PARTICLE ACCELERATION IN SOLAR FLARES

Vahe' Petrosian
Stanford University
Collaborators: Siming Liu
and several past and present students

SEE-2005, Nor-Ambert

OUTLINE

ACCELERATION: In General

I. OBSERVATIONS

II. ACCELERATION MECHANISMS

III. TOOLS OF THE TRADE

A. Kinetic Equations for Acceleration and Transport

B. Turbulence Cascade and Damping

C. Wave-Particle Interaction and Transport Coefficients

APPLICATION to Solar Flares

I. OBSERVATIONS

General Features

Where:	Planets to Clusters of Galaxies
Spatial scales:	10^8 to 10^{25} cm and beyond
Temporal scales:	Milliseconds to Gigayears
Energy scales:	10^3 to 10^{20} eV

I. OBSERVATIONS

Observing Methods

Direct as CRs: Solar, Galactic, Extragalactic
Electrons, Protons, Ions (Isotopes)

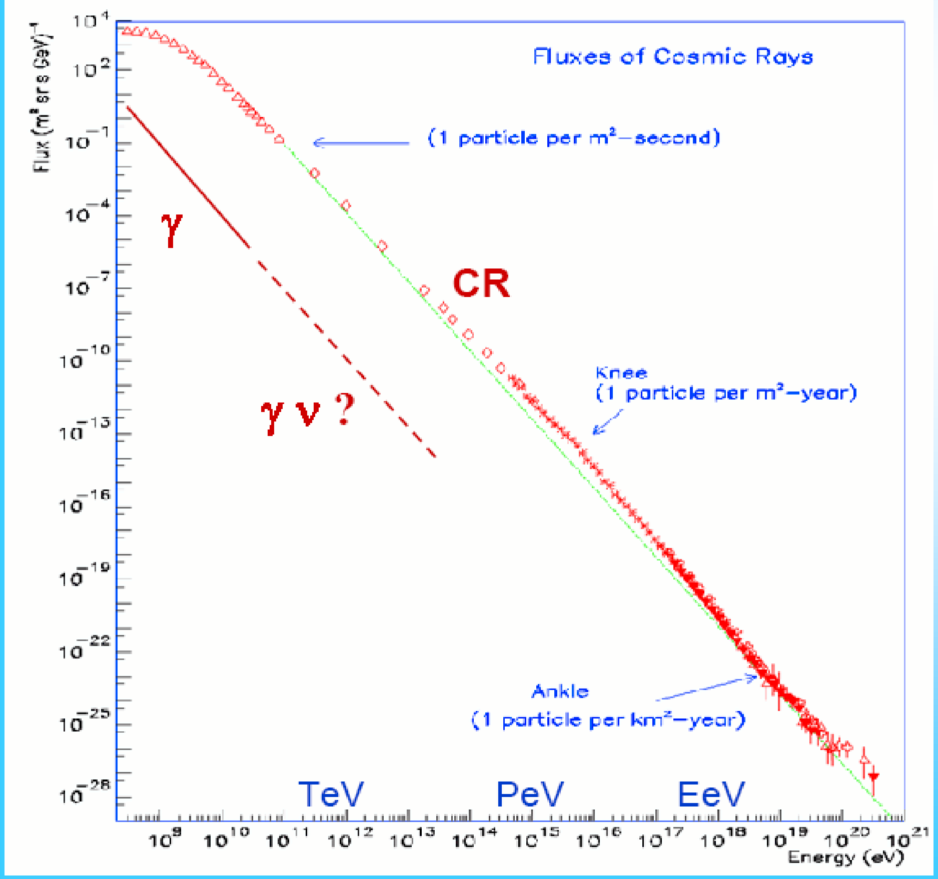
Indirect: Radiative Signature
Protons: Pi-meson Decays (70 MeV)
Electrons: Brem., Compton, Synch.
Broad Band, Power Law Spectra

Essentially all Radio and Gamma-ray emitters

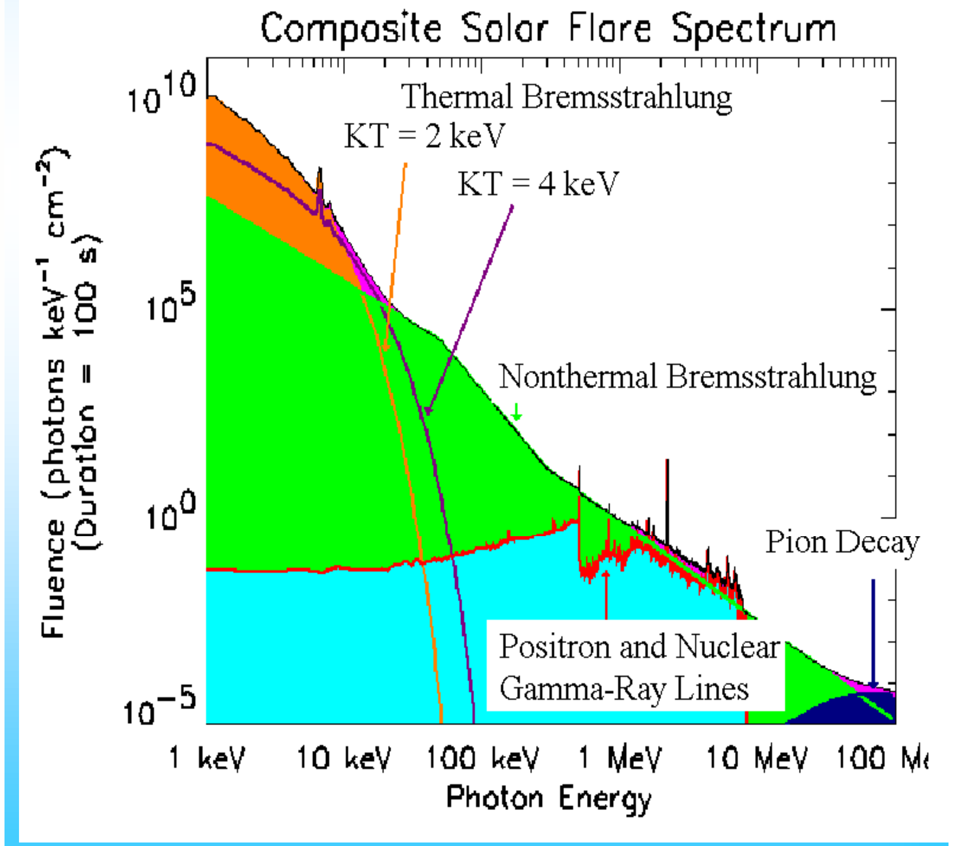
Most hard X-rays and some UV, Optical and IR

I. OBSERVATIONS

Cosmic Ray Spectrum



Solar Flare spectrum



II. ACCELERATION MECHANISMS

A: Electric Fields: **Parallel to B Field**

B: Fermi Acceleration

1. Shocks: **First Order Fermi**

2. Stochastic Acceleration: **Second Order Fermi**

II. ACCELERATION MECHANISMS

A. ELECTRIC FIELDS: $\mathcal{E}$ (parallel to **B** field)

Acceleration Rate: $dp/dt = e\mathcal{E}$

Astrophysical Plasmas Highly Conductive: $\mathcal{E} \to 0$

Dricer Field: $\mathcal{E}_D = kT/(e\lambda_{\rm Coul})$

$\mathcal{E} < \mathcal{E}_D$: Energy Gain $\Delta E < kT(L/\lambda_{\rm Coul})$

$\mathcal{E} > \mathcal{E}_D$: Runaway Unstable Distribution Leads to

PLASMA TURBULENCE

1. Double Layers (DLs) in Earth's Magnetosphere

Multiple DLs: Difussive Process like

PLASMA TURBULENCE

2. Unipolar Induction in High B field of Neutron Stars
Extreme Relativistic Energies: Pair Cascade

II. ACCELERATION MECHANISMS

B. FERMI ACCELERATION

Random scattering by moving scattering centers.
Diffusive Process: Why Acceleration?
More headon than trailing scatterings
Phase space availibility

$$\frac{1}{p^2}\frac{\partial}{\partial p}(p^2 D_{pp}\frac{\partial f}{\partial p}) \rightarrow \frac{\partial}{\partial E}(D(E)\frac{\partial N}{\partial E}) - \frac{\partial}{\partial E}(A(E)N) \quad (1)$$

1. SHOCK ACCELERATION: (First Order Fermi)
Energy Gain: $\dot{p} = \frac{p}{3}\frac{\partial u}{\partial x}, \quad \delta p/p \sim U_{\rm shock}/v$
Need Scattering Agent *i.e.* **TURBULENCE**

Diffusive Shocks
Scattering Rate $D_{\rm scat}$
Acceleration Rate $\sim (U_{sh}/v)^2 D_{\rm scat}$

Relativistic Shocks
Most Energy Gained in First Passage
Most Likely in High B Plasmas *e.g.* GRBs or AGN Jets
Most of the Energy in Protons; How to convert to Electrons?

2. STOCHASTIC ACCELERATION:

(Second Order Fermi)

Plasma Waves or **TURBULENCE**

Energy Gain; *e.g.* Alfven Waves: $\delta p/p \sim (V_{\rm Alfven}/v)^2$

Scattering Rate $\sim D_{\rm scat}$

Acceleration Rate $\sim D_{pp}/p^2 \sim (V_{\rm Alfven}/v)^2 D_{\rm scat}$

- **For $V_{\rm Alfven} > V_{\rm sound}$ TURBULENCE more efficient than SHOCKS**
- **At low energies or high B fields $D_{pp}/p^2 \gg D_{\rm scat}$ and TURBULENCE efficient accelerator**

III. TOOLS OF THE TRADE

Some General Points

● Acceleration of Background Particles

(no pre-acceleration)

● Radiating Sources

(electrons and protons)

● Losses at Acceleration Site

(Coulomb, Synchrotron, Compton)

A. KINETIC EQUATION

Liouville or Boltzmann equation in limit of many "small" scatterings leads to

The General Fokker-Planck equation:

$$\frac{\partial f}{\partial t} + v\mu \frac{\partial f}{\partial s} = \frac{1}{p^2}\frac{\partial}{\partial p}p^2\left[D_{pp}\frac{\partial f}{\partial p} + D_{p\mu}\frac{\partial f}{\partial \mu}\right] + \frac{\partial}{\partial \mu}\left[D_{\mu\mu}\frac{\partial f}{\partial \mu} + D_{\mu p}\frac{\partial f}{\partial p}\right] - \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 \dot{p}_L f) + S\,.$$

$f(p,\mu,s,t)$; gyrophase averaged particle distribution

s is the distance along the background B field

S is a source term

1. Isotropic, High Energy Limit:

$D_{\mu\mu} >> v/L$ and D_{pp}/p^2

$$F(p,s,t) \equiv \frac{1}{2}\int_{-1}^{1} \mathrm{d}\mu f(p,\mu,s,t),$$

$$\frac{\partial F}{\partial t} - \frac{\partial}{\partial z}\kappa_1\frac{\partial F}{\partial z} = (pv)\frac{\partial \kappa_2}{\partial z}\frac{\partial F}{\partial p} - \frac{1}{p^2}\frac{\partial}{\partial p}(p^3 v\kappa_2)\frac{\partial F}{\partial z} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^4\kappa_3\frac{\partial F}{\partial p} - p^2\dot{p}_L F\right) + Q(p,s,t)\,,$$

$$\begin{aligned}\kappa_1 &= \frac{v^2}{8}\int_{-1}^{1}\mathrm{d}\mu\frac{(1-\mu^2)^2}{D_{\mu\mu}}, \quad \kappa_2 = \frac{1}{4}\int_{-1}^{1}\mathrm{d}\mu(1-\mu^2)\frac{D_{\mu p}}{pD_{\mu\mu}}\\ \kappa_3 &= \frac{1}{2}\int_{-1}^{1}\mathrm{d}\mu(D_{pp} - D_{\mu p}^2/D_{\mu\mu})p^2, \quad Q(p,s,t) \equiv \frac{1}{2}\int_{-1}^{1}\mathrm{d}\mu S(p,\mu,s,t).\end{aligned}$$

The acceleration and scattering times are

$$\tau_{ac} = 1/\kappa_3 \quad \tau_{sc} = 8\kappa_1/v^2.$$

A. ISOTROPIC AND HOMOGENEOUS

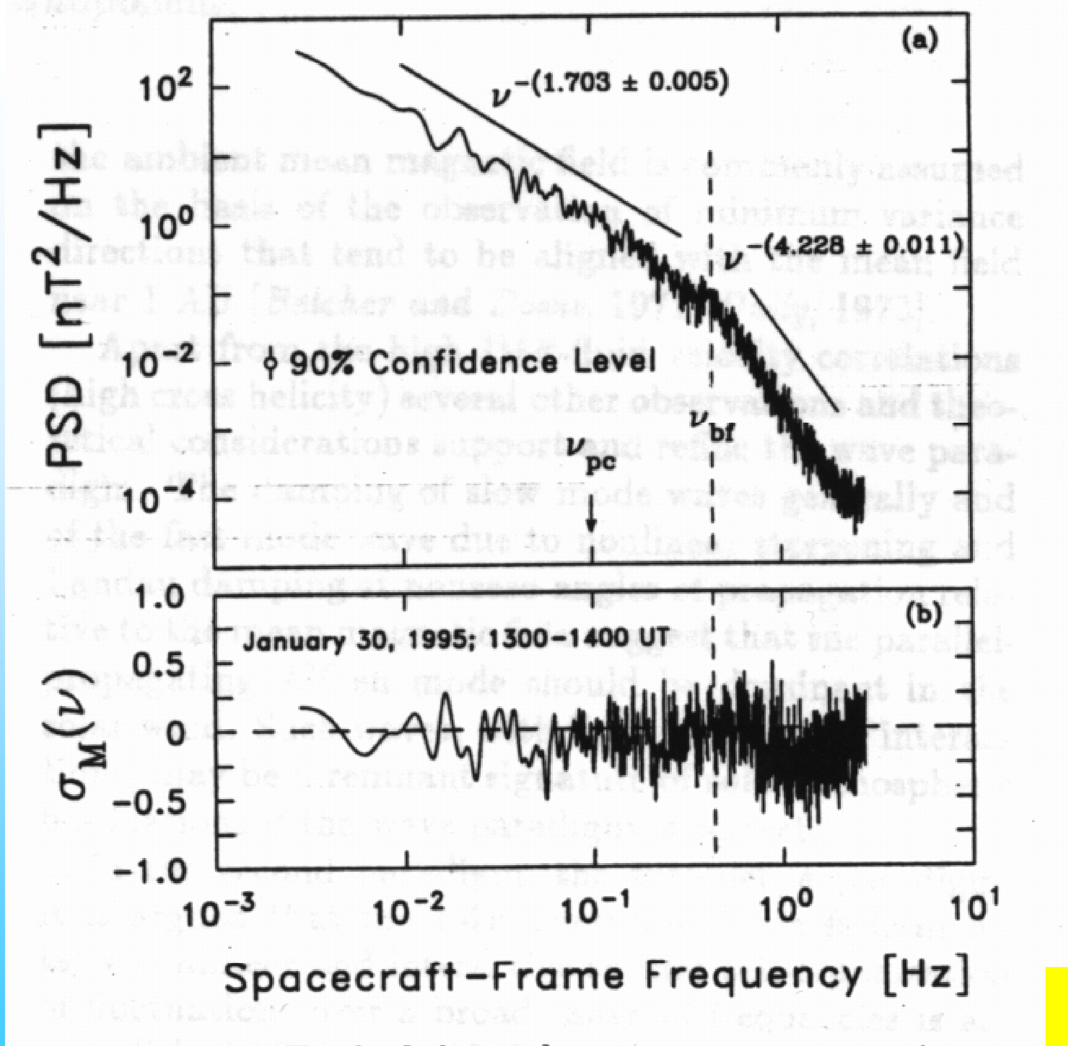
$$\frac{\partial N}{\partial t} = \frac{\partial^2}{\partial E^2}(D_{EE}N) + \frac{\partial}{\partial E}[(\dot{E}_{\mathrm{L}} - A)N] - \frac{N}{T_{\mathrm{esc}}} + Q$$

$$A(E) = \frac{\mathrm{d}D_{EE}}{\mathrm{d}E} + D_{EE}\frac{2\gamma^2 - 1}{(\gamma^2 - 1)\gamma mc^2}$$

$$T_{\mathrm{esc}} = \frac{L}{\sqrt{2}v}\left(1 + \frac{\sqrt{2}L}{v\tau_{\mathrm{sc}}}\right)$$

$$\tau_{\mathrm{sc}} = \frac{1}{2}\int_{-1}^{1}\mathrm{d}\mu\frac{(1-\mu^2)^2}{D_{\mu\mu}}$$

