Relativistic Solar Electrons - where and how are they formed?

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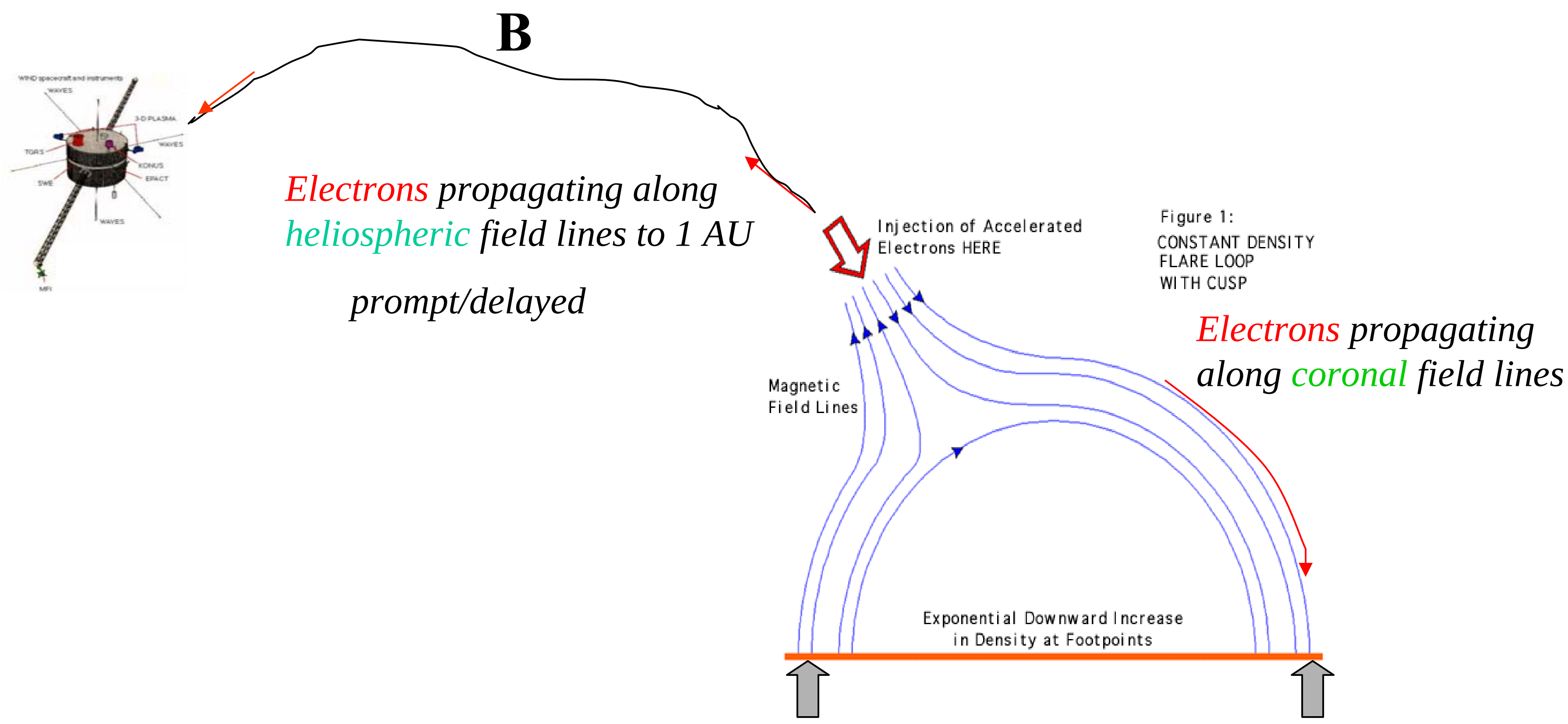
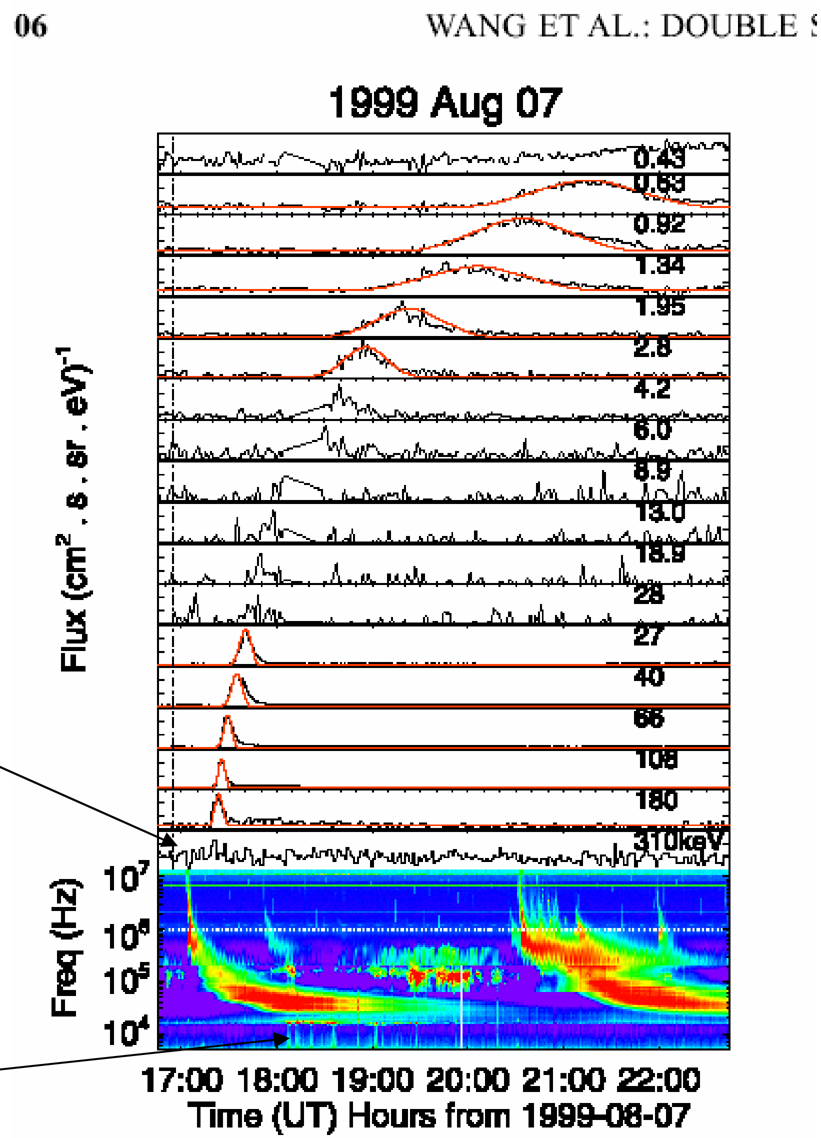
Generally, electrons are tied to the magnetic field; energization requires violation of one or more of the adiabatic invariants.

