Waves Upstream of Earth's Bow Shock

$$W_B = \frac{1}{3}\frac{V_A(\hat{e}_b \cdot \hat{e}_g)}{V_{sw}(\hat{e}_z \cdot \hat{e}_g) - V_A(\hat{e}_b \cdot \hat{e}_g)} W_p$$

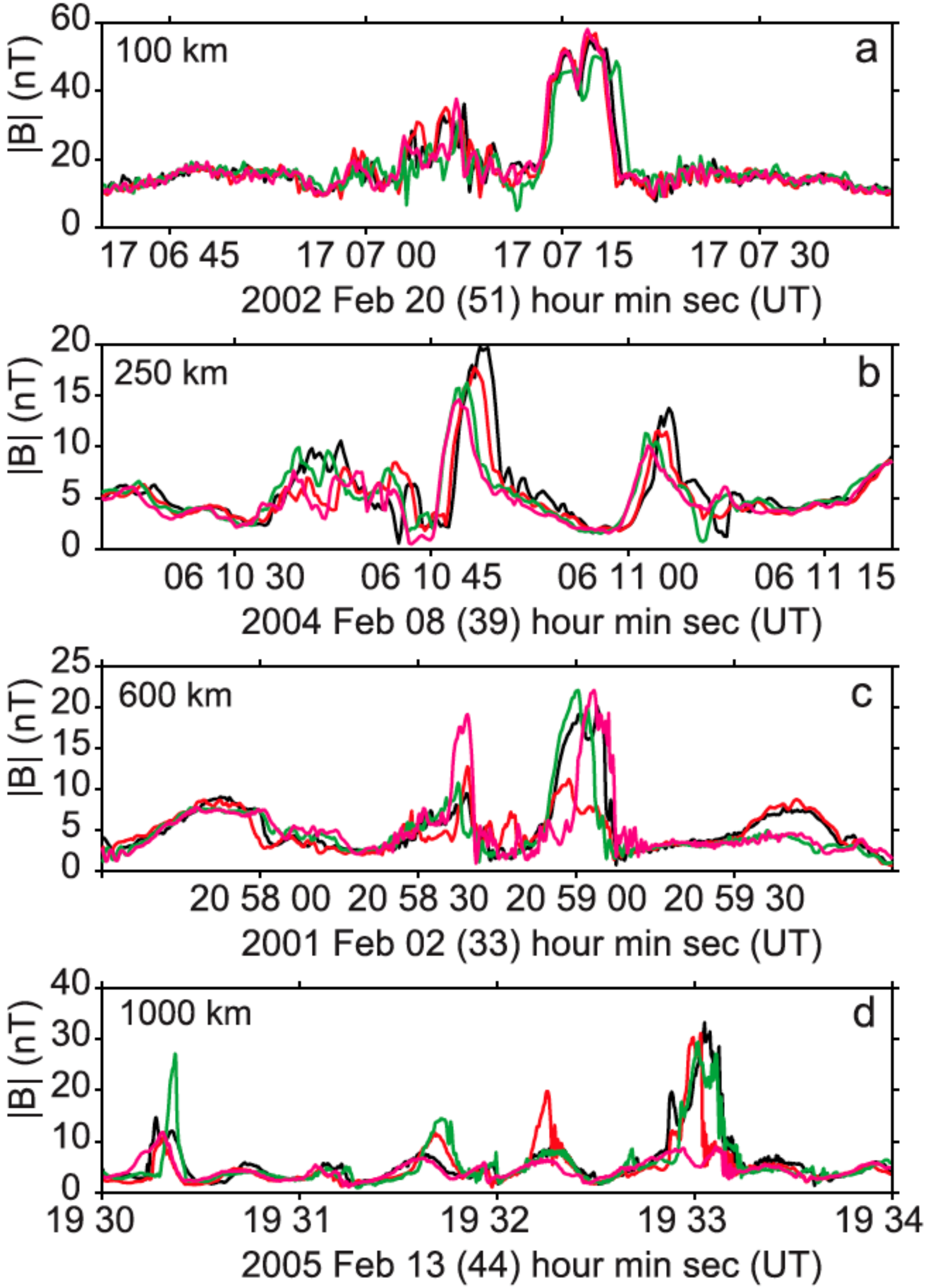


Gordon et al., 1999



Upstream Waves

Hoppe et al., 1981



SLAMS

Lucek et al., 2008