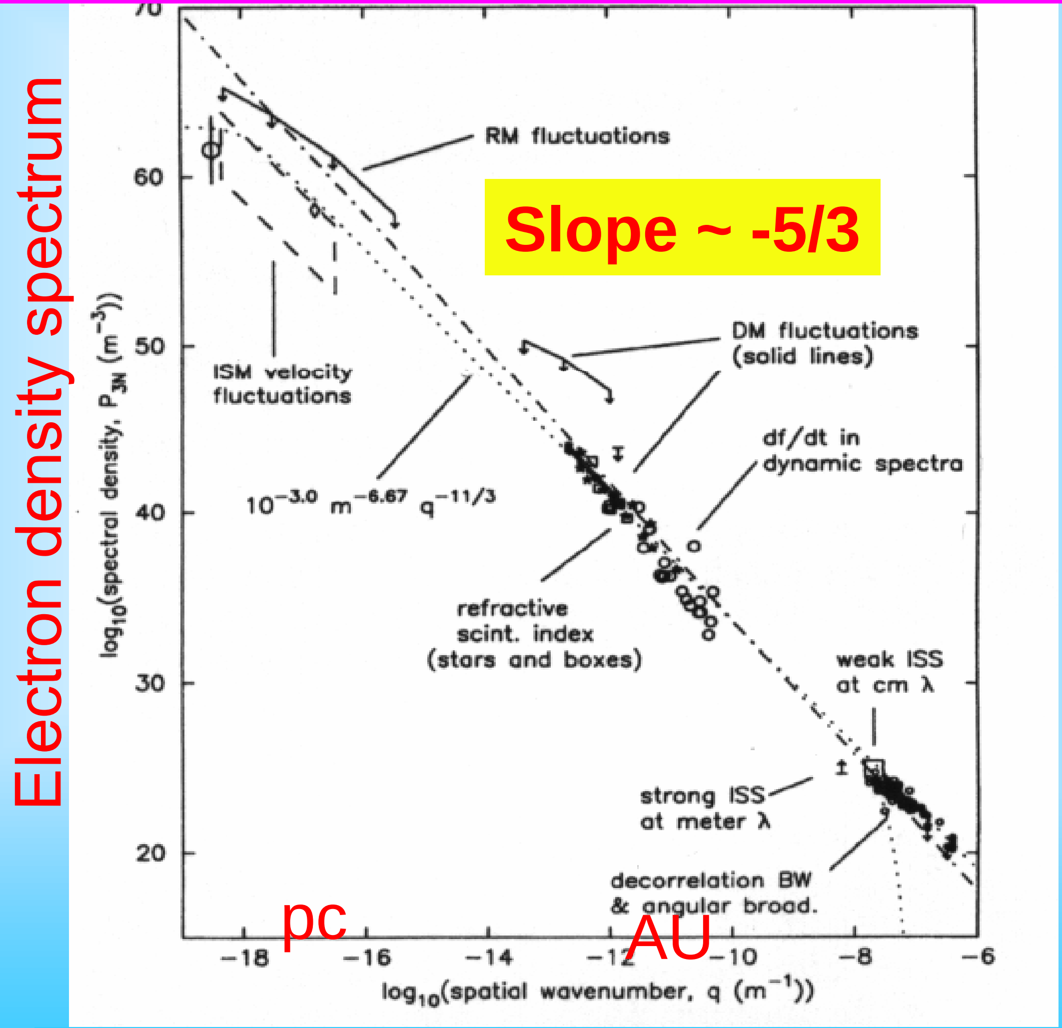
B. Magnetic fluctuations in Solar wind



Magnetic fluctuations in Solar wind

Leamon et al (1998)

B. ISM: Armstrong & Spangler (1995)

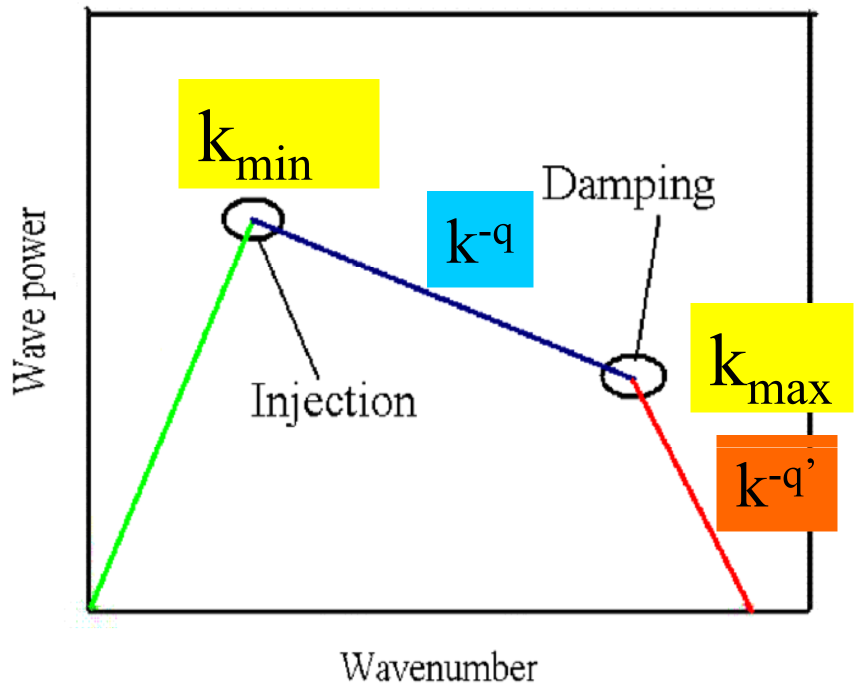


B. Turbulence Spectrum

$W(k) = ?$

General Features:

- Injection scale: $k_{\min}$
- Cascade and index q
- Damping scale or $k_{\max}$



Kinetic Equation:

$$\frac{\partial W(\mathbf{k},t)}{\partial t} = \dot{Q}_p(\mathbf{k},t) - \gamma(\mathbf{k})W(\mathbf{k},t) + \nabla_i\left[D_{ij}\nabla_j W(\mathbf{k},t)\right] - \frac{W(\mathbf{k},t)}{T^W_{\rm esc}(\mathbf{k})}$$

$\dot{Q}_p(\mathbf{k})$: Rate of wave generation.

$T^W_{\rm esc}$: Wave leakage timescale.

$\gamma(k) = \gamma_e + \gamma_p$: The damping coefficients.

D_{ij}: Wave diffusion tensor.

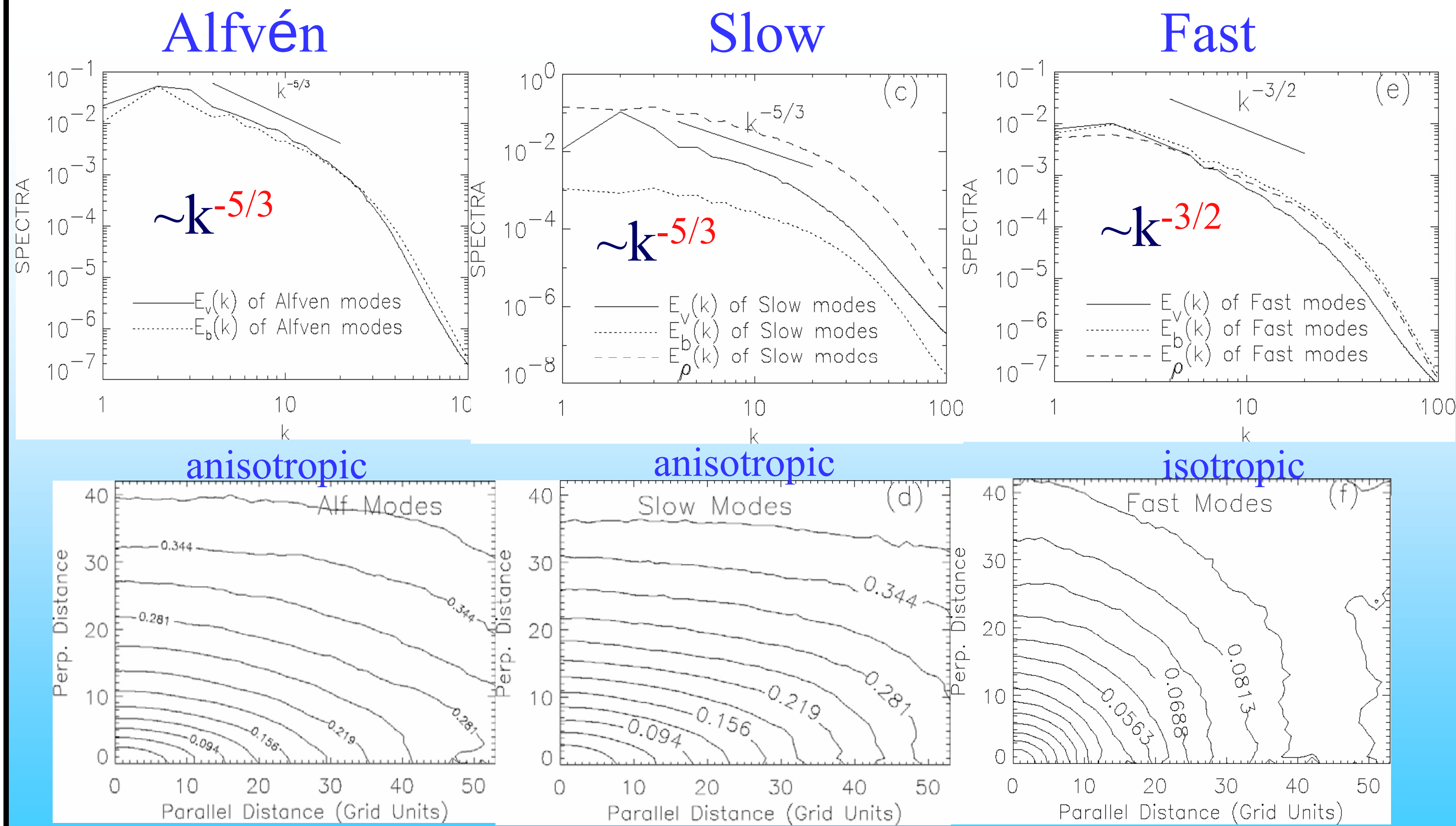
B. Cascade of MHD Turbulence

Table 1: Some Cascade Characteristics of Different Modes

Mode	Isotropy	scaling v_k	$D(k)$	$\hat{W}(k)$	τ_{cas}/τ_0
Alfvén$^{(a)}$	NO, $k_\perp \propto k_\parallel^{3/2}$	$k_\perp^{-1/3}$	$k^{7/2}\hat{W}^{1/2}$	$k_\perp^{-5/3}$	$5\times10^{-4}(k_\perp L)^{-2/3}$
Fast$^{(b)}$	Isotropic	$k^{-1/4}$	$k^4\hat{W}$	$k^{-3/2}$	$1.3\times10^{-2}(kL)^{-1/2}$
Whisteler$^{(c)}$	???	$k^{-1/4}$	$k^{9/2}\hat{W}^{1/2}$	$k^{-7/3}$	$2\times10^{-8}(kL)^{-4/3}$

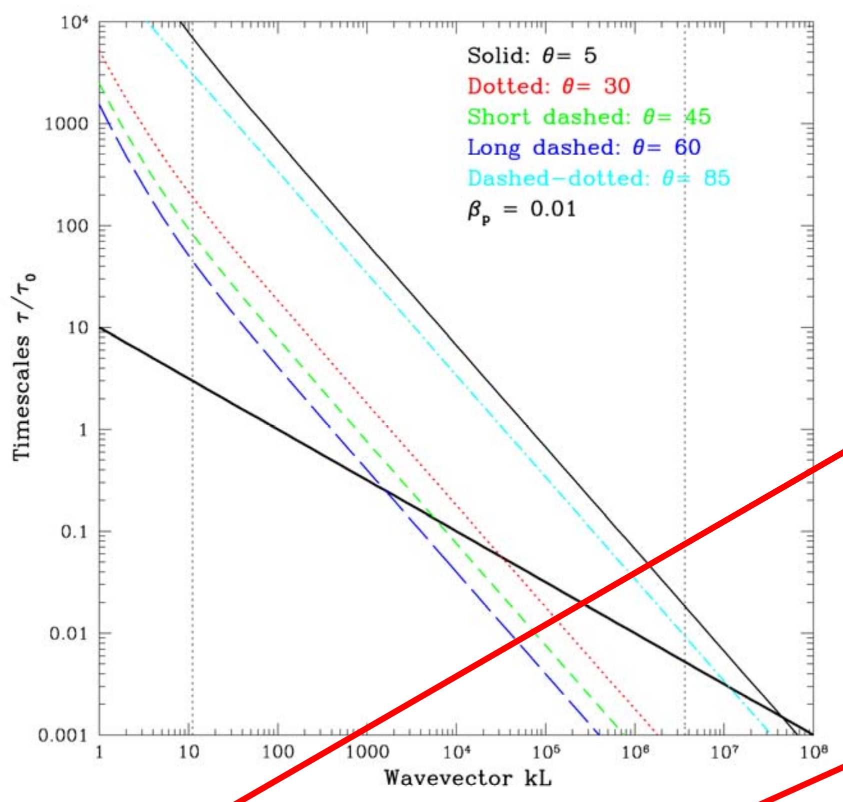
Table 1: (a) Goldreich & Sridahr (1995), CL02; (b) Iroshnikov (1963), Krachnan (1965); (c) Vainshtein (1973), Biskamp et al. (1999).

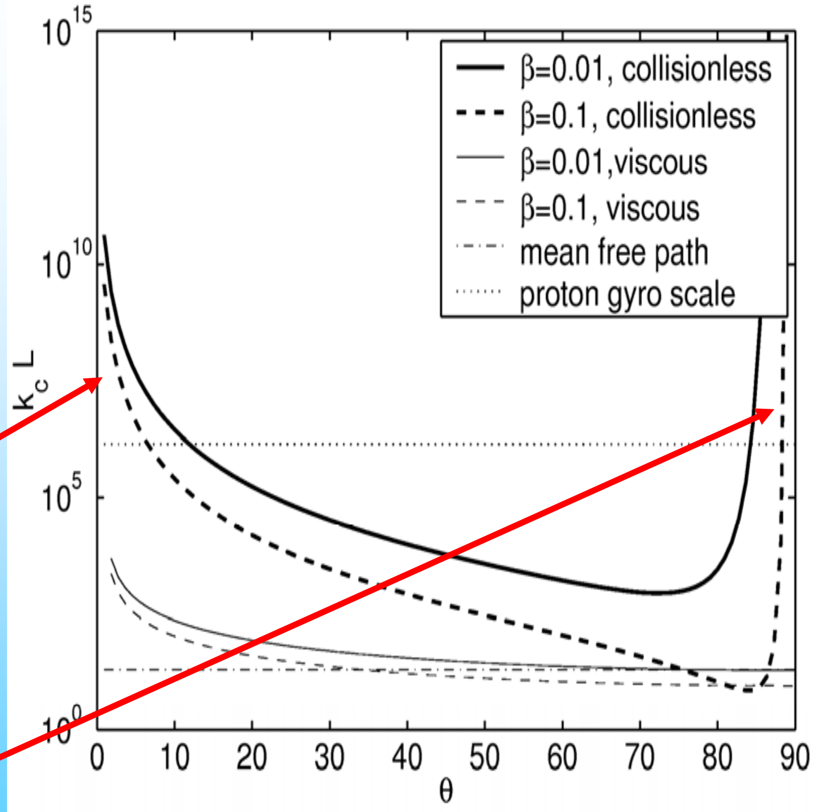
B. Cascade of MHD Turbulence



Cho & Lazarian 2002

B. Cascade vs. Damping of Turbulence





Parallel (and perpendicular) waves are not damped

C. Wave-Particle Interaction Rates

$$D_{ij} = \pi e^2 \sum_{n=-\infty}^{+\infty} \int d^3k \langle d_{ij} \rangle \delta\left(\boldsymbol{k} \cdot \boldsymbol{v} - \omega + \frac{n\eta_0}{\gamma} \boldsymbol{\Omega}_0 \right),$$

C. Dispersion Relation for the Waves (Propagating along Field Lines)

$$(ck)^2 = \omega^2 \left[1 - \sum_i \frac{\omega_{pi}^2}{\omega(\omega - q_i/|q_i|\Omega_i)} \right].$$

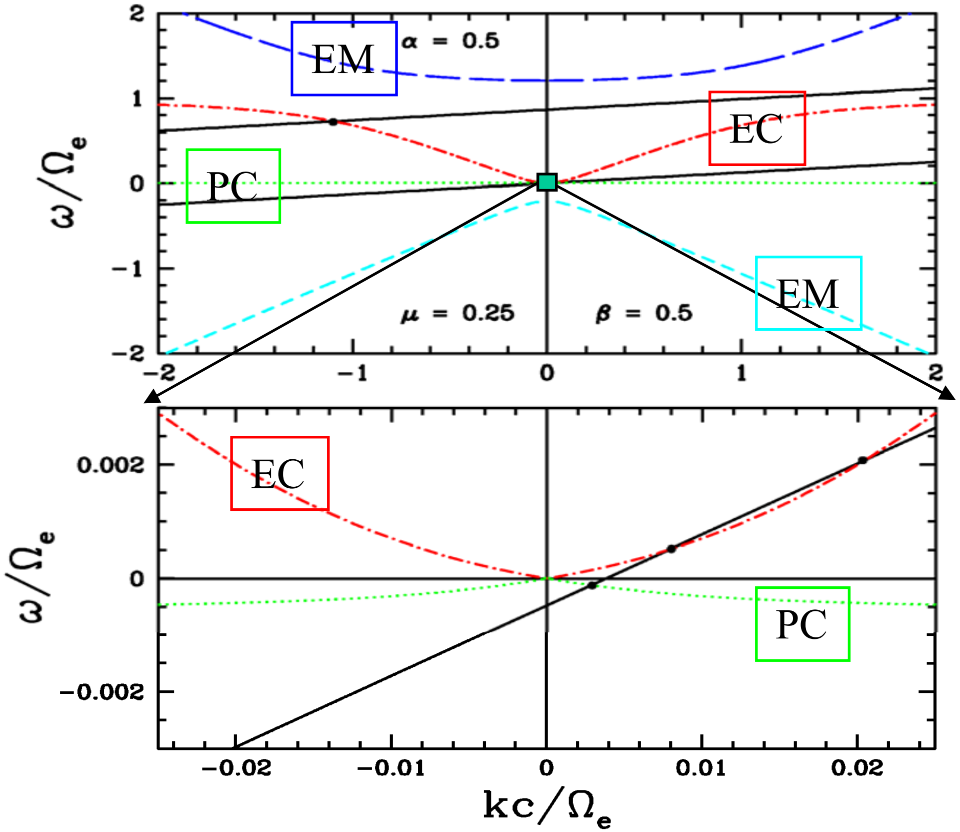
Plasma Parameter:

$$\alpha = \frac{\omega_{pe}}{\Omega_e} = 1.0 \left(\frac{n}{10^9 \mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{B_0}{100\mathrm{G}} \right)^{-1}$$

Ion Abundance.