Flare/Heliosphere Configuration



A. Impulsive electrons – delayed electrons



"Subtracted" type III onset

Langmuir

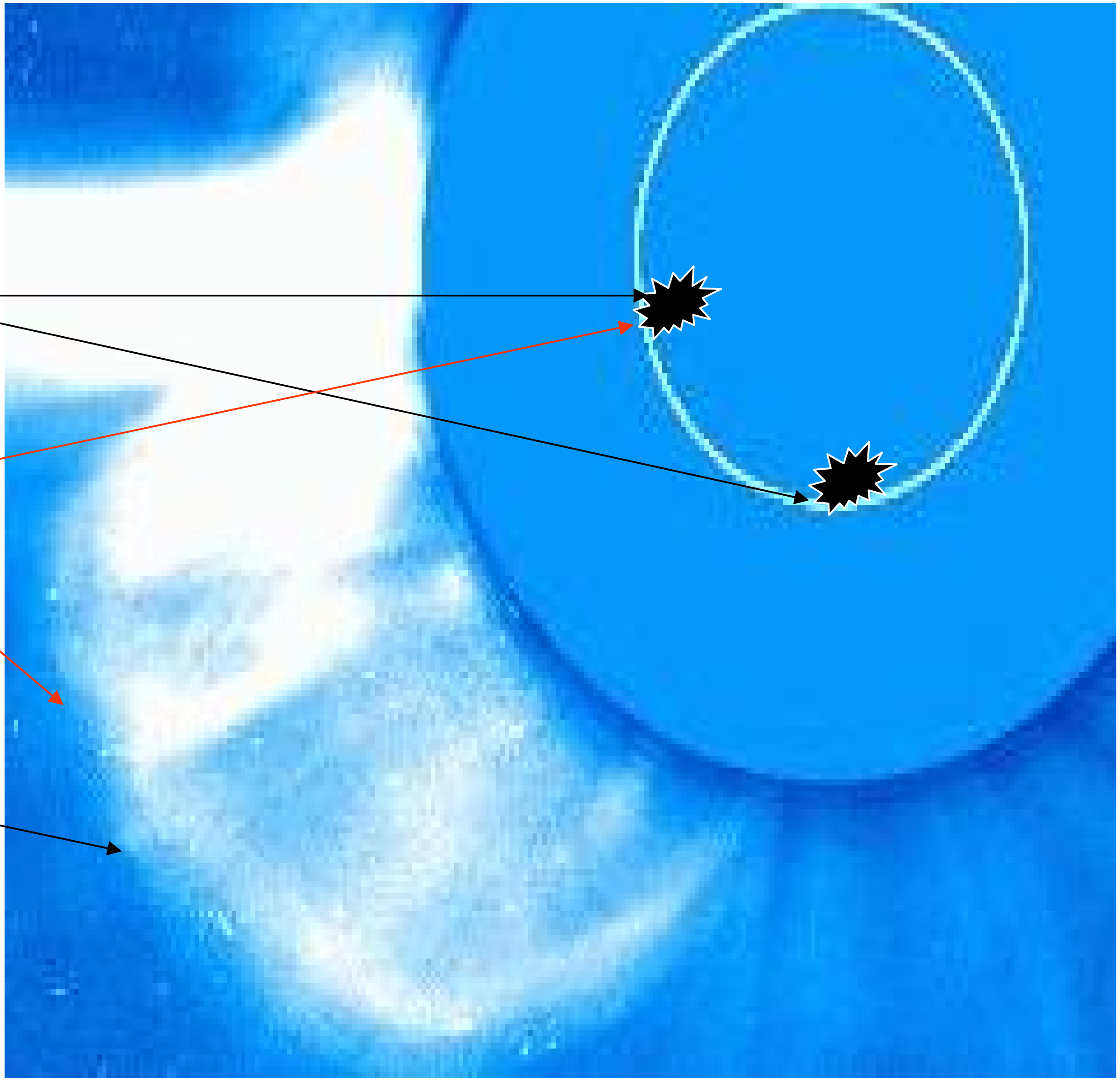
Double injection?

CME: 10^{15} g plasma; supersonic propagation

100s MHz Radio signatures

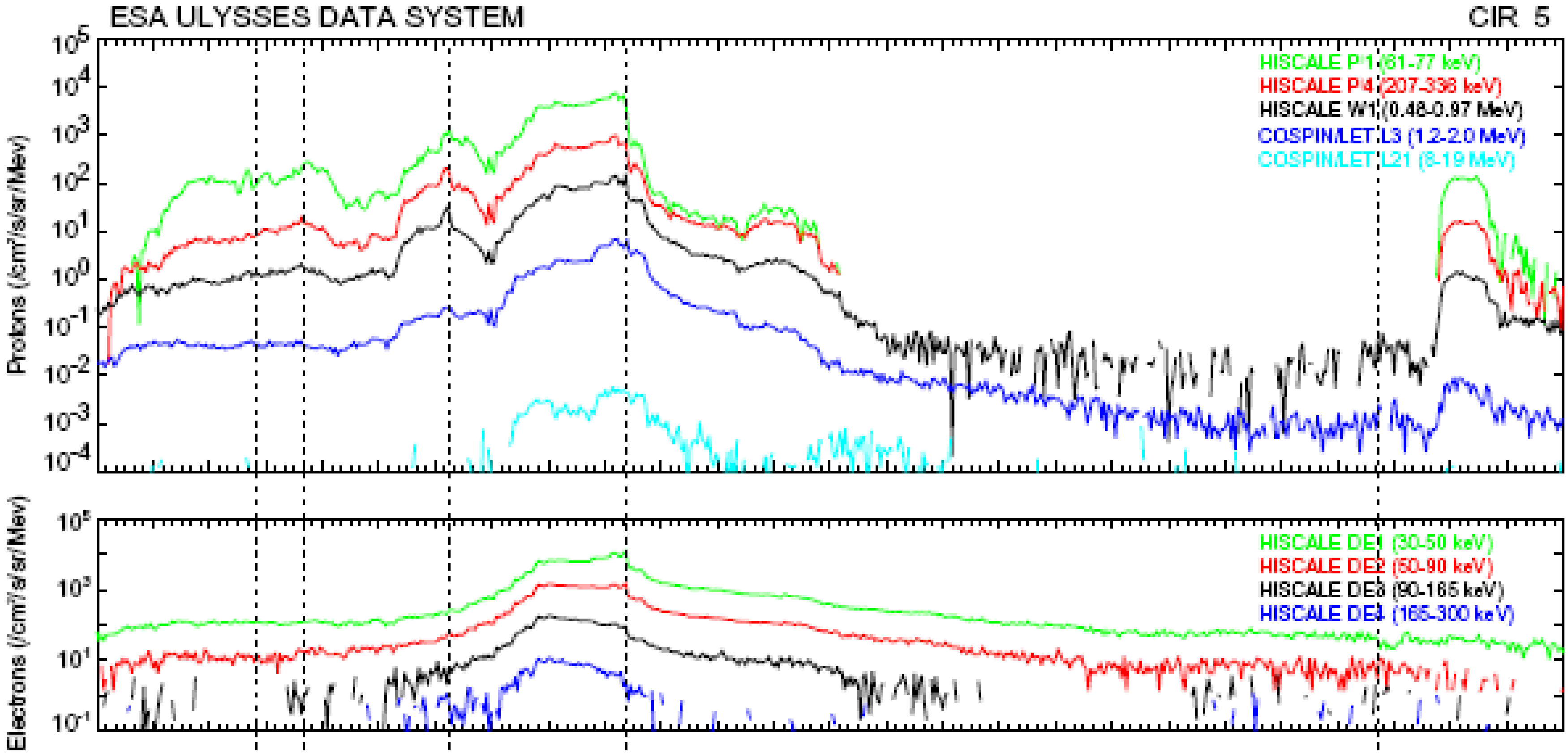
Acceleration Sites?