Galactic Cosmic Rays

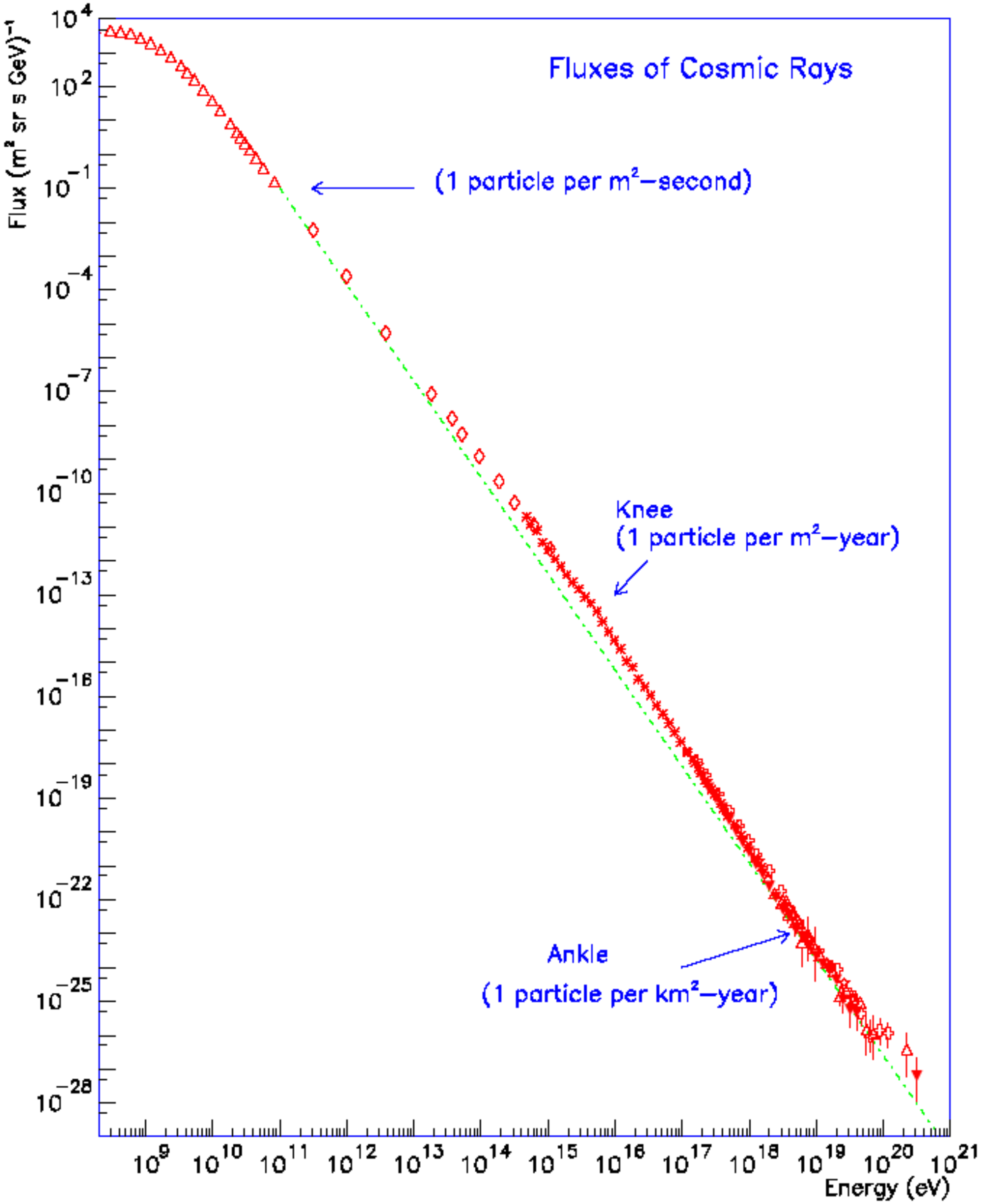


Figure 1. The all particle spectrum of cosmic rays - Cronin, Gaisser, Swordy 1997

The GCR spectrum continues as a power, in energy (index of about -2.7)

Highest energy cosmic rays have the kinetic energy of a major league baseball.