C. Dispersion Relation and Resonance Condition

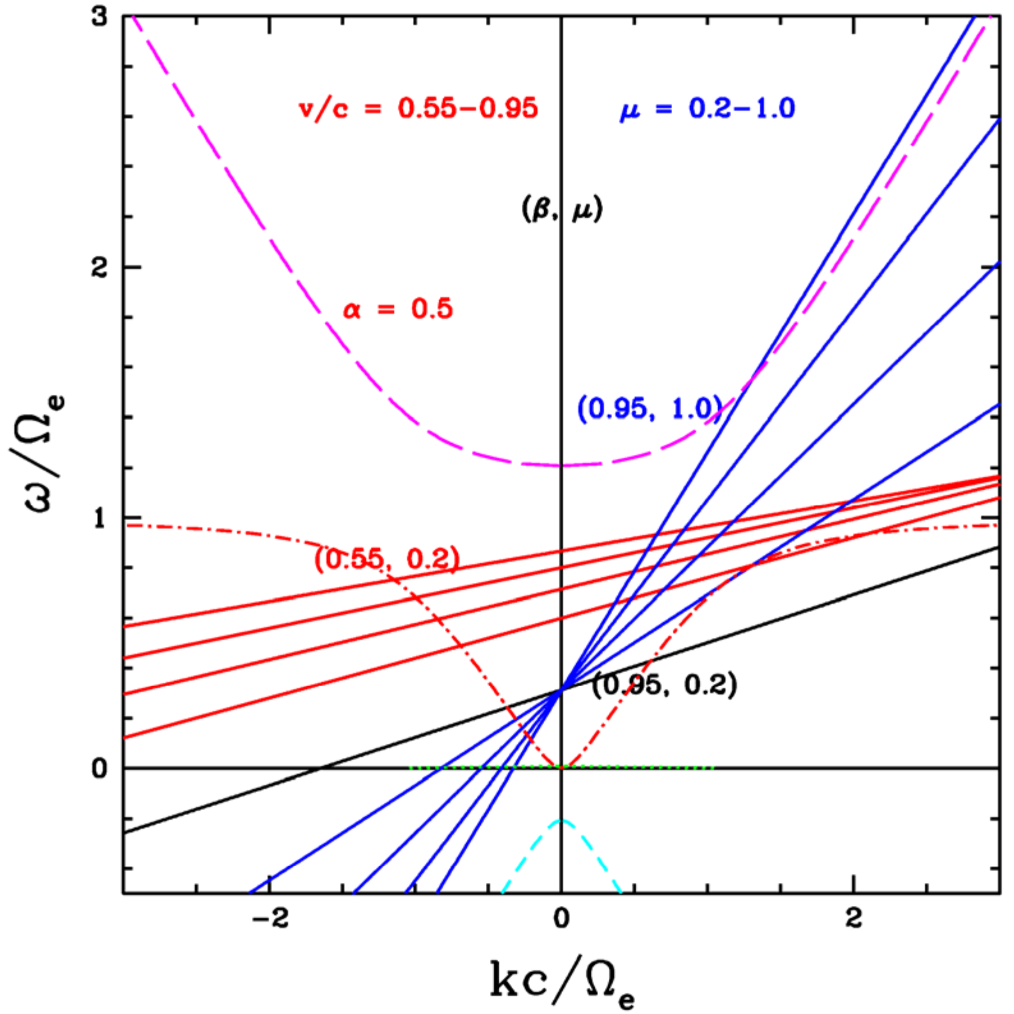
$$\omega = \mu v k + \frac{\Omega_i}{\gamma}.$$



Pure Hydrogen Plasma

C. Resonant Wave-Particle Interaction

$$\omega = \mu v k + \frac{\Omega_i}{\gamma}.$$



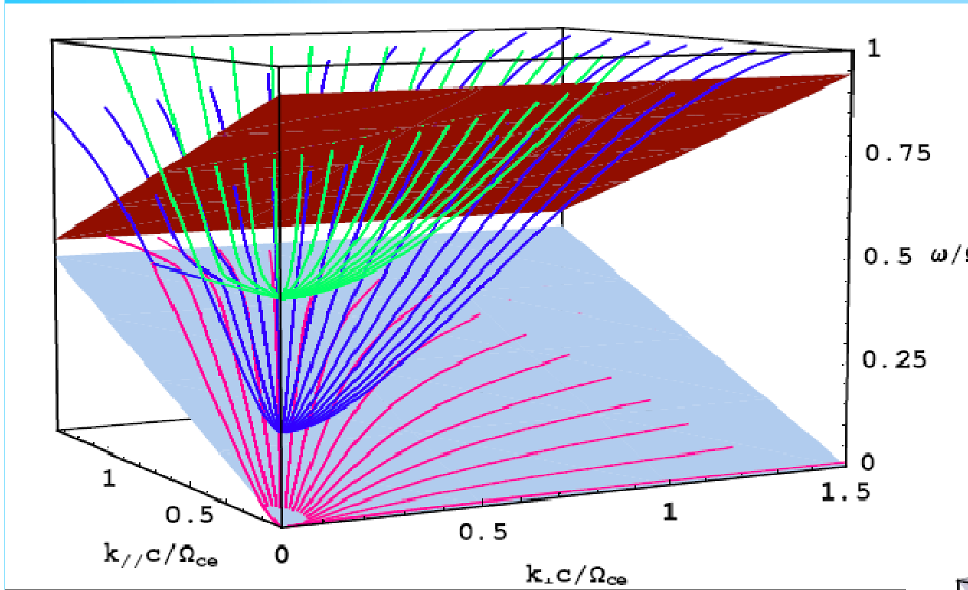
C. Transport Coefficients

$$D_{ab} = \frac{(\mu^{-2} - 1)}{\tau_{\mathrm{p}i}\gamma^2} \sum_{j=1}^{N} \chi(k_j) \begin{cases} \mu\mu(1 - x_j)^2, & \text{for } ab = \mu\mu; \\ \mu p x_j (1 - x_j), & \text{for } ab = \mu p; \\ p^2 x_j^2, & \text{for } ab = pp, \end{cases}$$

$$\chi(k_j) = \frac{|k_j|^{-q}}{|\beta\mu - \beta_{\mathrm{g}}(k_j)|} \qquad \text{and} \qquad x_j = \mu\omega_j/\beta k_j\,.$$

$$\tau_{\mathrm{p}}^{-1} = \frac{\pi}{2}\Omega_{\mathrm{e}} \left[\frac{\mathcal{E}_0}{B_0^2/8\pi} \right] (q-1) k_{\mathrm{min}}^{q-1}$$

C. Resonant Wave-Particle Interaction



Dispersion Relation

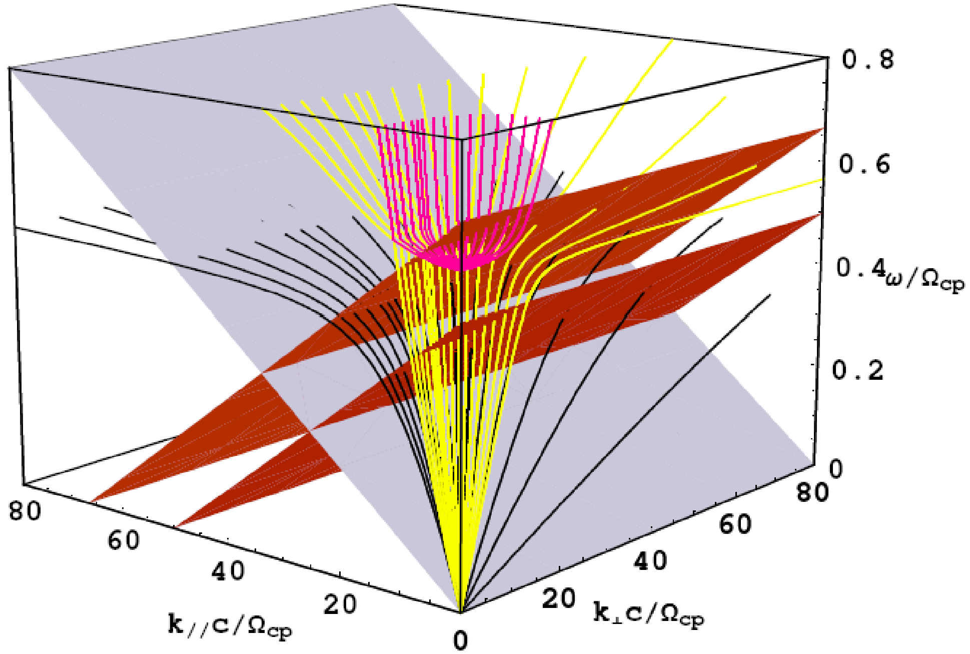
$$\tan^2\theta = \frac{-P(n^2-R)(n^2-L)}{(Sn^2-RL)(n^2-P)}$$

$$S=\frac{1}{2}(R+L), \quad D=\frac{1}{2}(R-L), \quad P=1-\sum_i \frac{\omega_{pi}^2}{\omega^2}, \quad R=1-\sum_i \frac{\omega_{pi}^2}{\omega^2}\left(\frac{\omega}{\omega+\epsilon_i\Omega_i}\right),$$

$$L=1-\sum_i \frac{\omega_{pi}^2}{\omega^2}\left(\frac{\omega}{\omega-\epsilon_i\Omega_i}\right), \quad \omega_{pi}^2=\frac{4\pi n_i q_i^2}{m_i}, \quad \Omega_i=\frac{|q_i|B}{m_i c}, \quad \epsilon_i=\frac{q_i}{|q_i|}$$

Resonance Condition

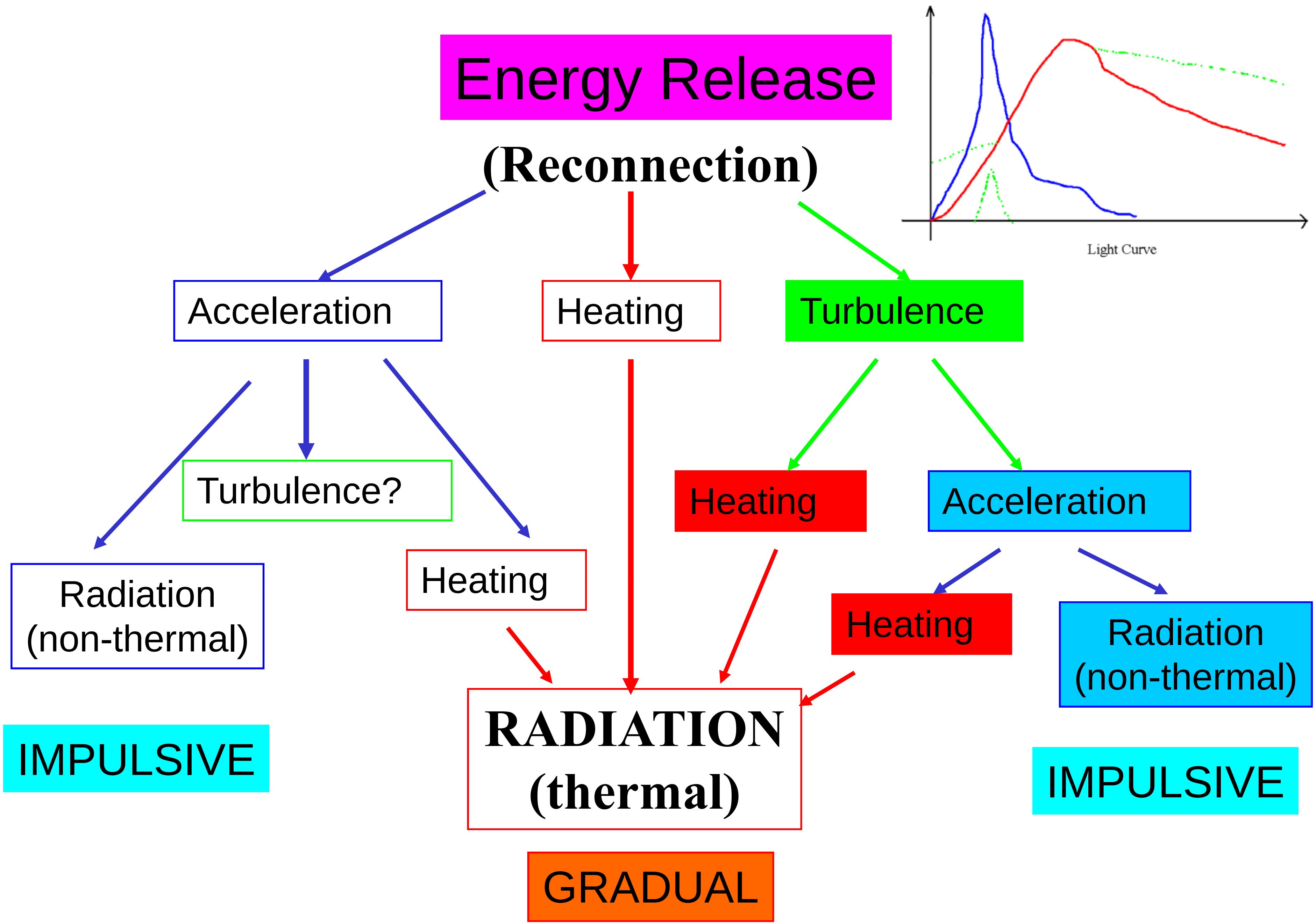
$$\omega = k_\parallel v\mu + n\Omega_i/\gamma$$