Shock related Type II signature

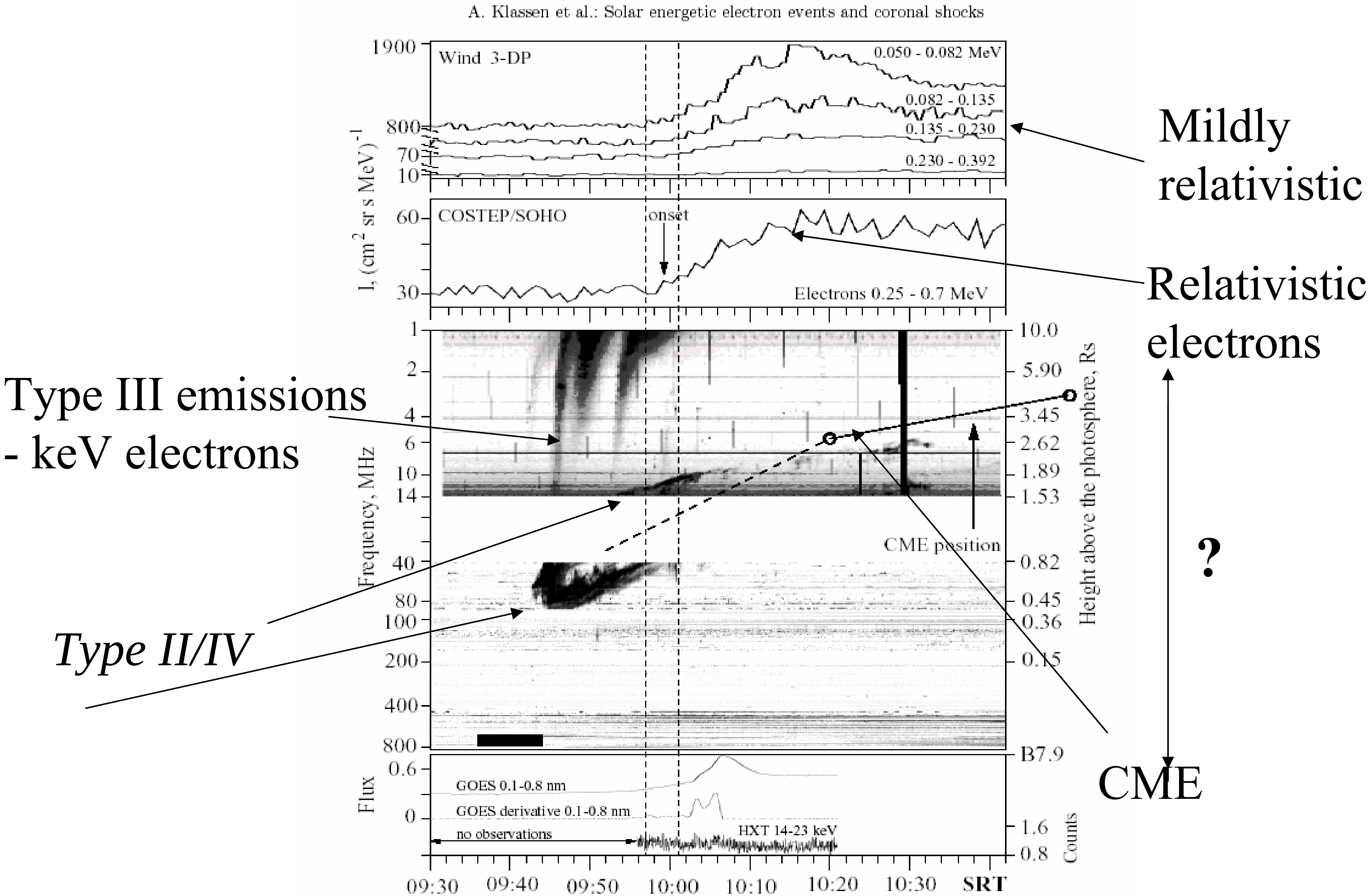


Rare CIR shock electron energization – 300keV

G. Mann et al.: On electron acceleration at CIR related shock waves



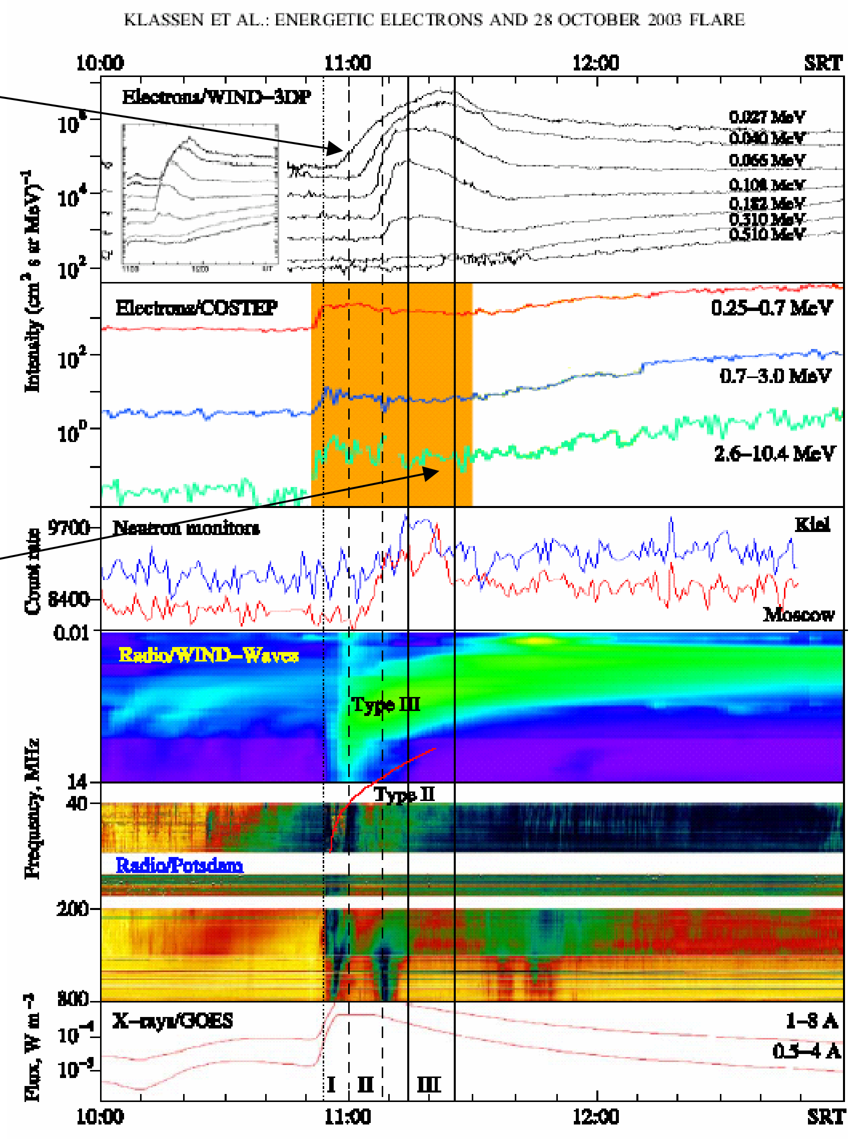
B. Relativistic solar electrons - correlated with CME shock?