Modulation: Motivation for the Parker Equation

$n = \int 4\pi p^2 f dp, \; \mathbf{V}_D = 0, \; \nabla = \mathbf{e}_r d/dr, \; \partial/\partial t = 0, \; K = K(r), \; \mathbf{V} = \mathbf{e}_r V$

$$\frac{1}{r^2}\frac{d}{dr}\left[r^2\left(Vn - K\frac{dn}{dr}\right)\right] = 0$$

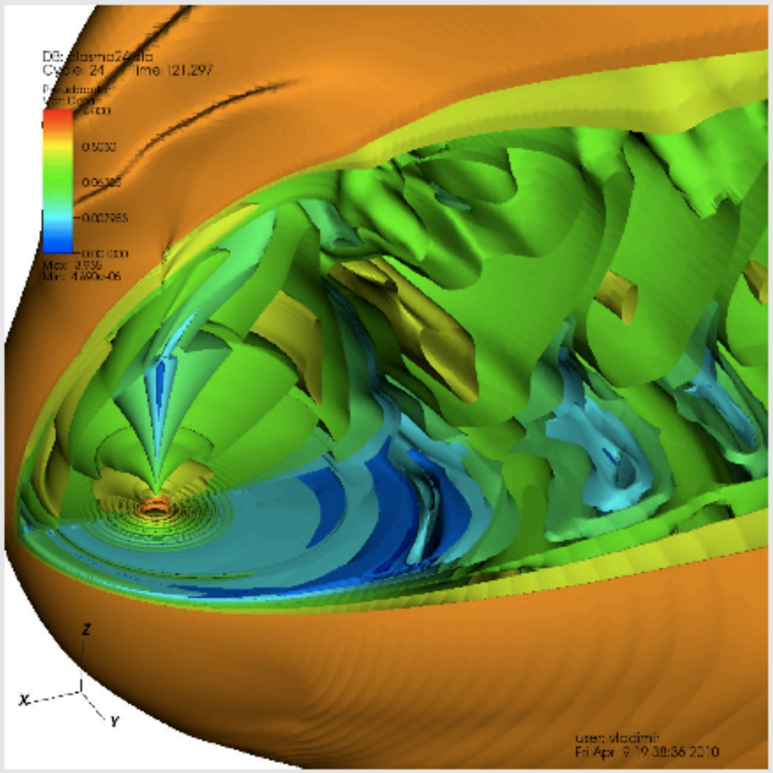
$$Vn - K\frac{dn}{dr} = \frac{C}{r^2} \qquad\qquad C = 0$$

$$n(r) = n(r = R)\exp\left(-\int_r^R \frac{Vdr'}{K(r')}\right)$$

Example 3 in Heliospheric Problems (M. Lee)

Modulation in the Heliosheath

Understanding magnetic field topology III



Model of N. V. Pogorelov – Log $|\mathbf{B}|$ (μG)

3D MHD GHMs (with neutral H) that are being actively developed

Izmodenov (Moscow)
Opher (Michigan)
Pogorelov (Alabama)
Ratkiewicz (?)
Washimi (Kyushu)

Solar cycle, 9^0 tilt at minimum (snapshot)