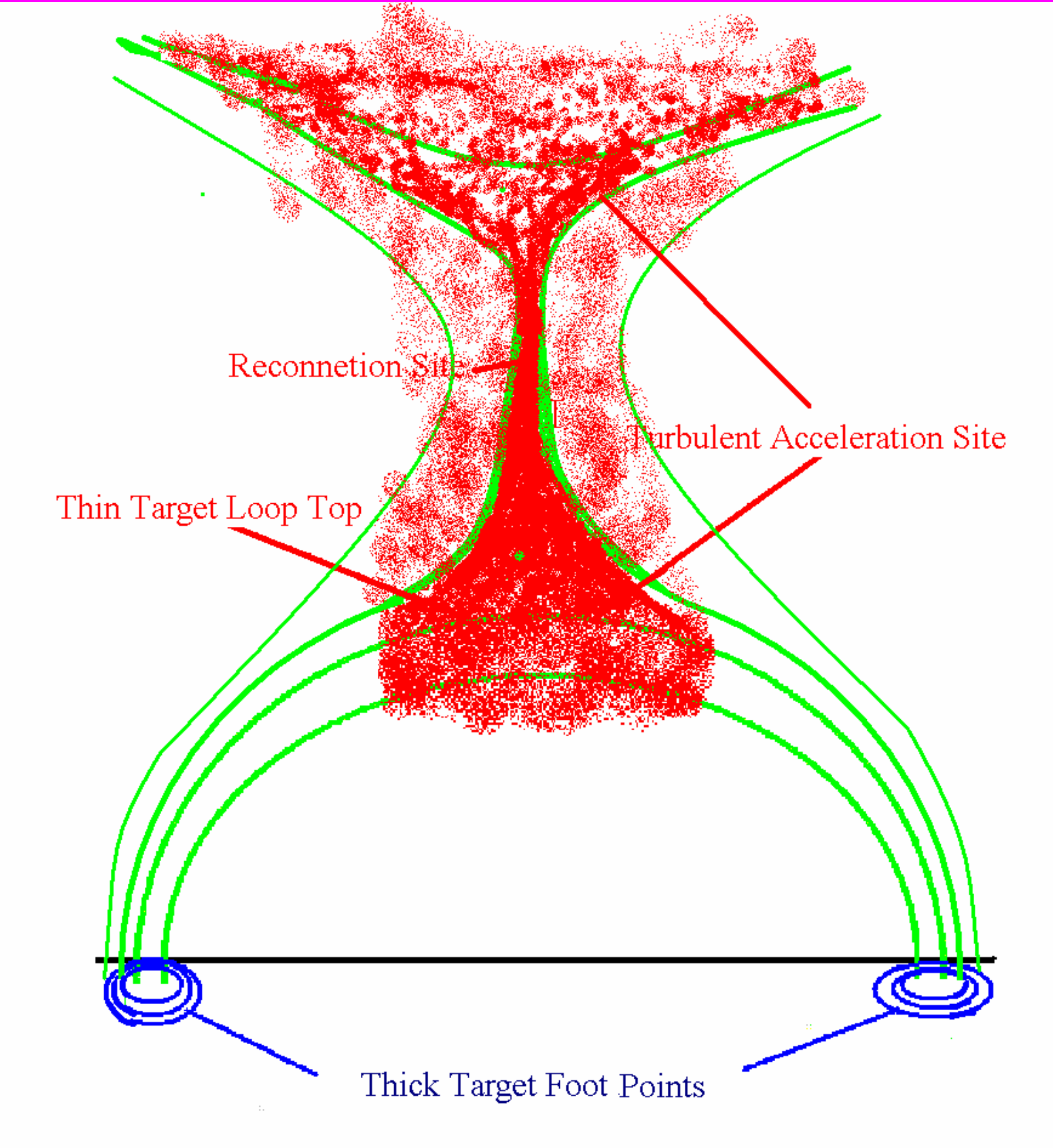
Application to Solar Flares

General view

1. Electron Acceleration
2. Proton Acceleration
3. ^{3}He and Heavy Ions Enrichment
4. Conduction Suppression

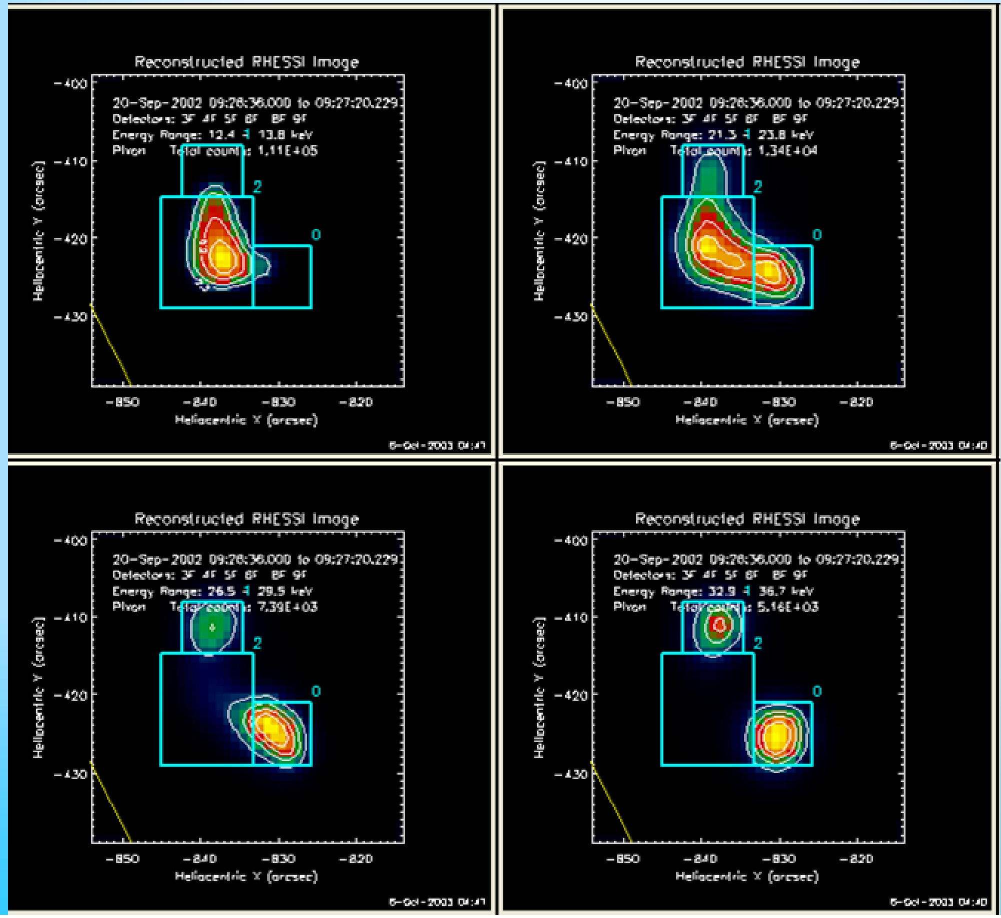

Energy Release
(Reconnection)
Acceleration
Heating
Turbulence
Turbulence?
Radiation
(non-thermal)
Heating
Heating
Acceleration
Heating
Radiation
(non-thermal)
RADIATION
(thermal)
IMPULSIVE
GRADUAL
IMPULSIVE
Light Curve

Model Descriptions



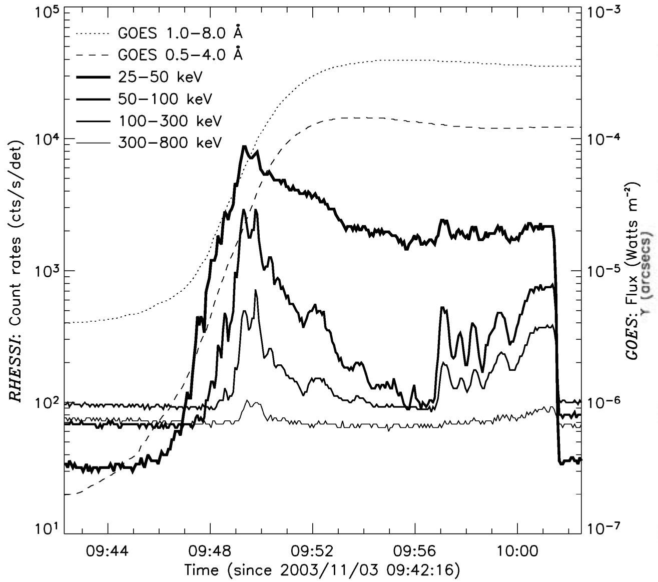
A: LT and FP HXRs

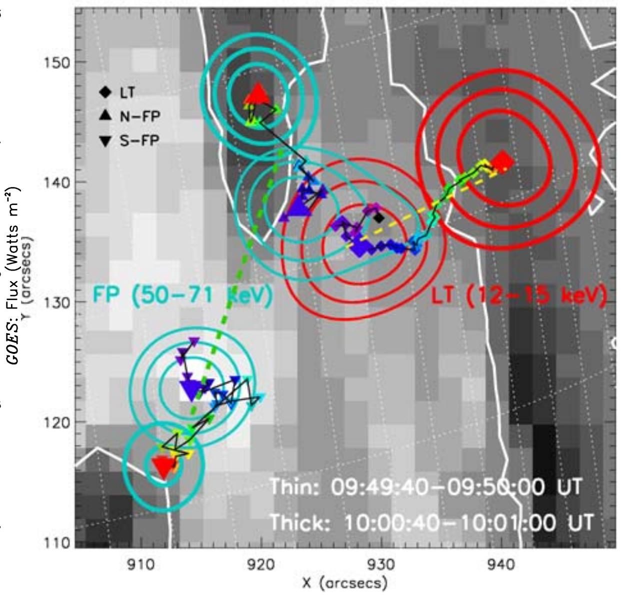
(Heating vs. Acceleration)