Energetic electrons – delayed 17 minutes after type III, type II

Impulsive

Gradual



Distinct delay between Type III and energetic electron injections

Post-flare, post-CME: Gradual electrons

Heliospheric Signatures

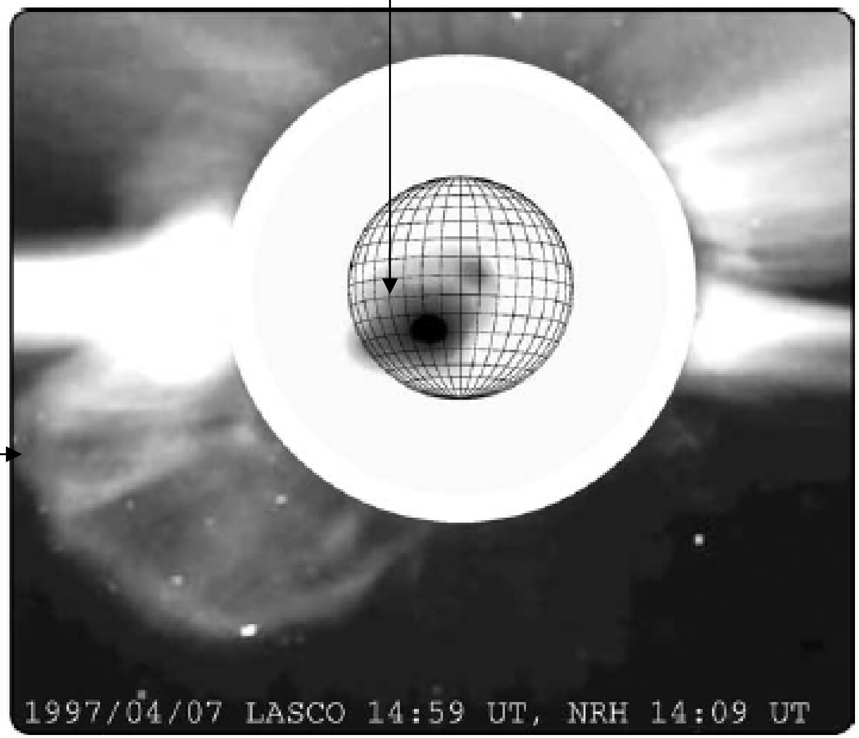
Relation between coronal and IP perturbations

164 MHz NRH images

Injection of electrons into heliosphere

LASCO/SOHO

CME

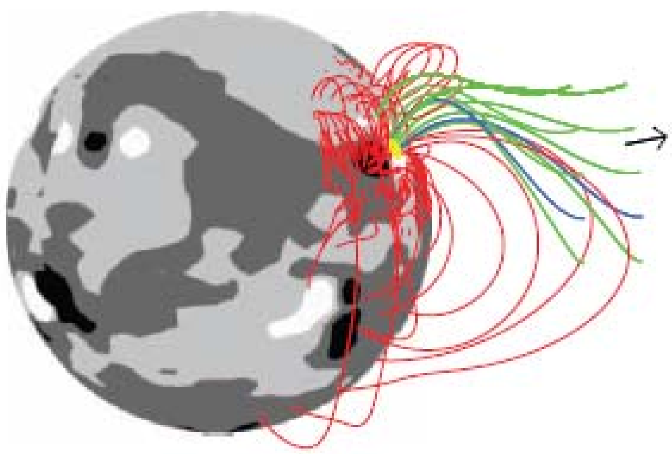


Maia, 2001

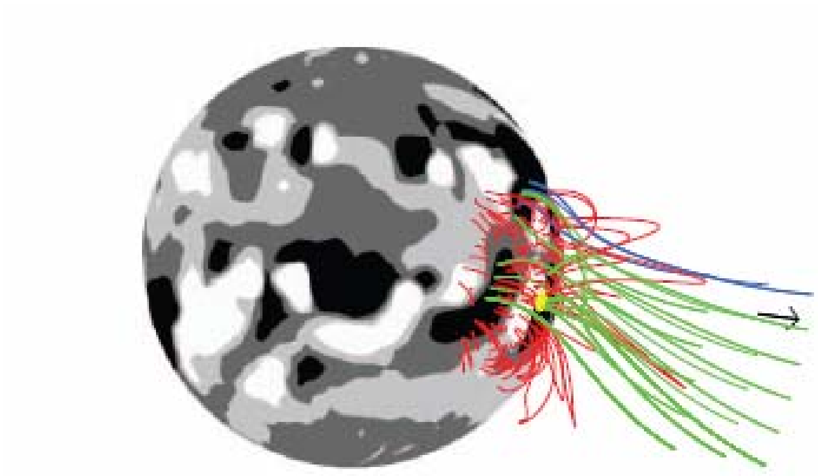
Energization - occurs behind the CME?