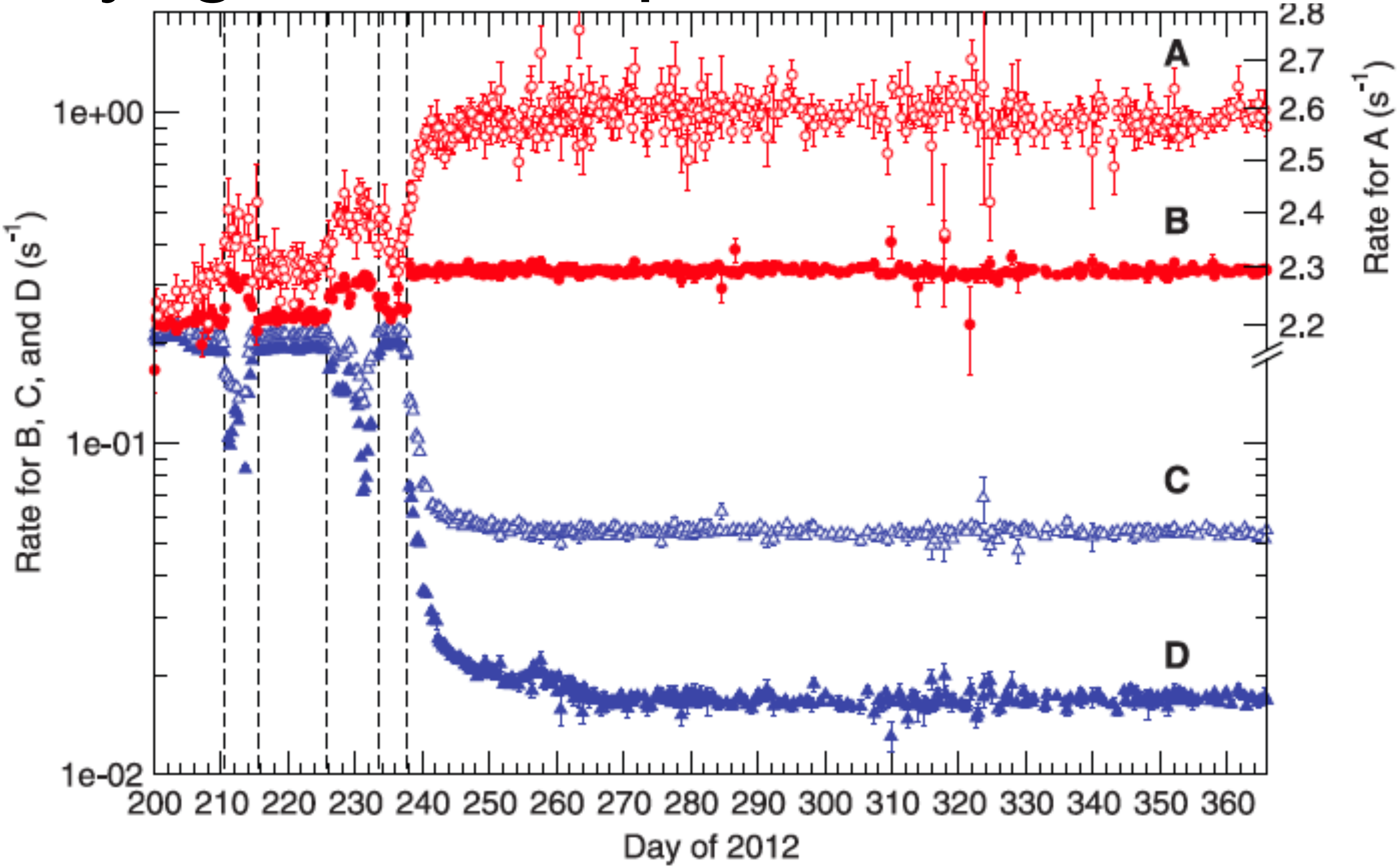
Fast/slow SW

LISM **B** in the HDP, 0.3 nT

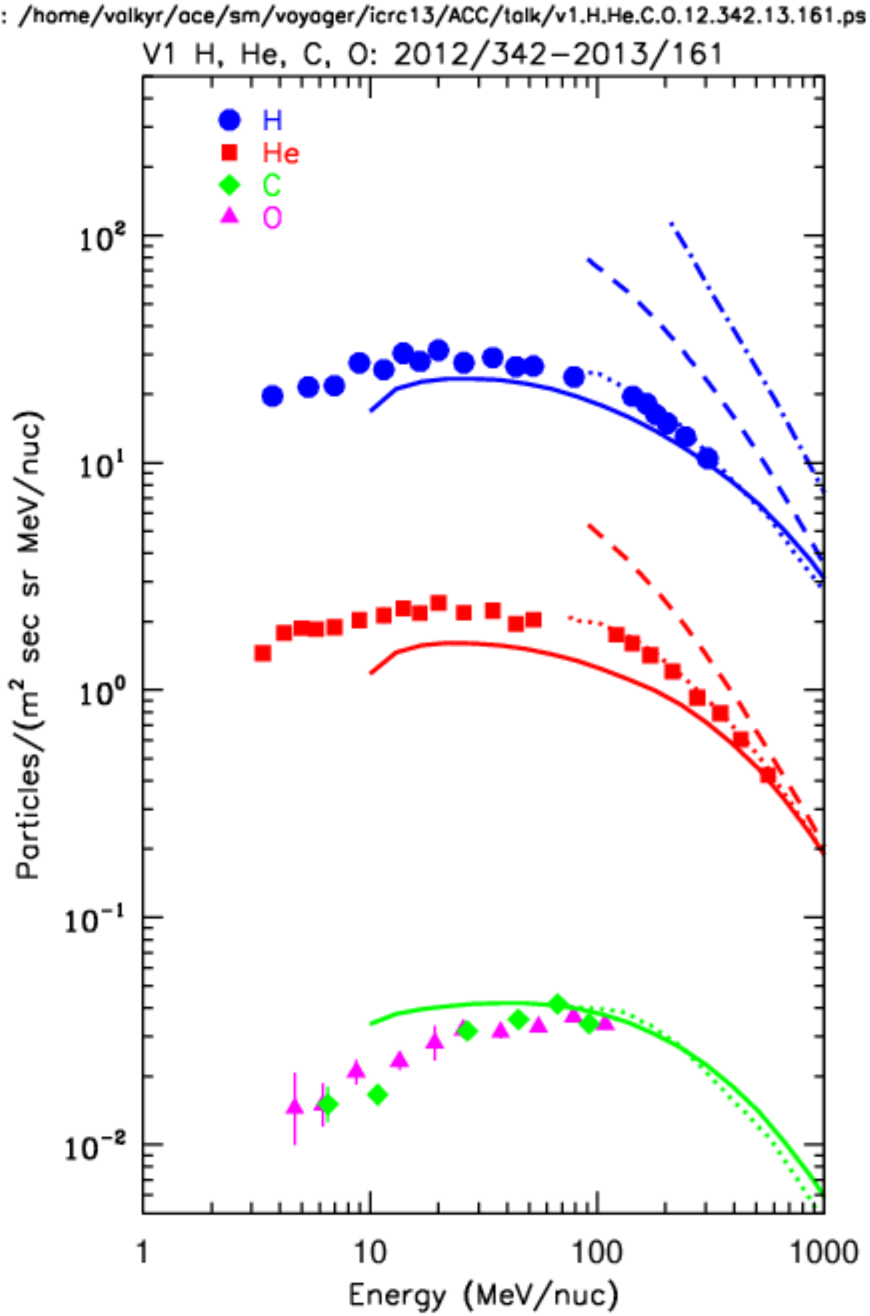
Modulation wall

Florinski, 2010

Voyager 1: GCRp, GCRe, HET, LET



Stone et al., 2013



Fisk & Gloeckler 2012 -- pump