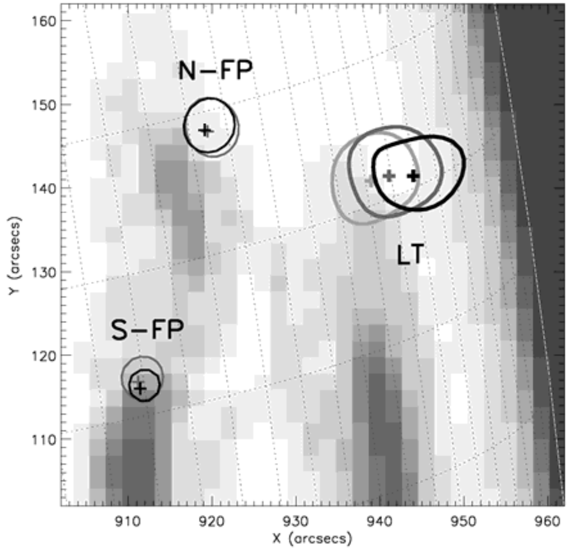


A Simple Solar Flare

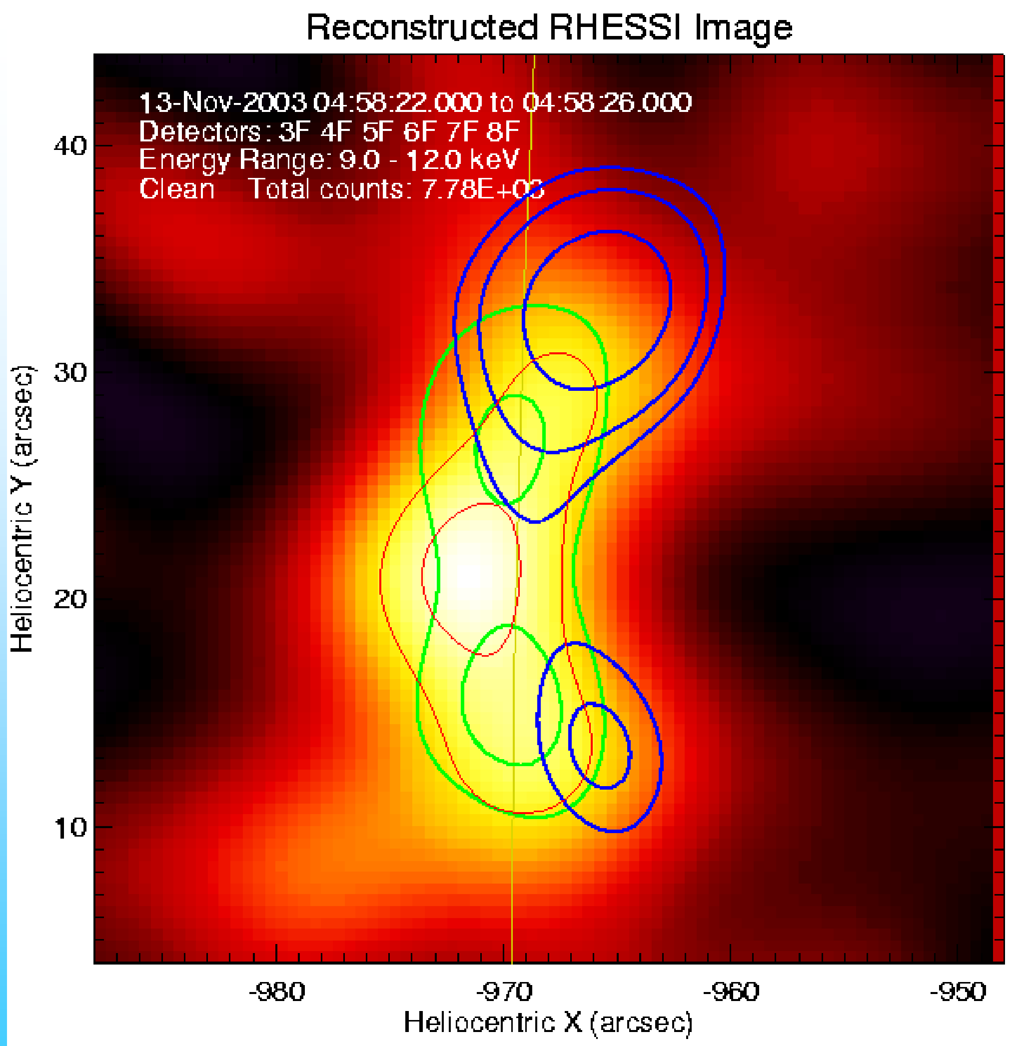
11032003, N09W77, X3.9



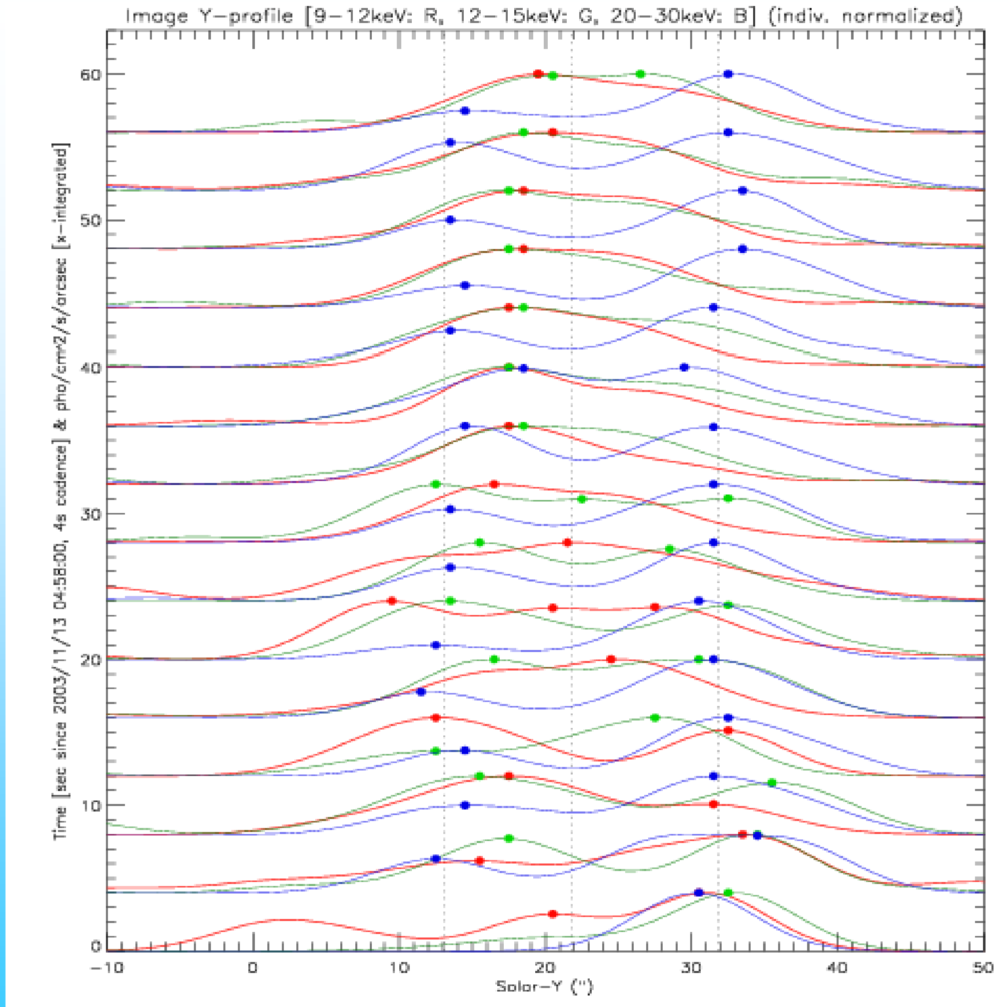




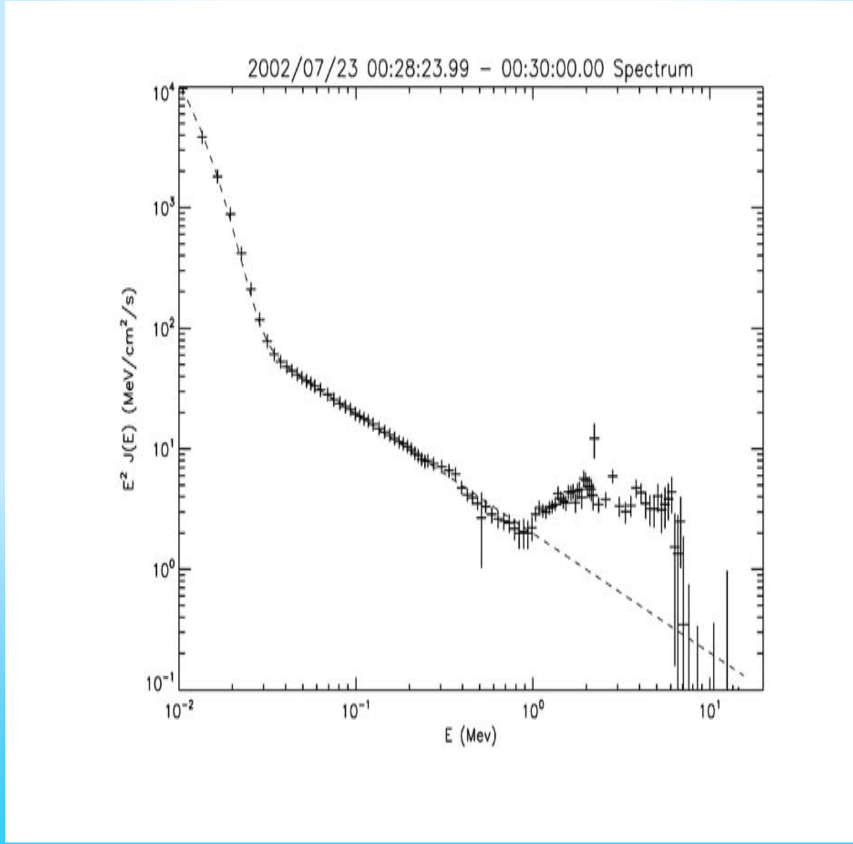
Leg Emission



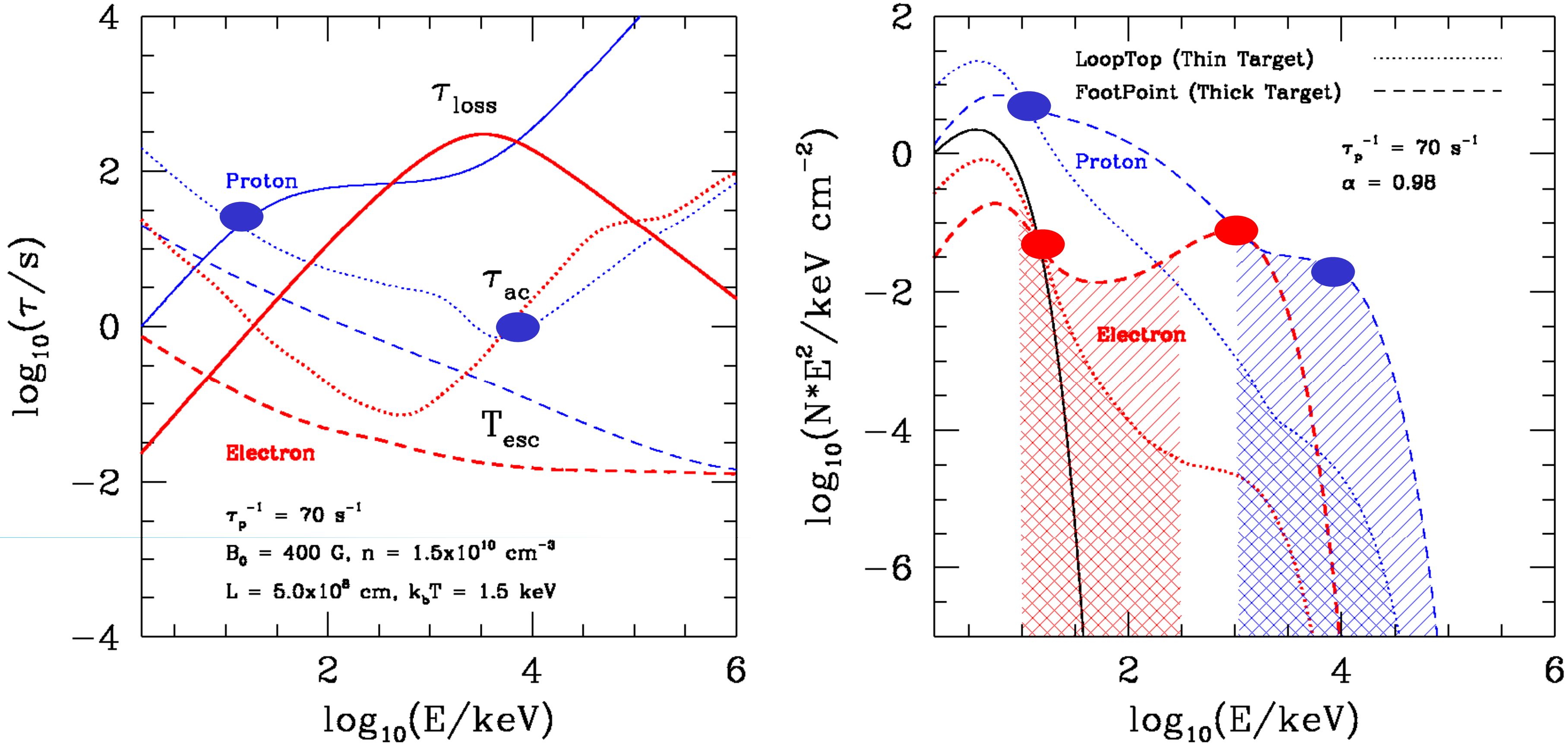
Chromospheric Evaporation



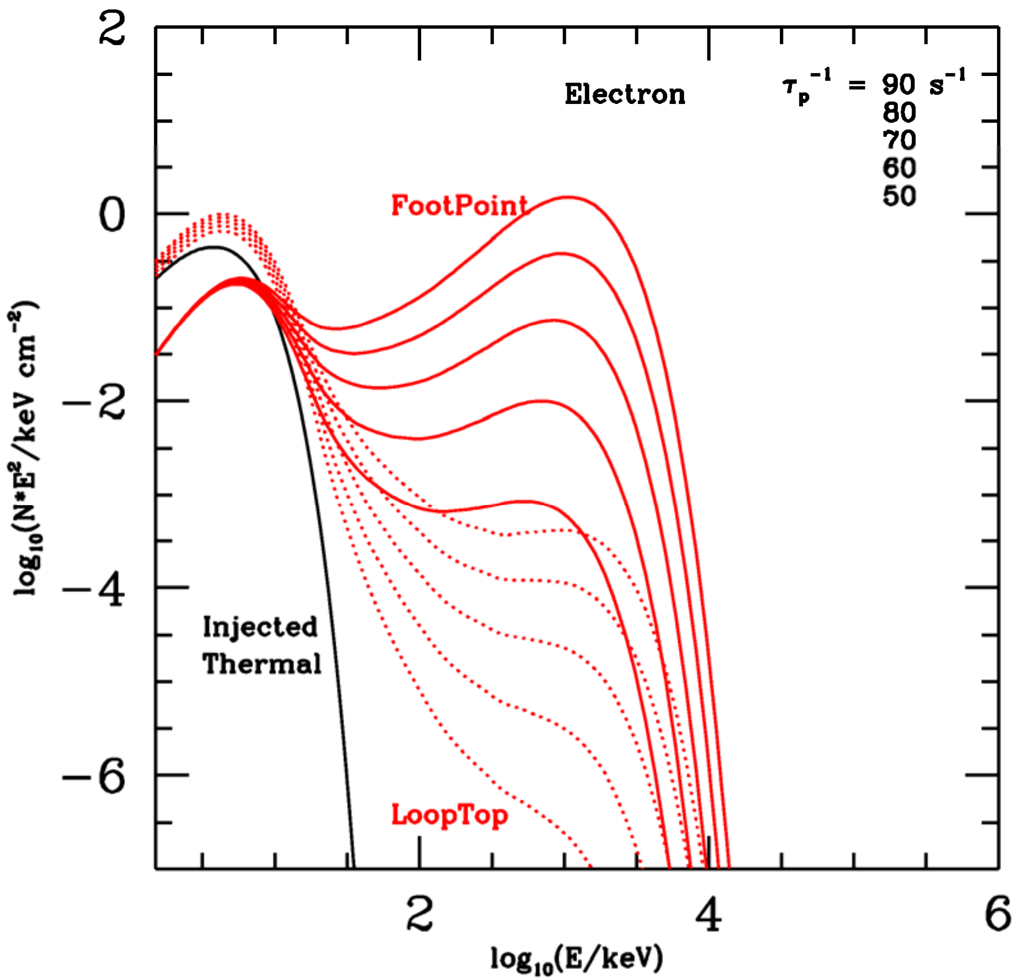
B: Spectral Breaks
(Losses vs. Acceleration)



$$\tau_{\rm ac} = E^2/D_{EE} \qquad \tau_{\rm loss} = E/\dot{E}_{\rm L}$$

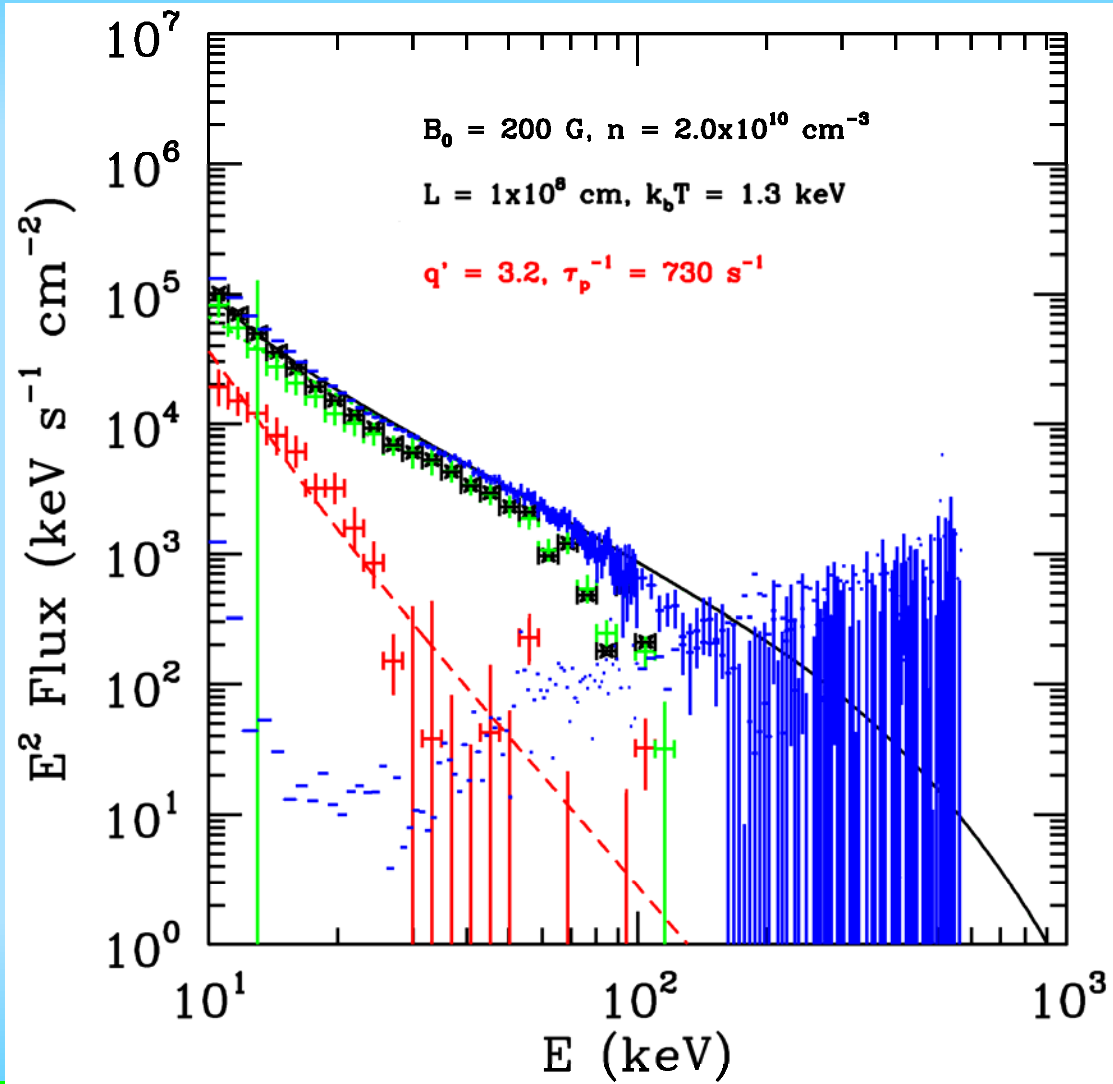


1. Electron Acceleration



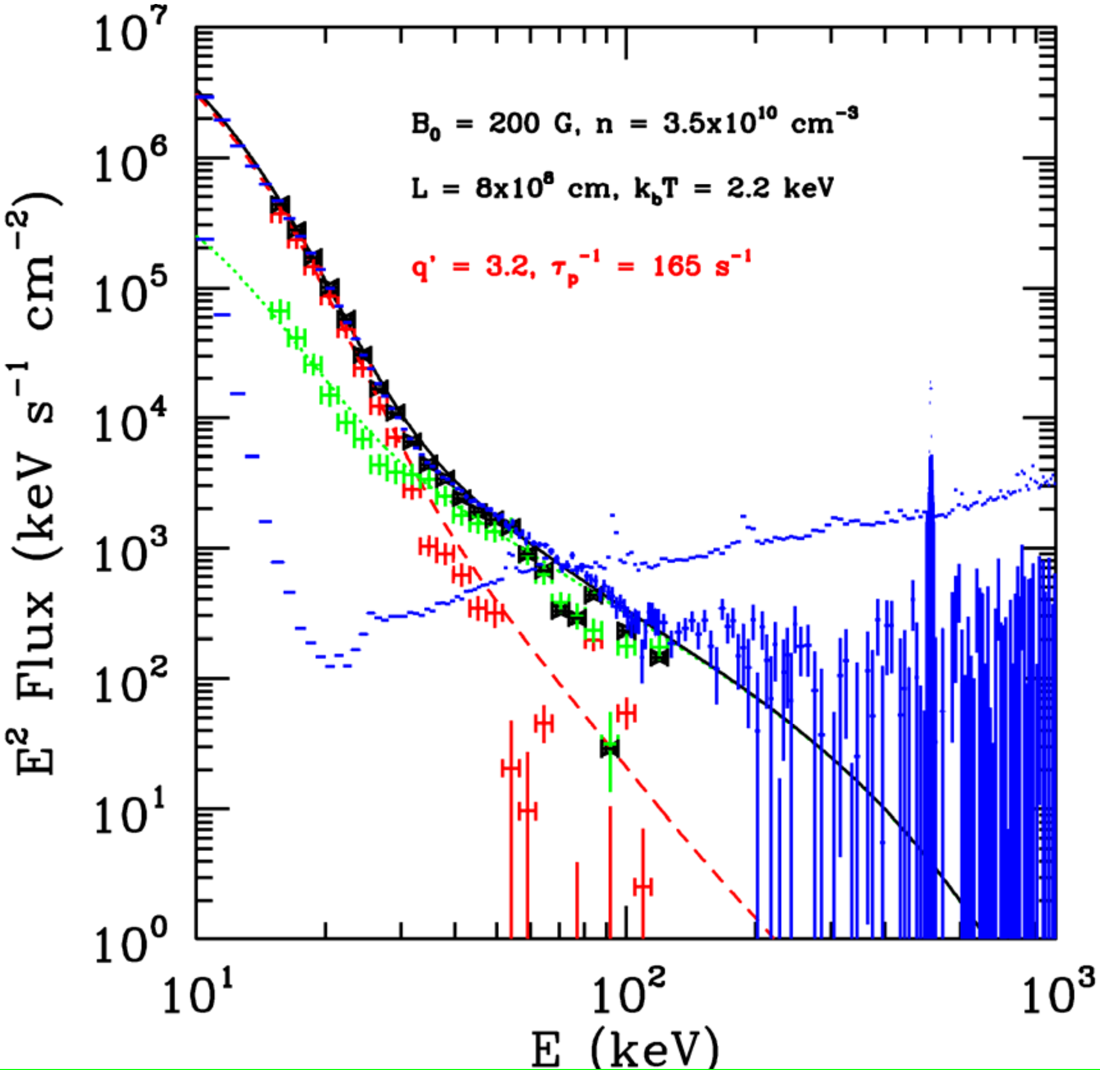
Dependence of FP/LT e Distribution on τ_p