Wang, 2006

Post CME reconstruction



(a) 1997 NOVEMBER 24



(b) 2000 MARCH 7

Yellow – flare site

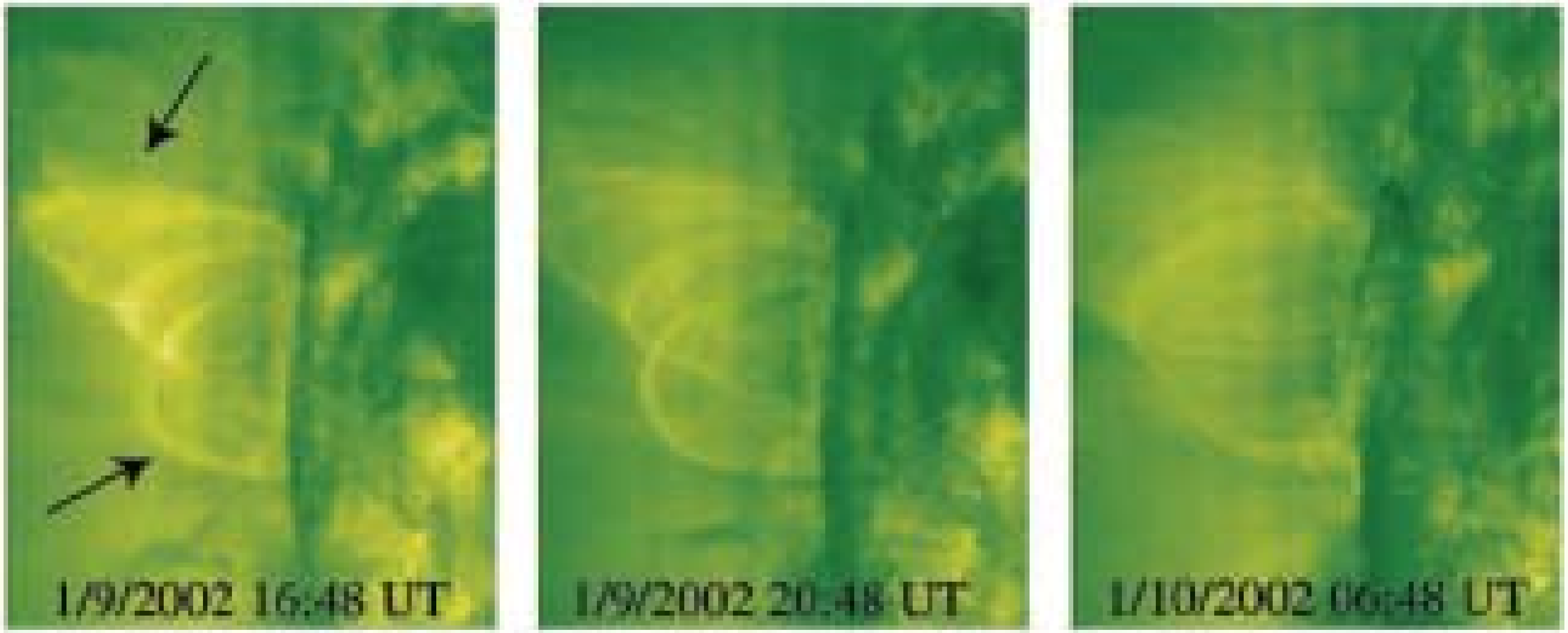
Black arrow – CME direction

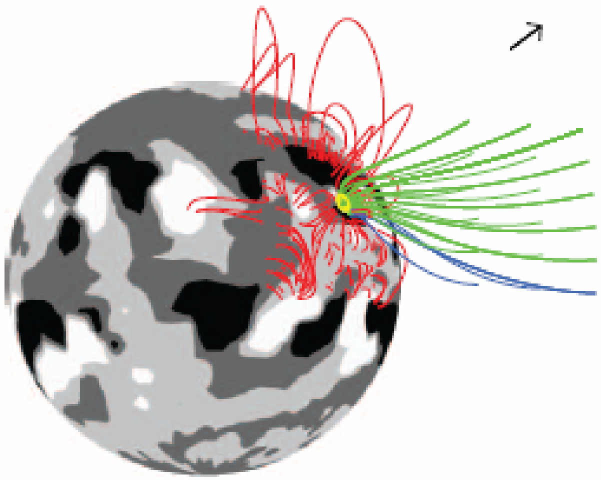
Red – closed (stretched) magnetic field lines