Moskalenko et al. 2002 – DC

Webber & Higbie 2009 -- LB

GALPROP tuned to ACE by Lave et al 2013

V1 H, He, C, and O spectra for 2012/342-2013/161.

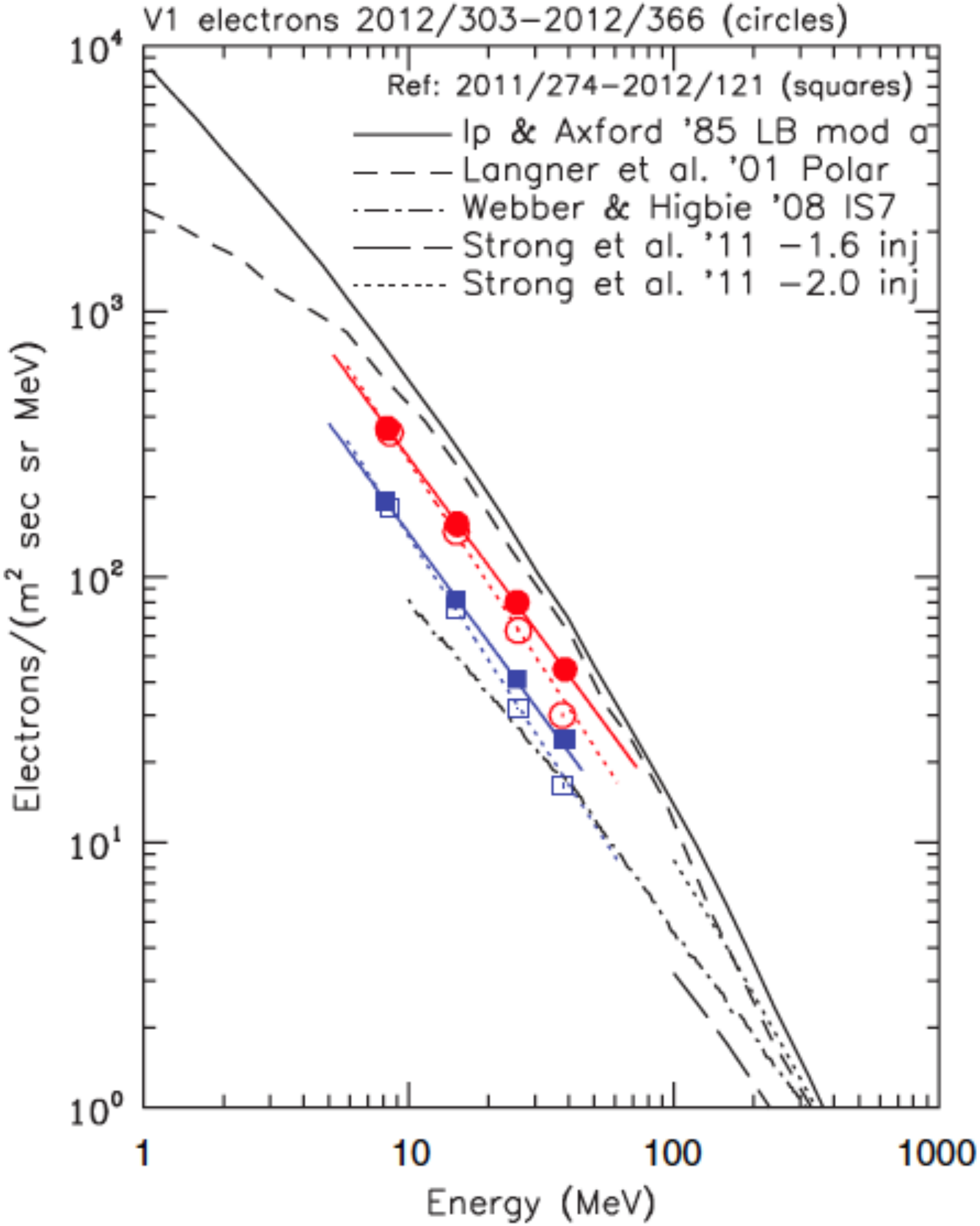
Spectra flattten below few hundred MeV/nuc due to ionization energy losses.