1. Looptop and Footpoint Spectra



Best Fit to the LT and FP Spectra of
the First Peak of a Flare on Aug. 3 2002

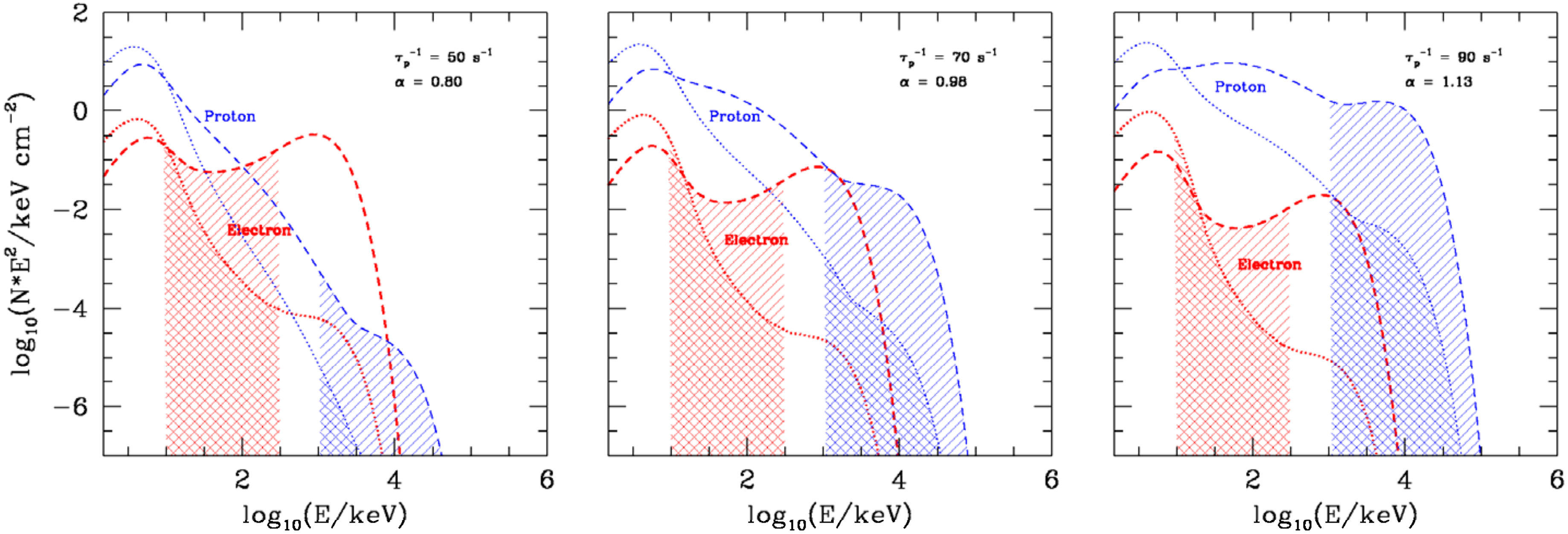
1. Looptop and Footpoint Spectra



Best Fit to the LT and FP Spectra of
the Third Peak of a Flare on Aug. 3 2002

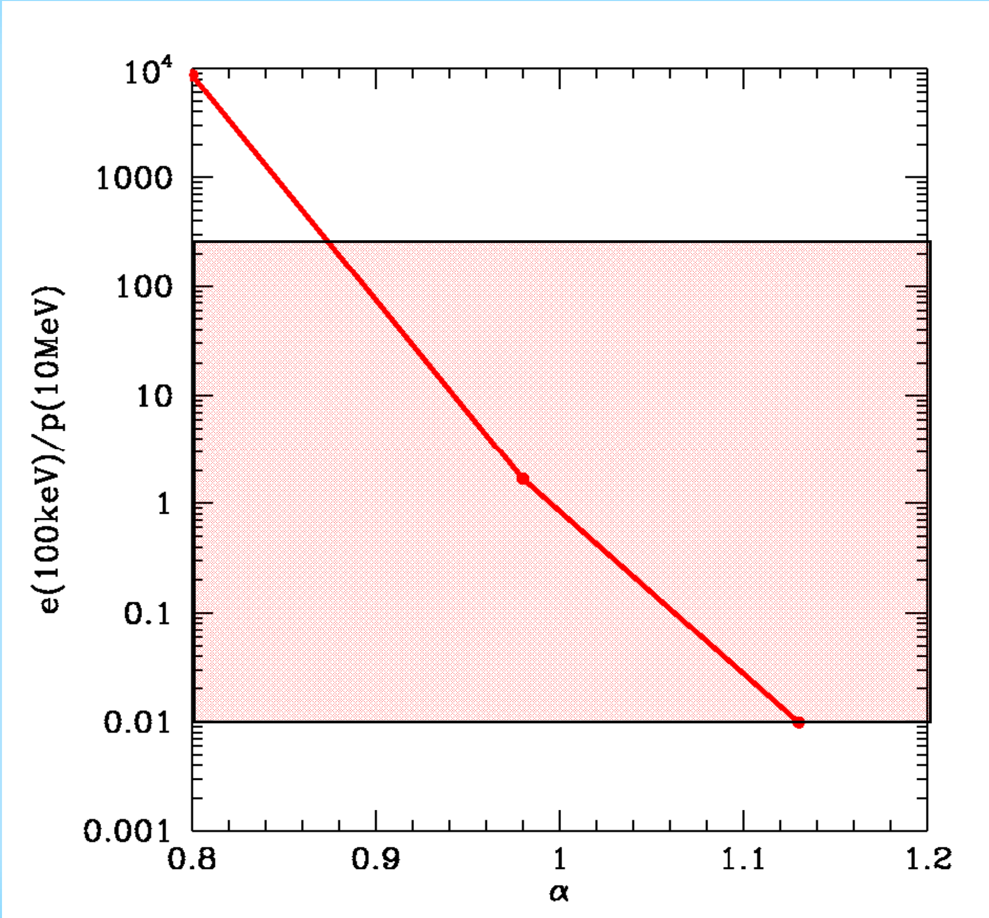
2. Protons vs. Electrons

$\alpha = 0.80$ $\alpha = 0.98$ $\alpha = 1.13$

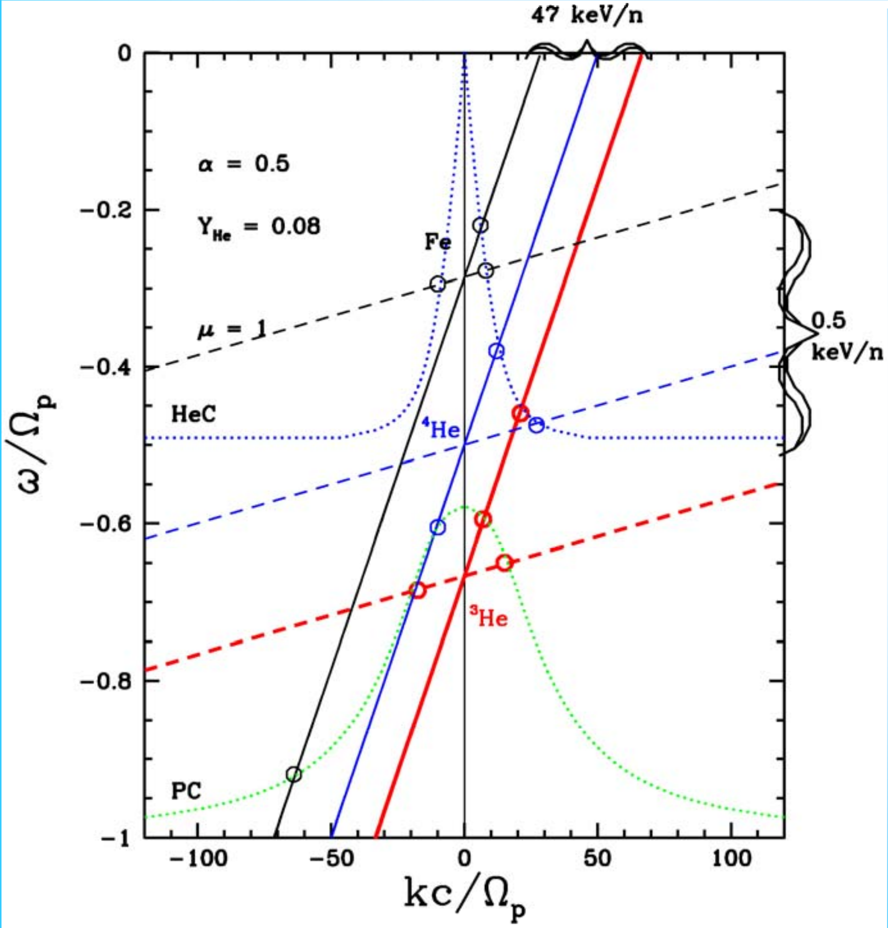


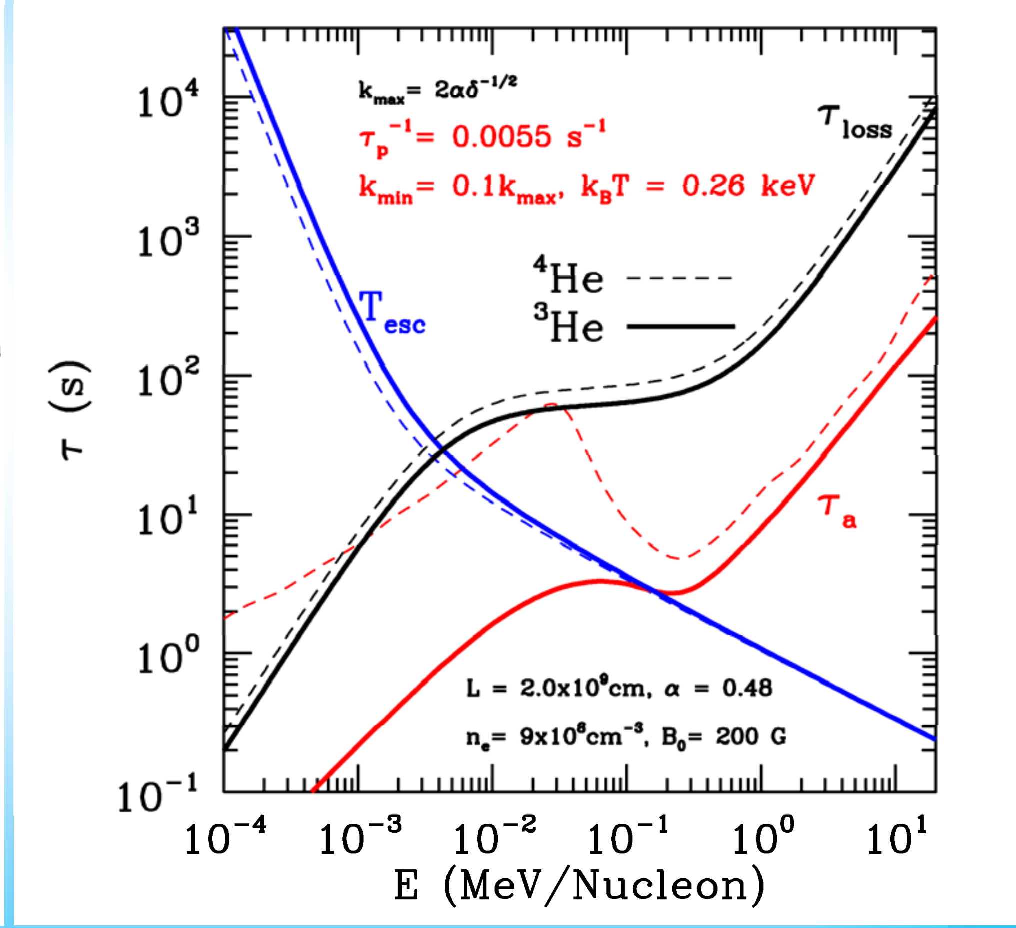
Dependence on the Plasma Parameter

2. Protons vs. Electrons

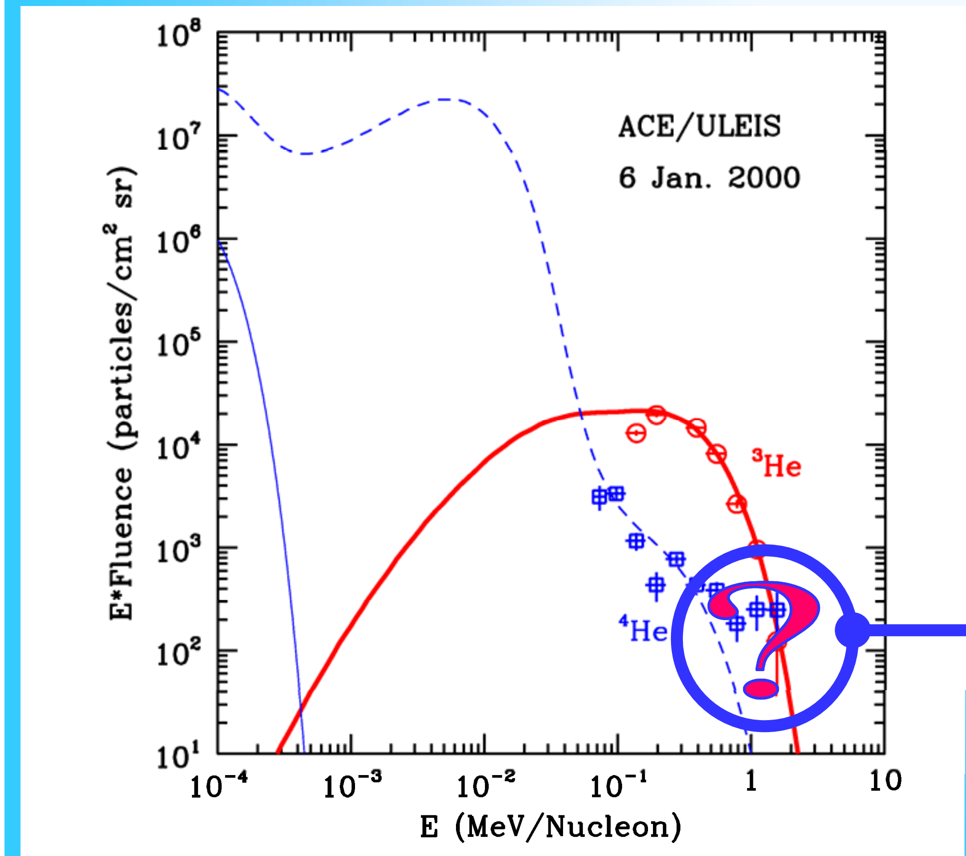


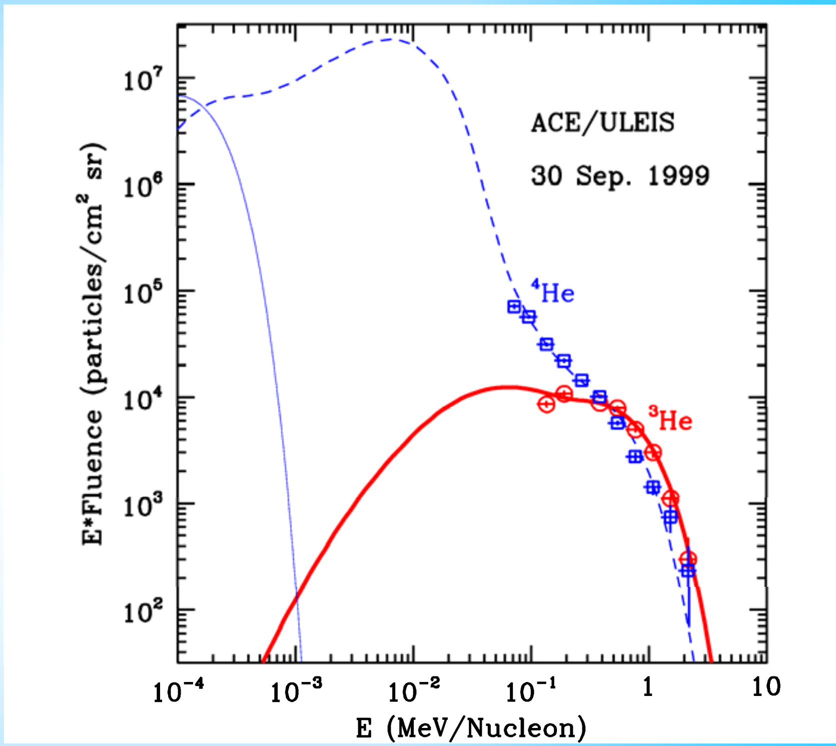
3. Acceleration of ^{3}He and ^{4}He by Parallel Propagating Waves