Blue - open, in ecliptic plane

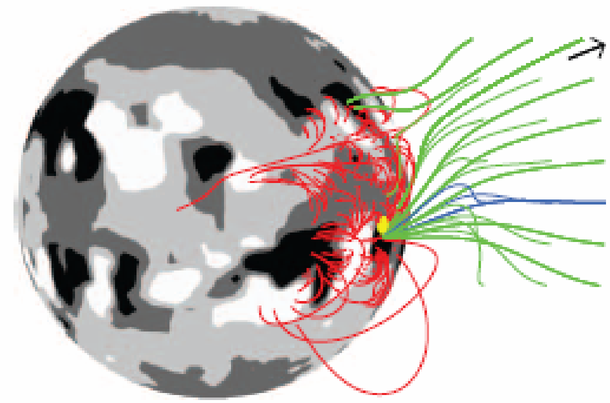
green – open, non-ecliptic

Post CME loops *Ko, 2003*

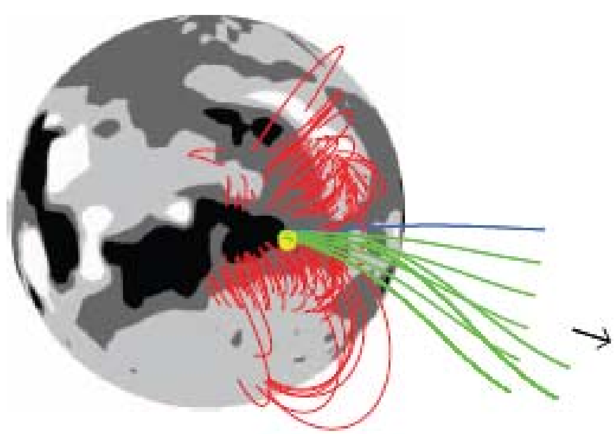




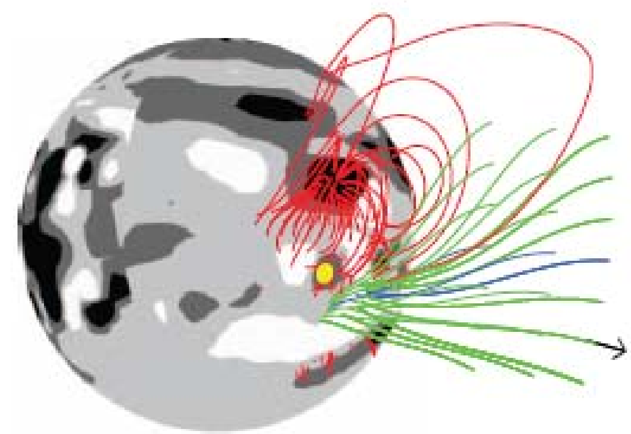
(c) 2000 MAY 1



(d) 2000 JUNE 4



(e) 2003 MARCH 2



(f) 2003 MARCH 17

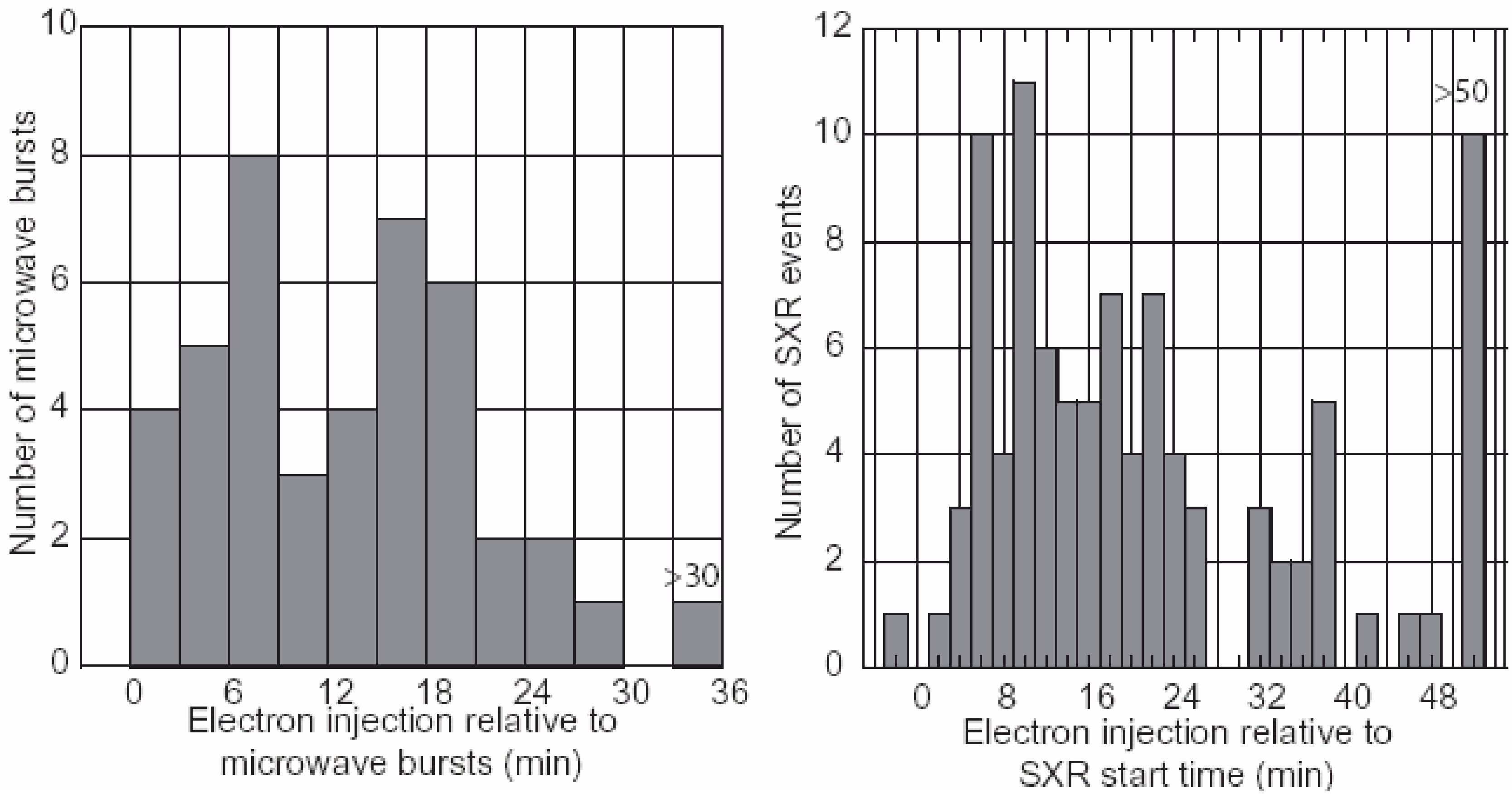
Timing of CME propagation, electromagnetic emissions and energetic electrons observations.

Is there a delay between the onset of the X-ray, gyro-synchrotron, electromagnetic

type III emissions and the inferred delayed electron “release” time?

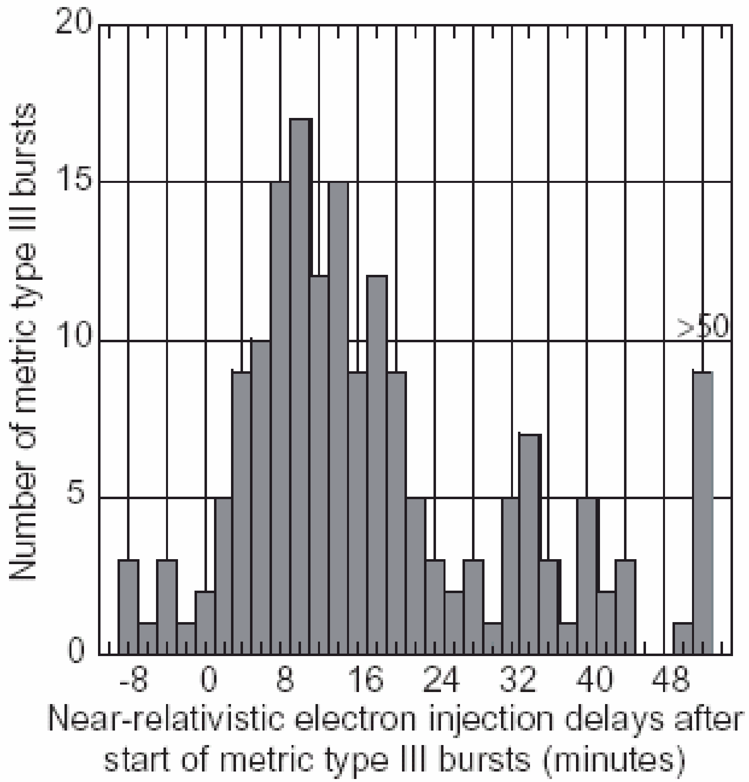
Are electrons at different energies ejected simultaneously?

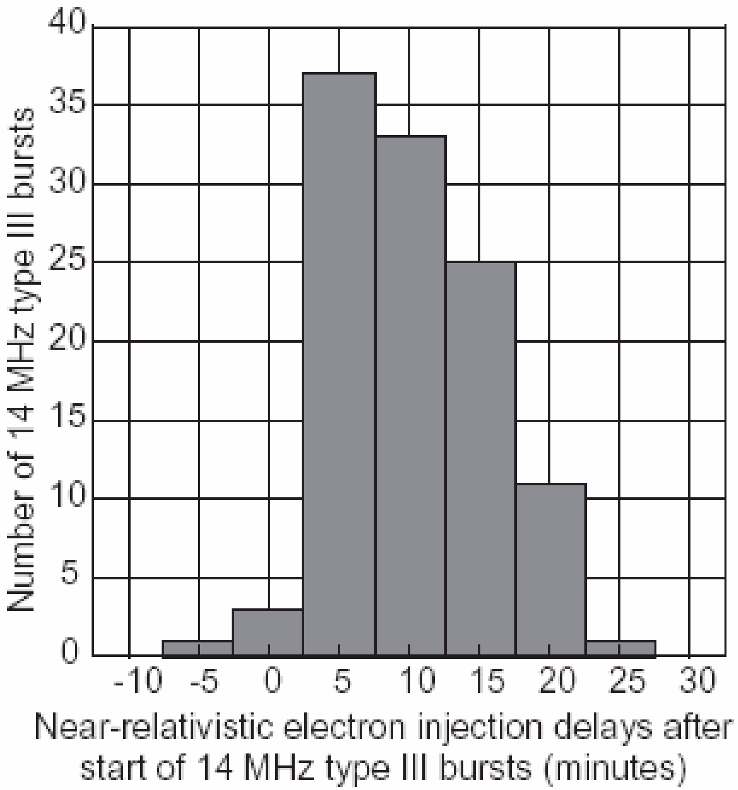
(Mildly) relativistic fluxes are delayed vs Microwave/hard X rays and soft X rays



Haggerty & Roelof

(Mildly) relativistic electron fluxes are delayed vs low energy type III fluxes





Energetic Electrons - Observations

The delayed relativistic electrons are observed in conjunction with an uplift of coronal transient (CME).

They are not correlated to type III emissions.

They are not correlated to X-ray emissions.

They are correlated to NRH emissions.