Believe we are observing GCRs down to ~3 MeV/nuc for H and He;
C & O down to ~5 MeV/nuc.

GCR H, He spectra peak at ~10-40 MeV/nuc with H/He ratio =13 at 7.8-57 MeV/nuc.

GCR C/O ratio ~1. ACRs not contributing to low-energy GCR spectrum, contrary to Scherer et al 2008.

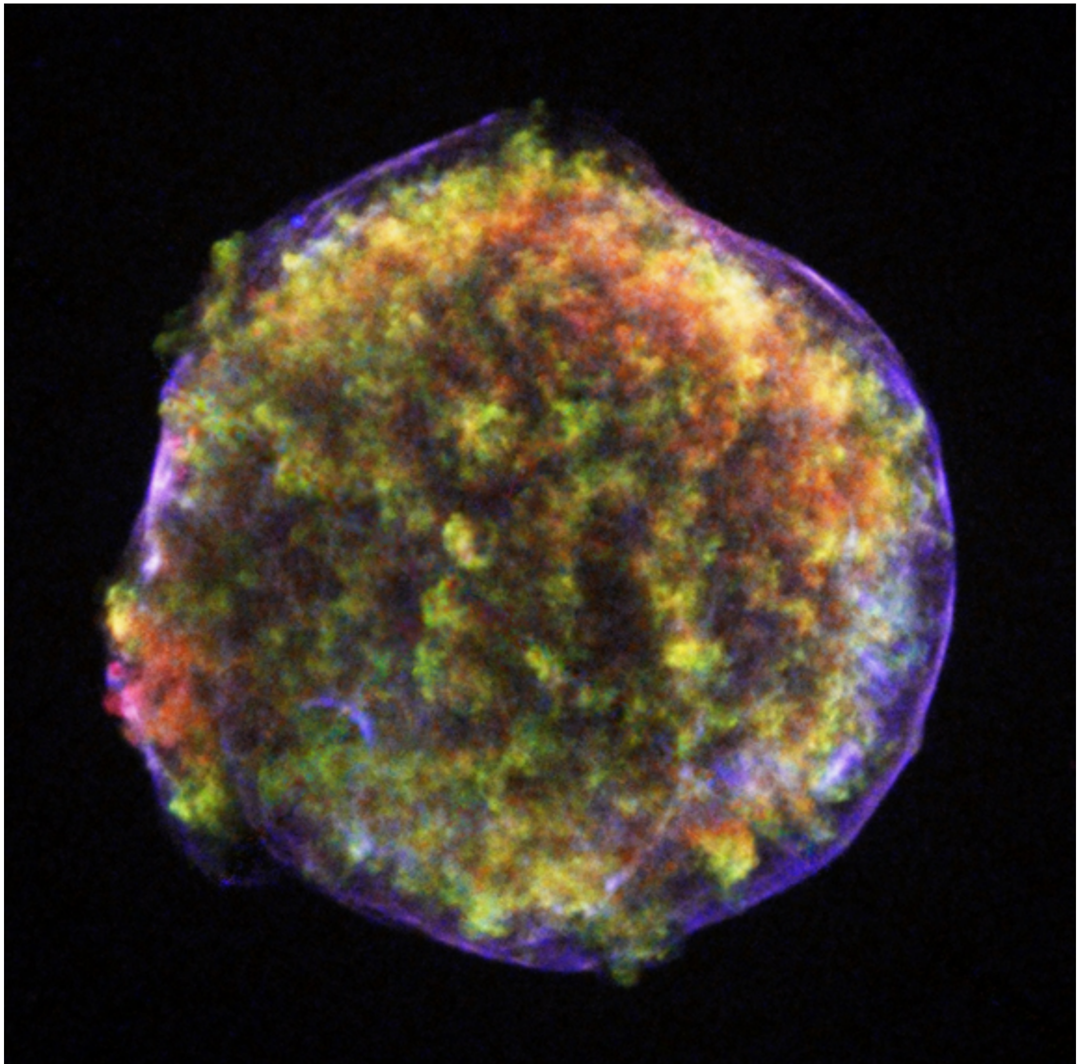
Stone et al., 2013



V1 GCR Electrons

Stone et al., 2013

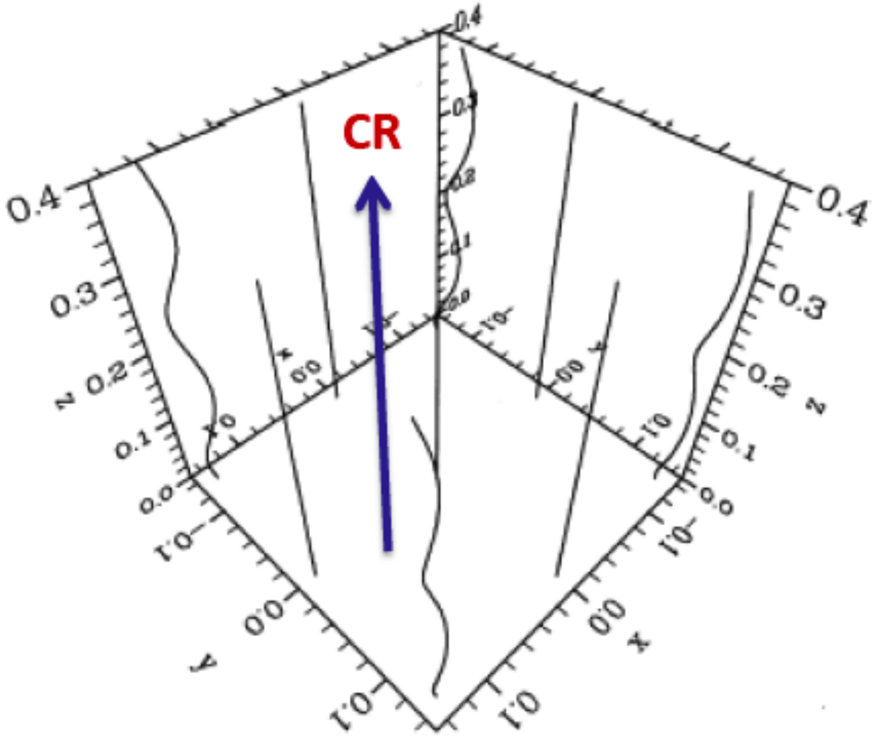
Tycho’s Supernova



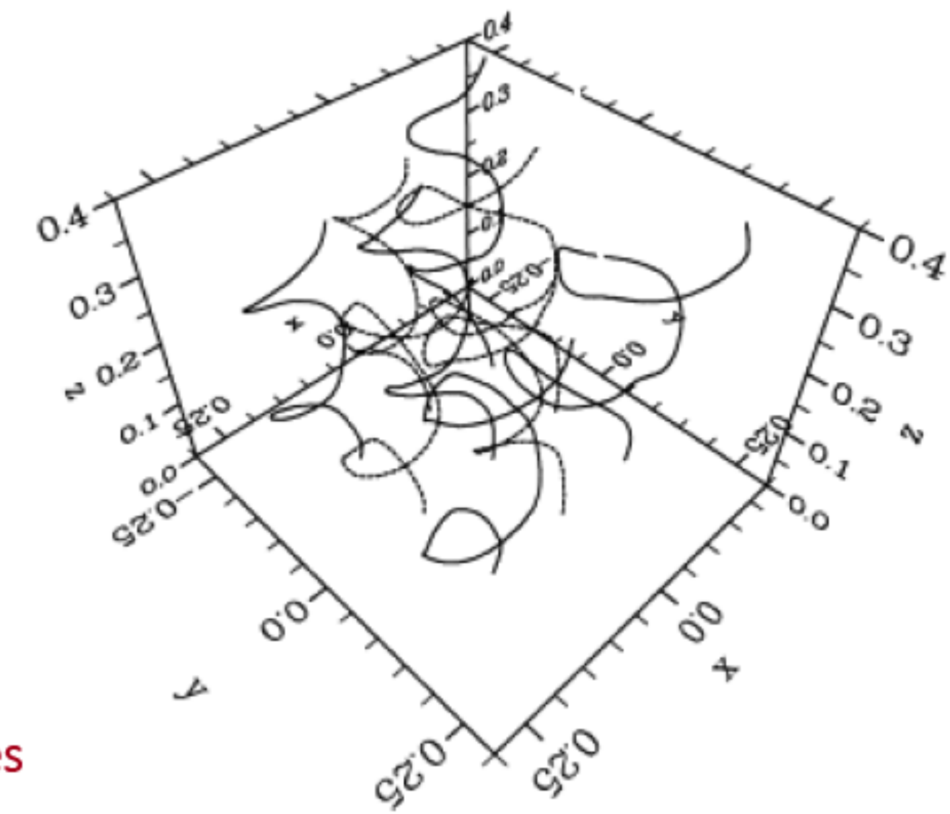
Streaming instability driven by cosmic rays