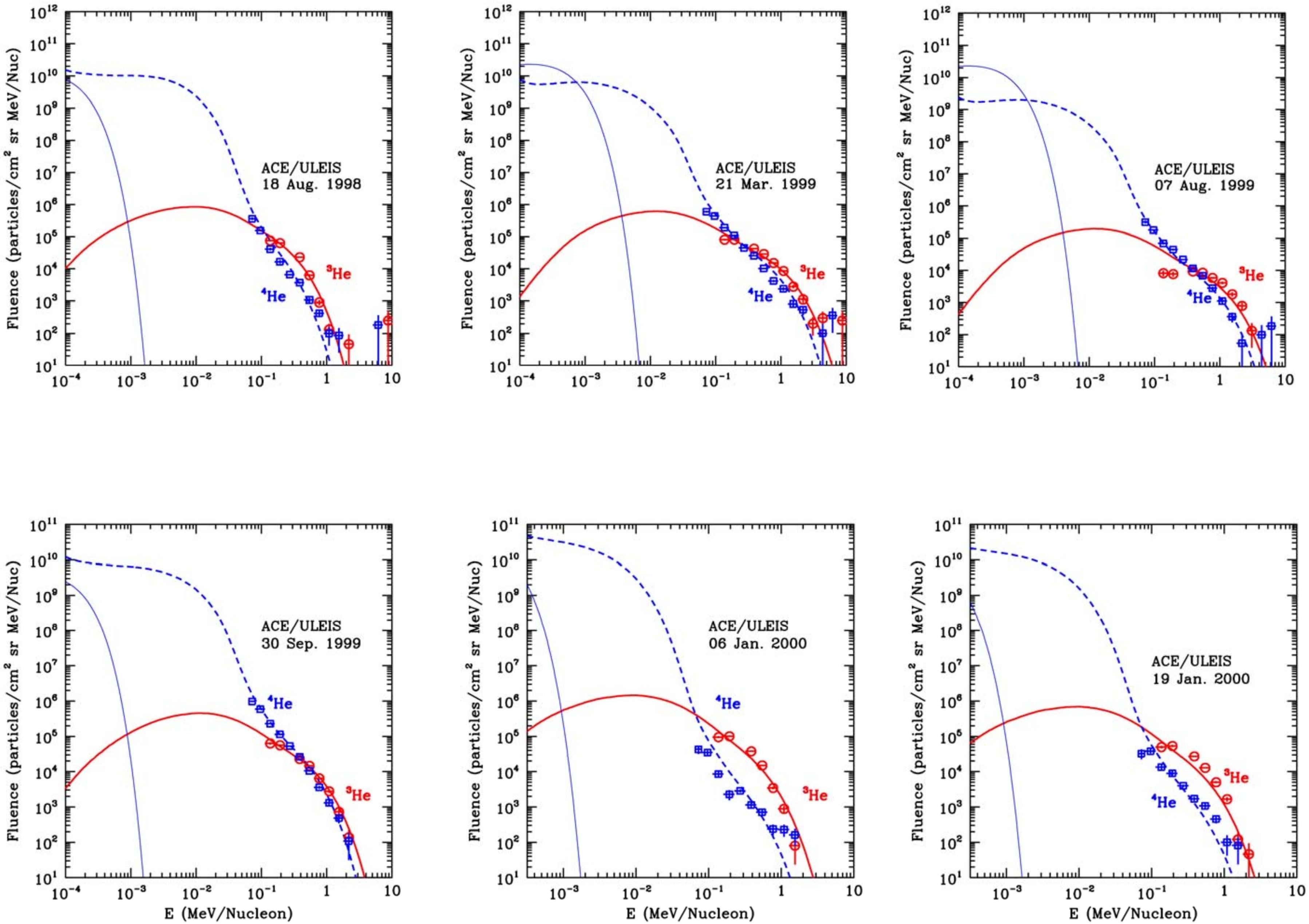


3. Acceleration of ^{3}He and ^{4}He by Parallel Propagating Waves



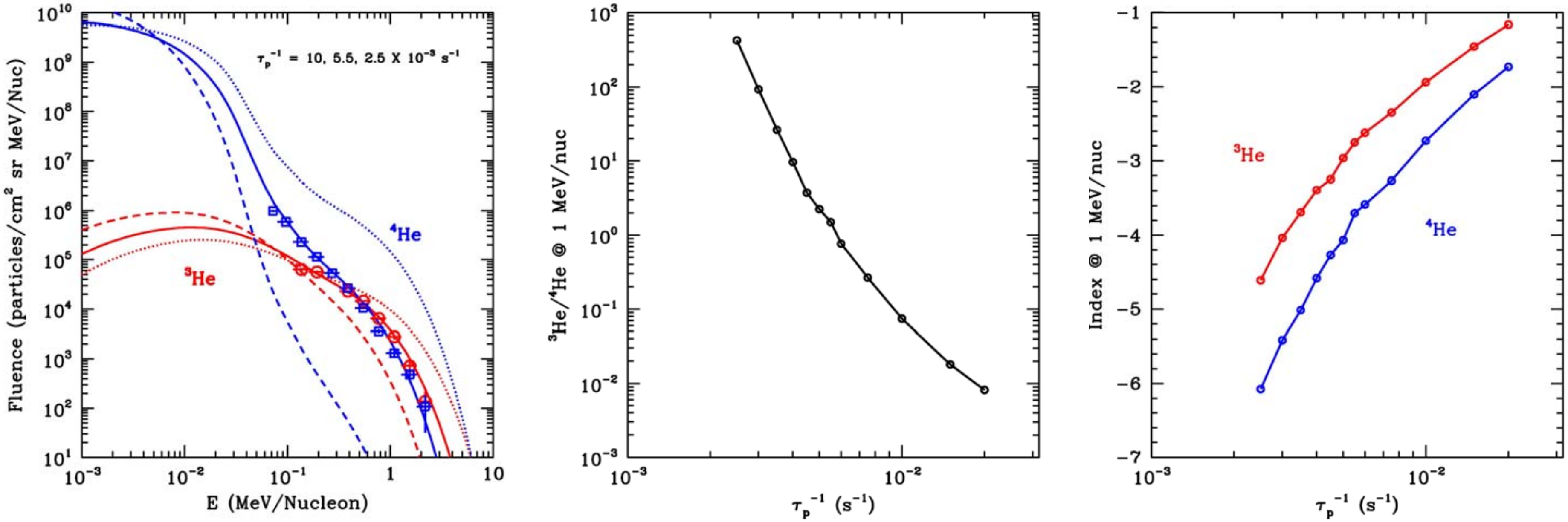


Transit-Time Damping?



Fluence (particles/cm^2 sr MeV/Nuc)
ACE/ULEIS
18 Aug. 1998
^{3}He
^{4}He
ACE/ULEIS
21 Mar. 1999
^{3}He
^{4}He
ACE/ULEIS
07 Aug. 1999
^{3}He
^{4}He
ACE/ULEIS
30 Sep. 1999
^{4}He
^{3}He
ACE/ULEIS
06 Jan. 2000
^{4}He
^{3}He
ACE/ULEIS
19 Jan. 2000
^{3}He
^{4}He
E (MeV/Nucleon)

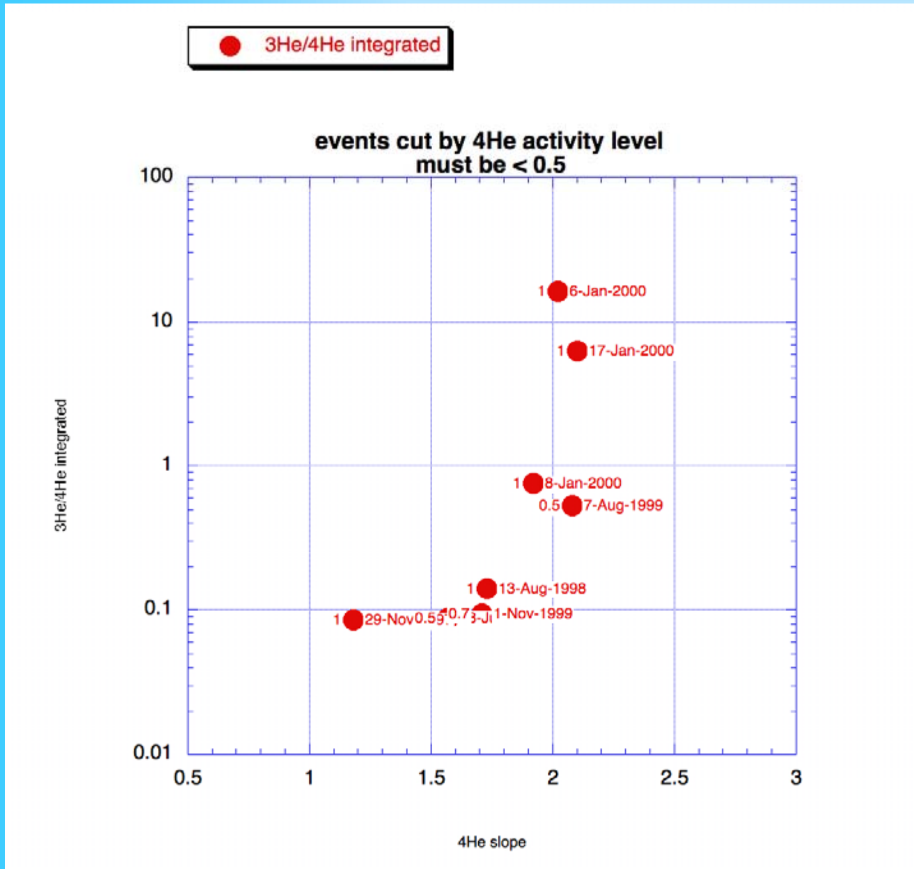
3. Dependence on τ_p

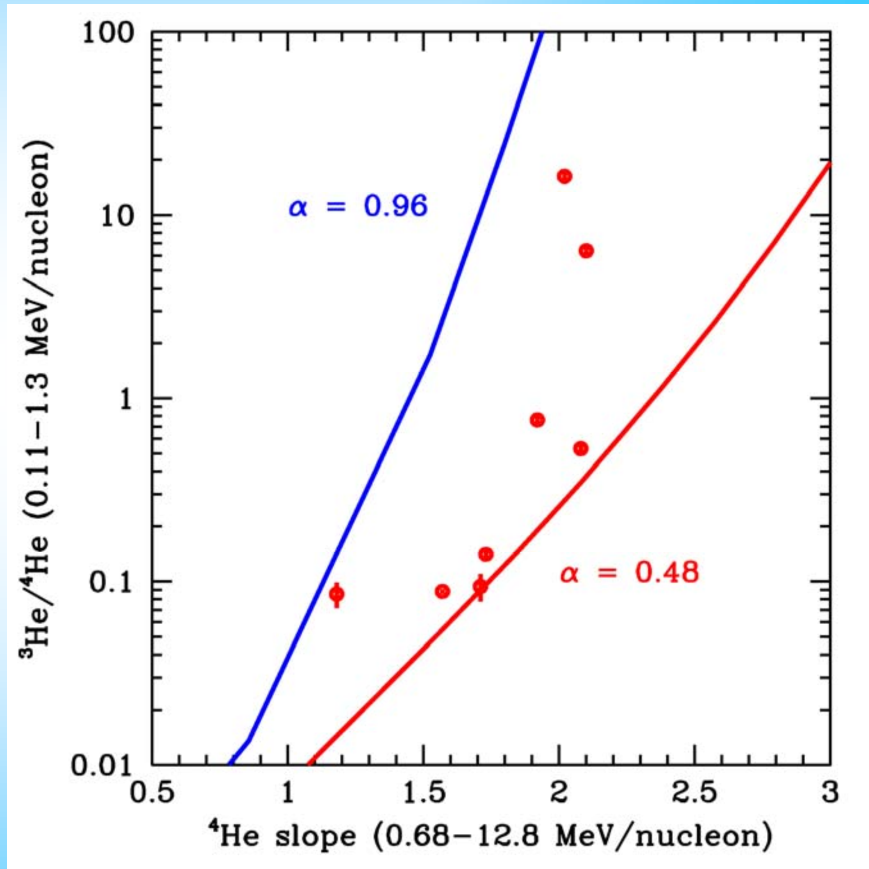


$$\left[\frac{\mathcal{E}_0}{B_0^2/8\pi}\right] = 10^{-8}\,(1\text{sec}/\tau_p)$$

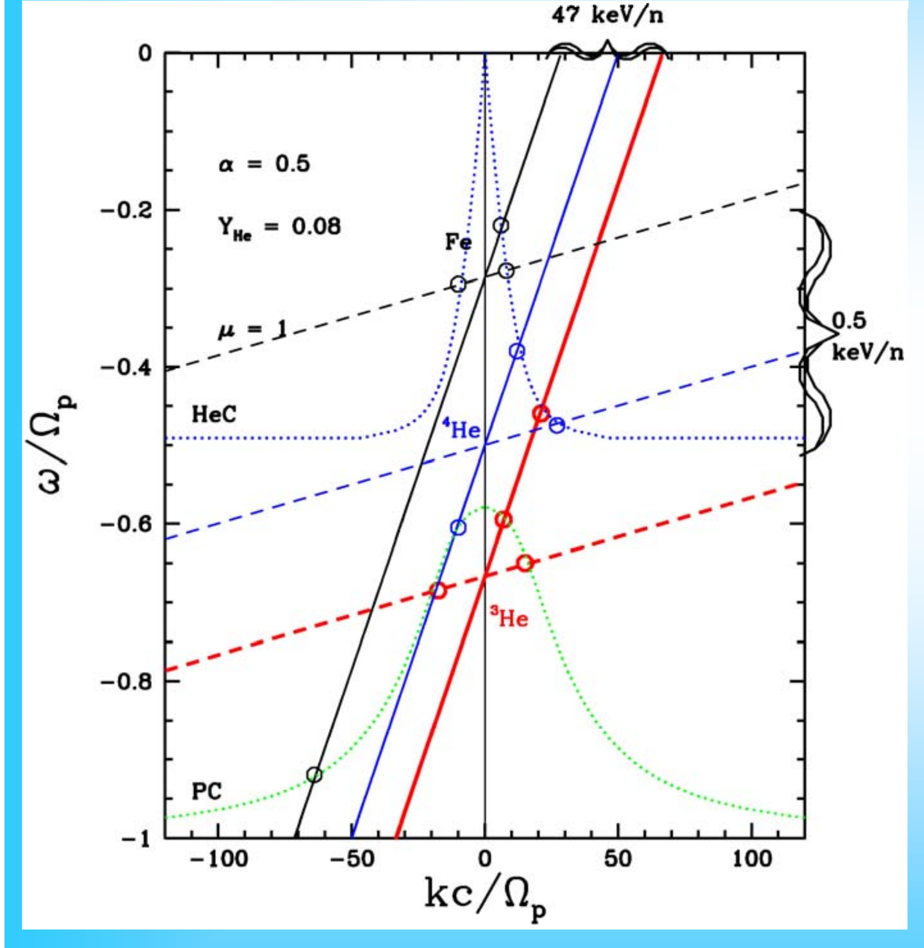
$$\tau_p^{-1} = \frac{\pi}{2}\Omega_e\left[\frac{\mathcal{E}_0}{B_0^2/8\pi}\right](q-1)k_{\min}^{q-1}$$