Physical process – forms relativistic electrons

Statistical process - determines their distribution

Bootstrap Energization

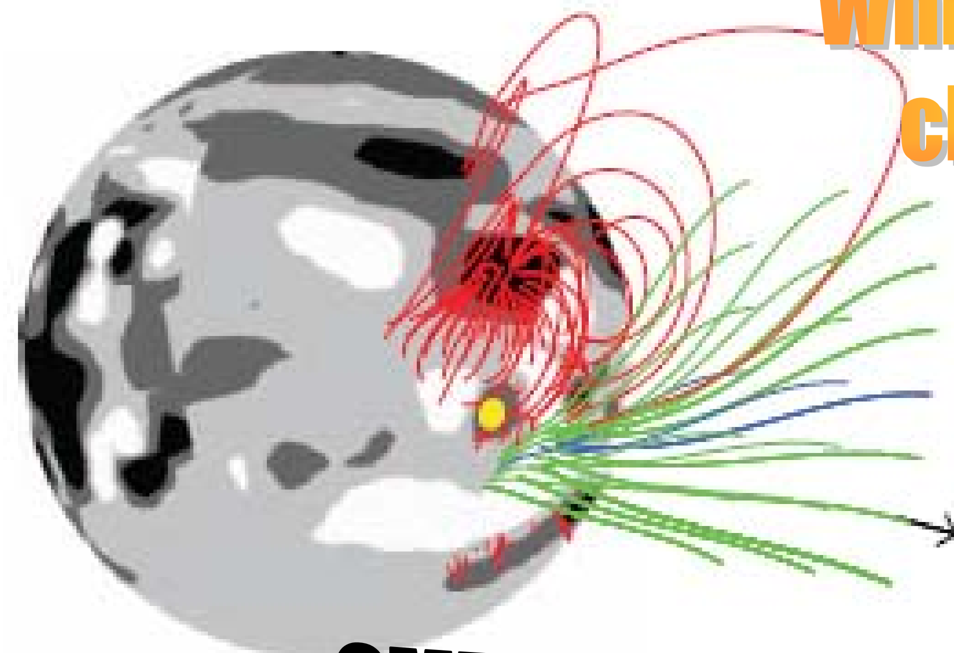
Solar Scenario

Injection of ~10 keV-50 keV anisotropic electron distribution due to a distant reconfiguration behind CME; these anisotropic distributions excite whistler waves which diffuse in pitch angle the low energy electrons while energizing the tail of the electron population. CME plays role in opening a venue to the IP medium.

The low energy electrons transfer energy to the high energy electrons while diffusing in pitch angle.

Foot-points Radio emissions

Whistlers Interact on closed field lines



CME propagates along the arrow

(f) 2003 MARCH 17

Extragalactic jets- electron signature

AGN radiation - accretion on a massive black hole, synchrotron emissions over 100s k-psec.

Electron lifetime in jets

Lifetimes short compared to extent of jets => additional acceleration required.

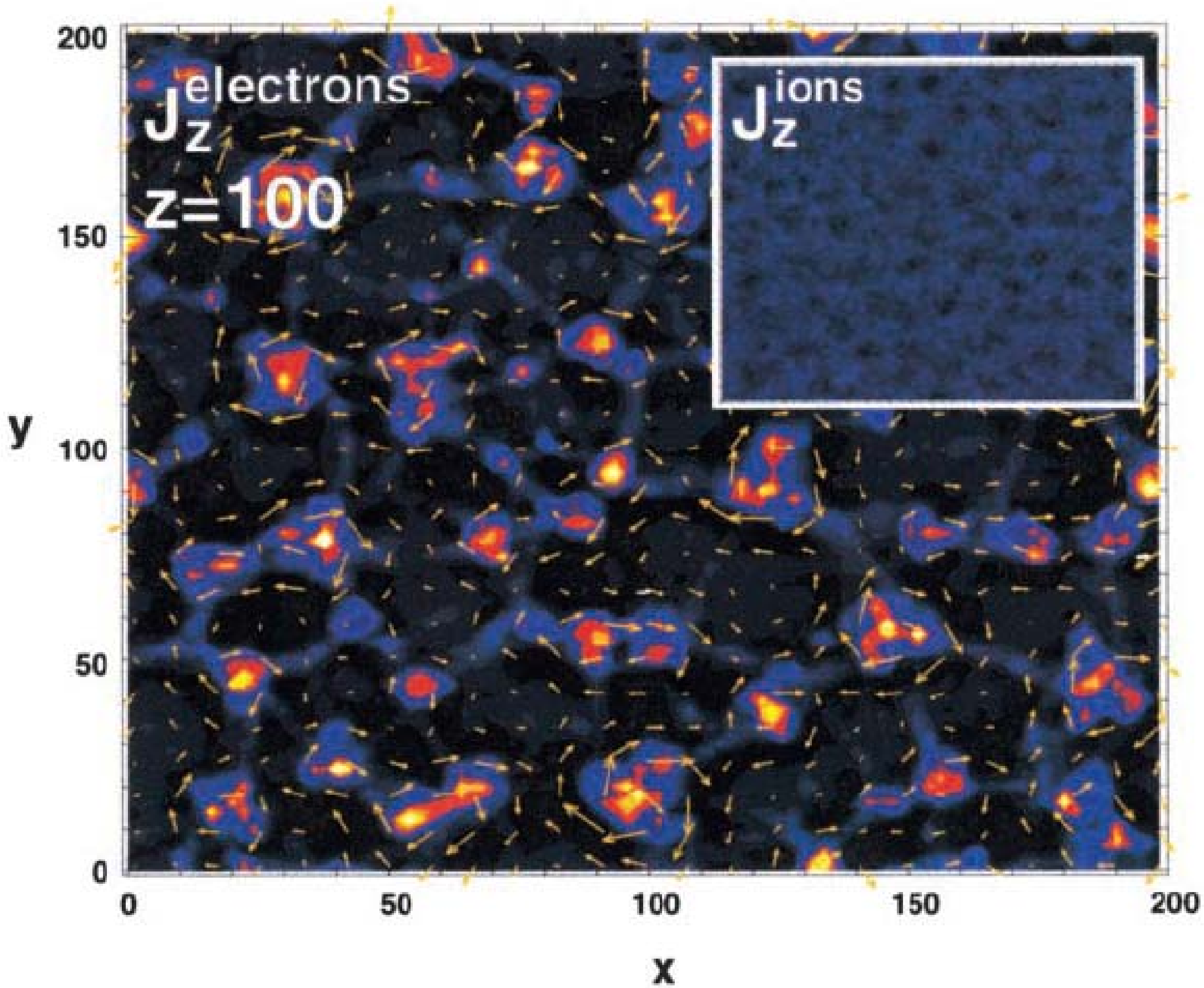
Direct synchrotron radiation in a homogeneous magnetic field does not confirm the observation;

jet spectra indicate unusual radio emission and UV flattening – requiring a significant

small-scale inhomogeneous magnetic field,

which modifies the synchrotron spectrum.