Lucek & Bell 2000

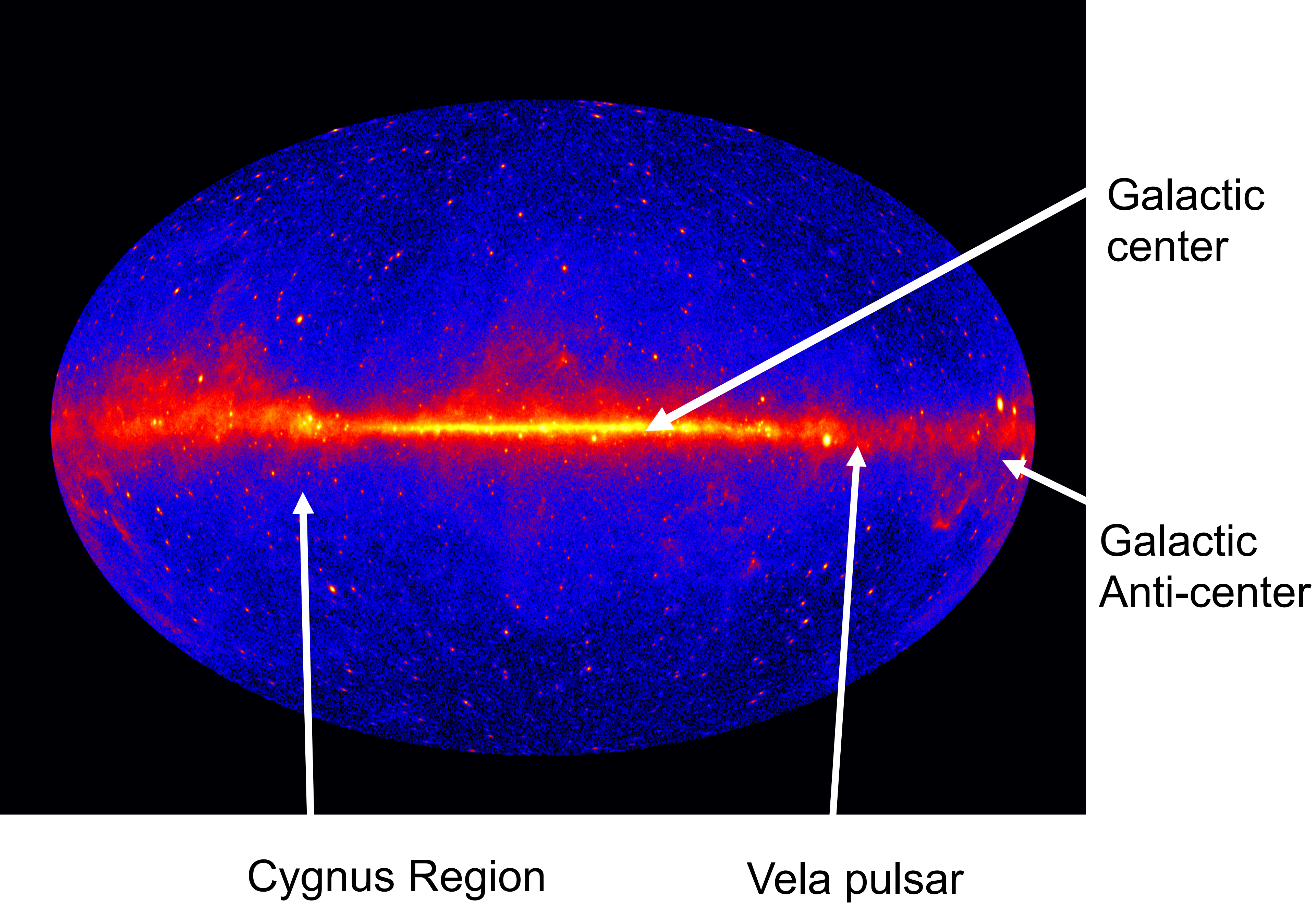
B field lines, t = 0



B field lines, t = 2



$\delta B/B$>>1 scatters energetic particles


Galactic
center
Galactic
Anti-center
Cygnus Region
Vela pulsar