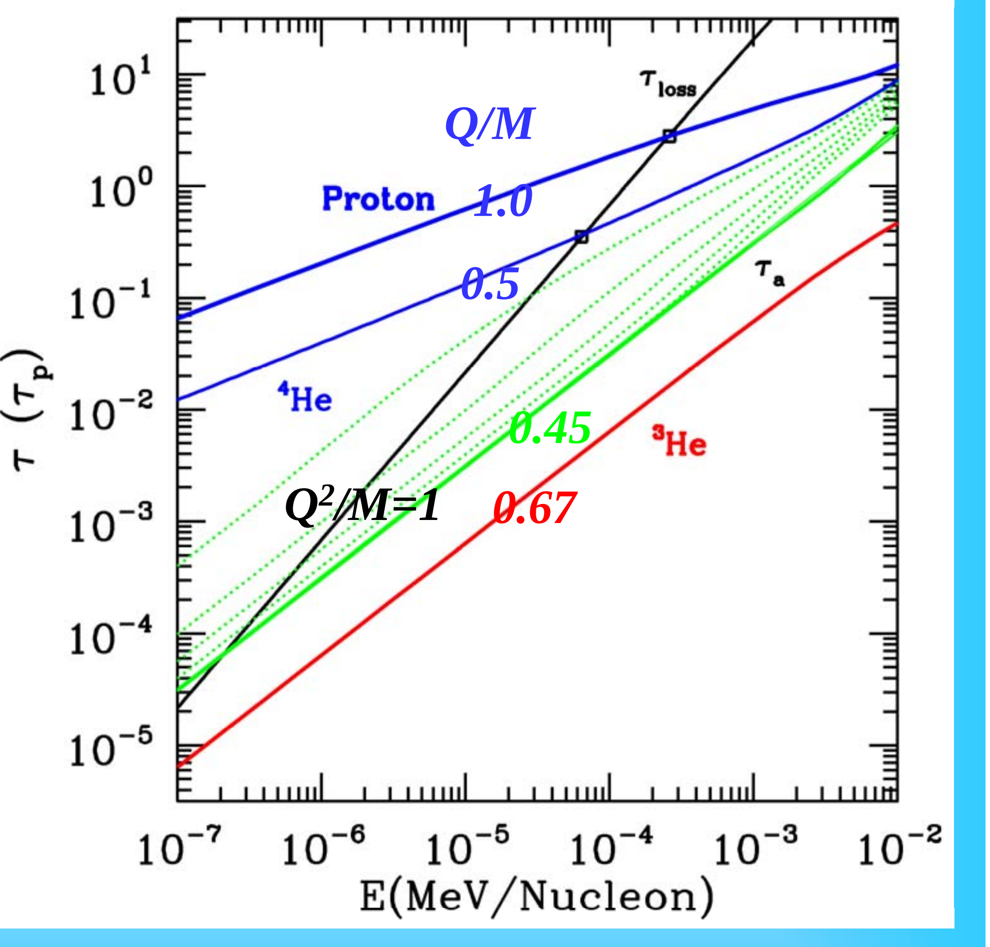
3. Acceleration of ^{3}He and ^{4}He by Parallel Propagating Waves



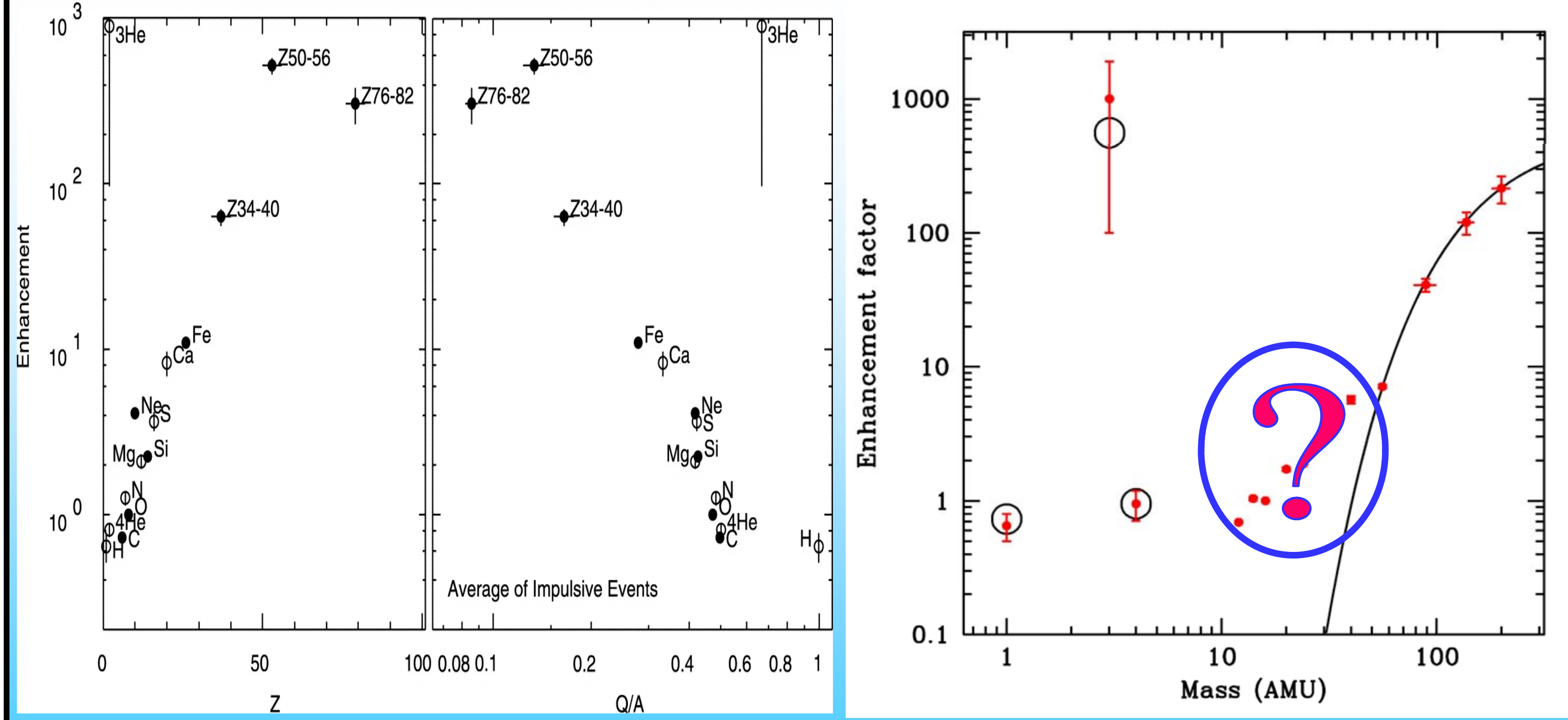


3. Ion Acceleration by Parallel Propagating Waves

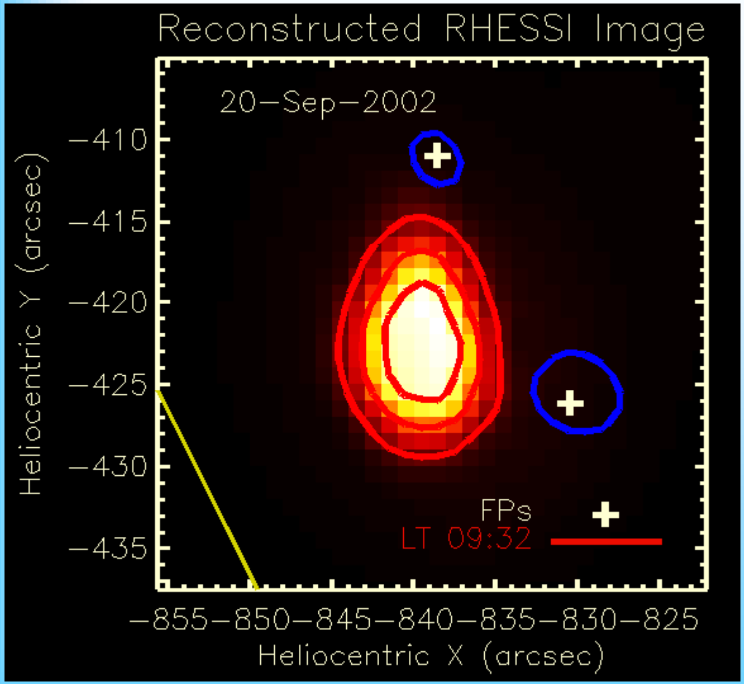


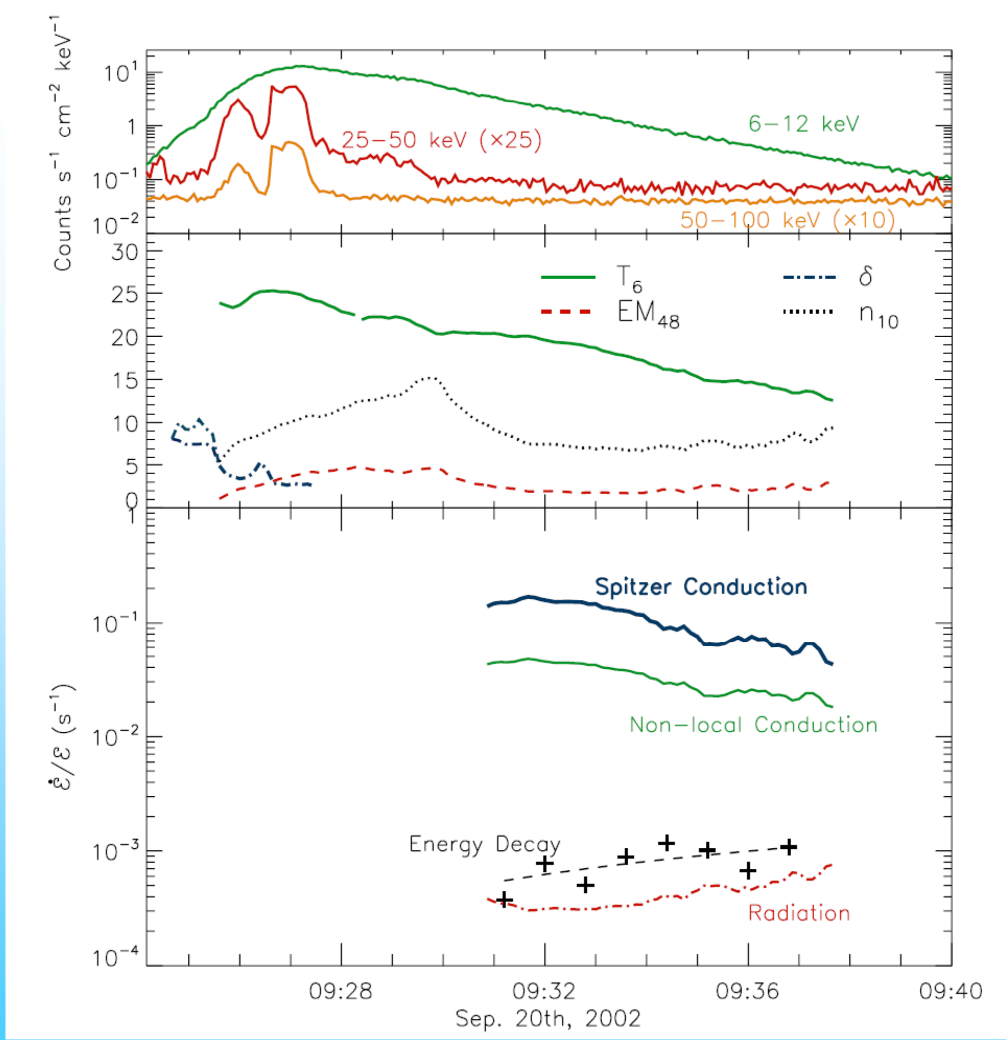


3. Heavy ion enrichment



4. The Roles of Turbulence in the Decay Phase





Heating & Suppression of Conduction

4. Suppression of Conduction

$$\mathcal{F}_{\mathrm{cond}} = \frac{\mathrm{d}\int \frac{1}{2} m v^3 \lambda \mu f v^2 \mathrm{d}\mu \mathrm{d}\phi \mathrm{d}v}{\mathrm{d}L}$$

For Coulomb collision dominated cases, $\lambda = \lambda_{\mathrm{Coul}} \propto v^4/n$

$$\mathcal{F}_{\mathrm{Spit}} \propto T^{5/2} \nabla T$$

When turbulence is present,

$$\lambda = \frac{\lambda_{\mathrm{Coul}} \lambda_{\mathrm{sc}}}{\lambda_{\mathrm{Coul}} + \lambda_{\mathrm{sc}}} = f \lambda_{\mathrm{Coul}}$$

4. Suppression of Conduction & Heating by Turbulence

$$\mathcal{F}_{\rm cond} = f\mathcal{F}_{\rm Spit}$$

$$f \equiv \frac{1}{\lambda_{\rm Coul}/\lambda_{\rm sc} + 1}$$

For Transit-Time Damping, $\lambda_{\rm sc} = v\tau_{\rm sc}$

$$f \simeq \frac{1}{aT^{5/2} + 1}$$

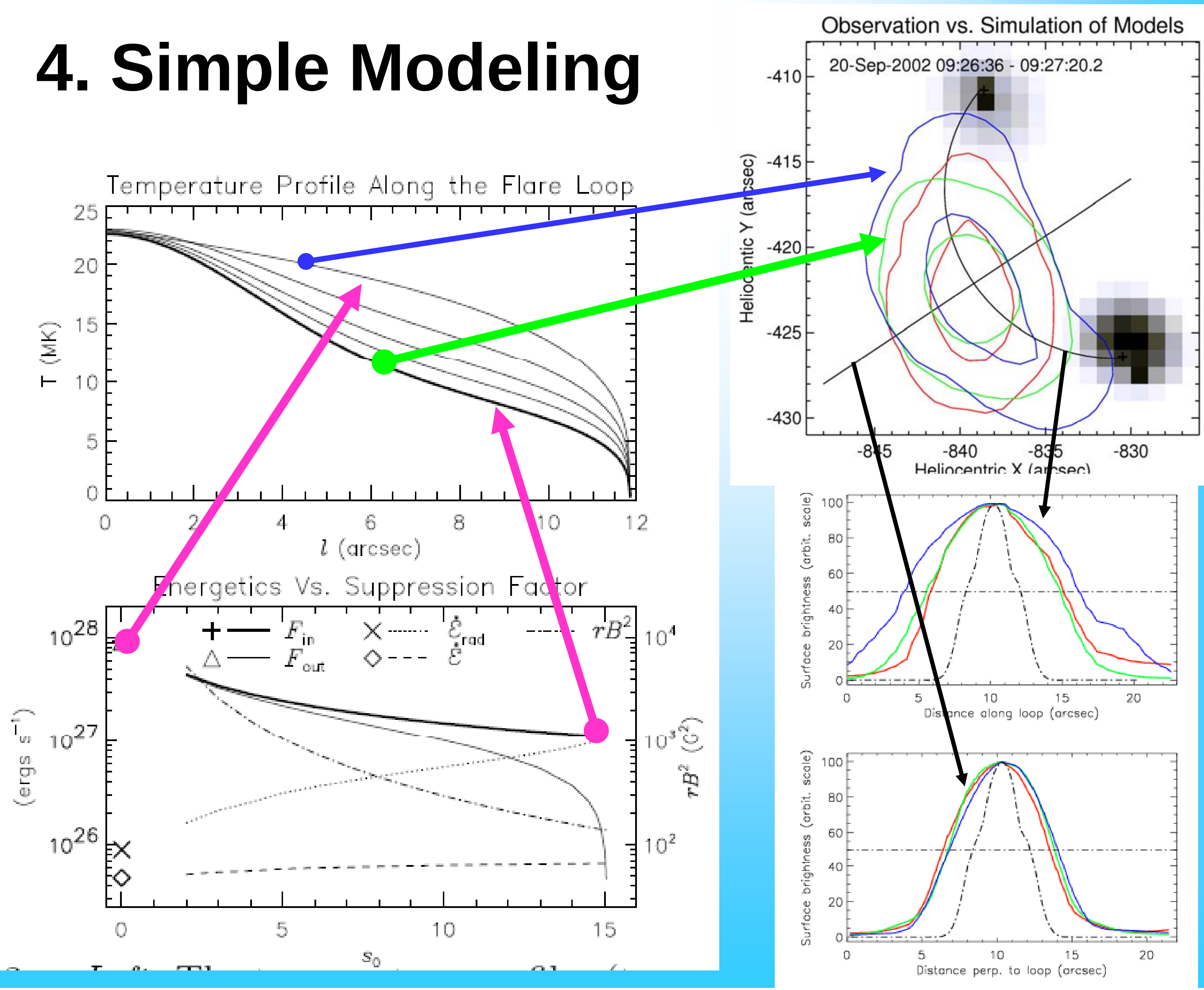
The turbulence can also energize the particles with the acceleration time $\tau_{ac} \approx C\tau_{sc}(v/v_A)^2 \approx C\,\tau_{Coul}(v/v_A)^2$

4. Equation of Energy Conservation

$$\frac{\mathrm{d}(A\mathcal{F}_{\mathrm{cond}})}{A\mathrm{d}l} = -\dot{\varepsilon}_{\mathrm{rad}}(l) + \dot{\mathcal{E}}/V$$

$$\mathcal{F}_{\mathrm{cond}} = \left(1.0 \times 10^{-6} T^{5/2} \right) \nabla T$$

4. Simple Modeling



Summary

- Most solar flares are associated with magnetic loops
- There are usually one LT with soft spectrum and two FPs with hard spectrum
- SA of particles in the LT region by PWT generated via the magnetic reconnection can explain most of the flare characteristics:

Soft LT + hard FPs; Energy partition between electrons and protons; Enrichments of ^{3}He and heavy ions in impulsive SEPs; the slow decay of the LT in the gradual phase.

Conclusions

Plasma Wave Turbulence appears to be
an important channel for the release of energy
during flares
&
Stochastic Acceleration by it can explain
many of the observed flare characteristics