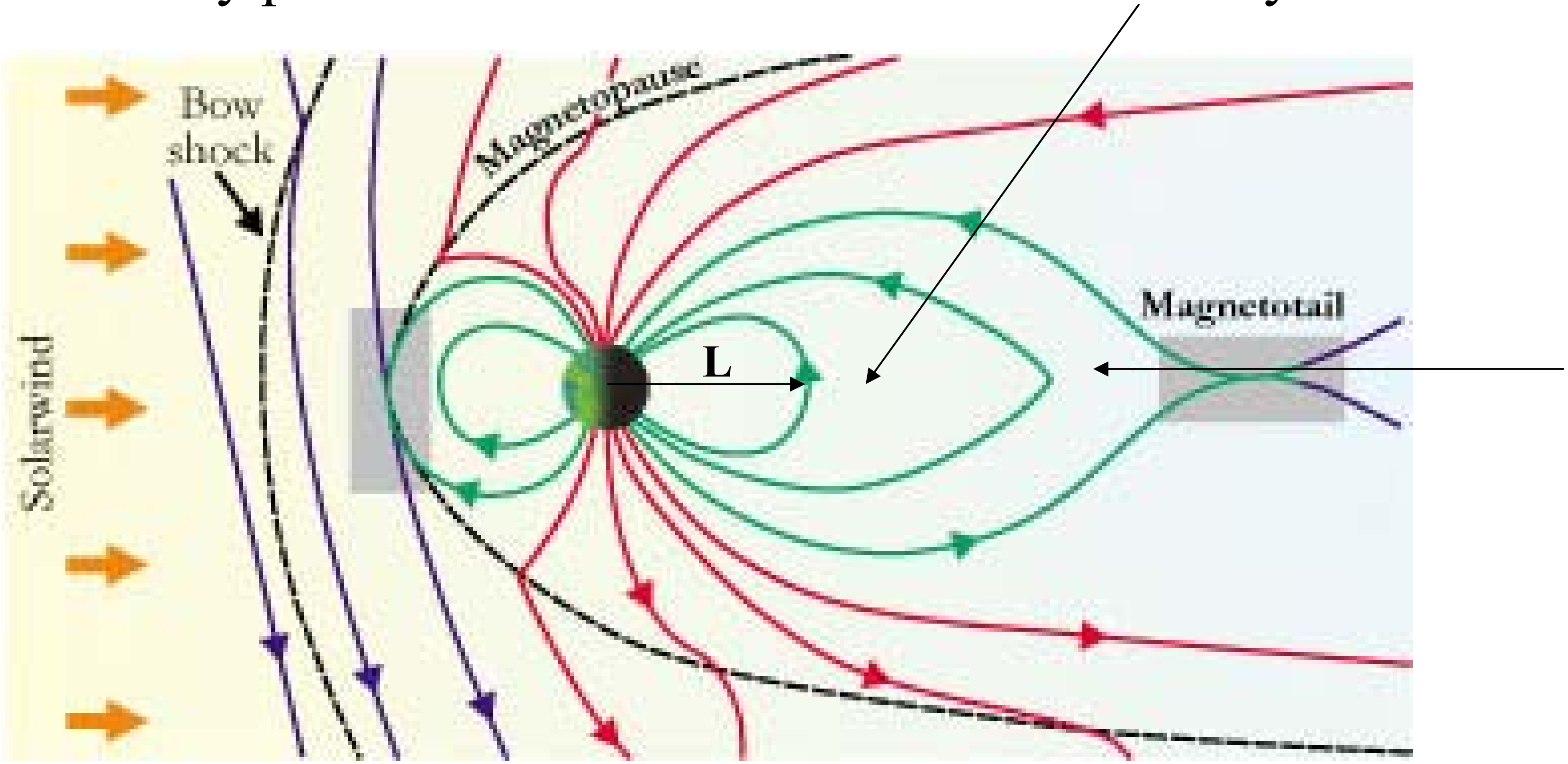
Simulation - Formation of localized magnetic fields (Frederickson, 2003)



Cross section of longitudinal current

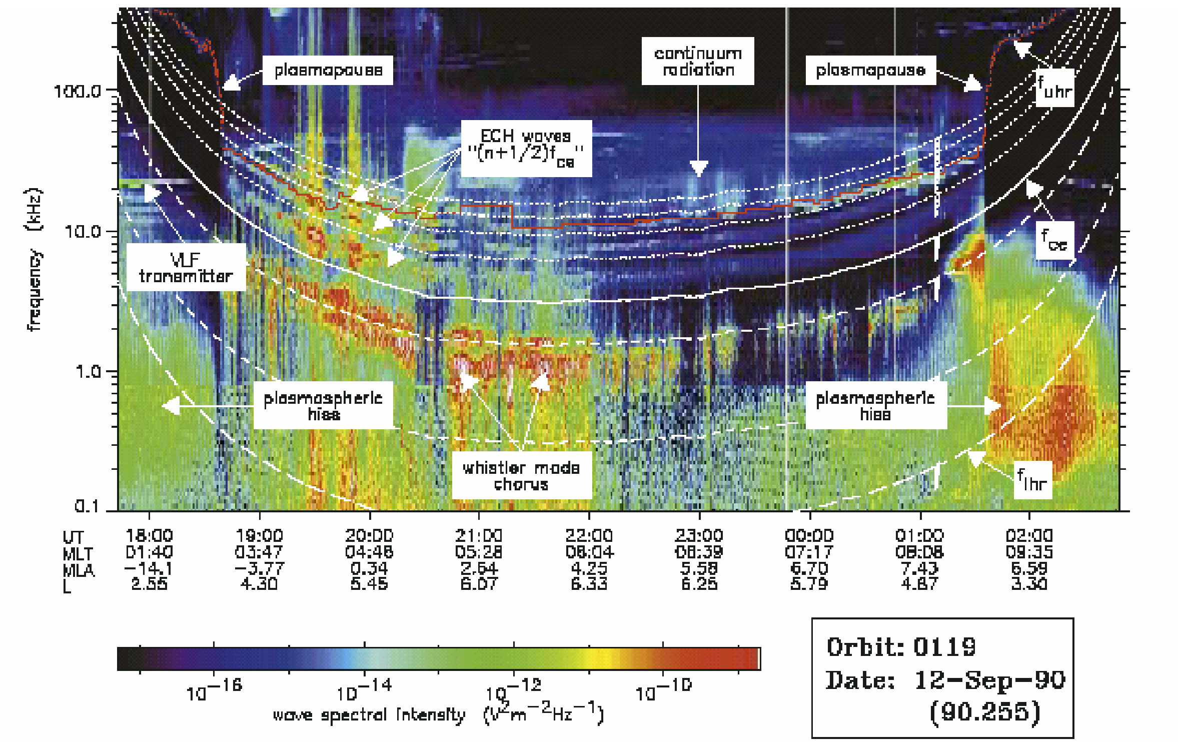
Active Magnetosphere – Electron Signatures

Fluxes of relativistic electrons increase often in the storm recovery phase due to substantial sub-storm activity



Injection of low energy electrons - substorm reconfiguration

Terrestrial Substorm injection: Nonisotropic low energy electrons + Whistler Waves

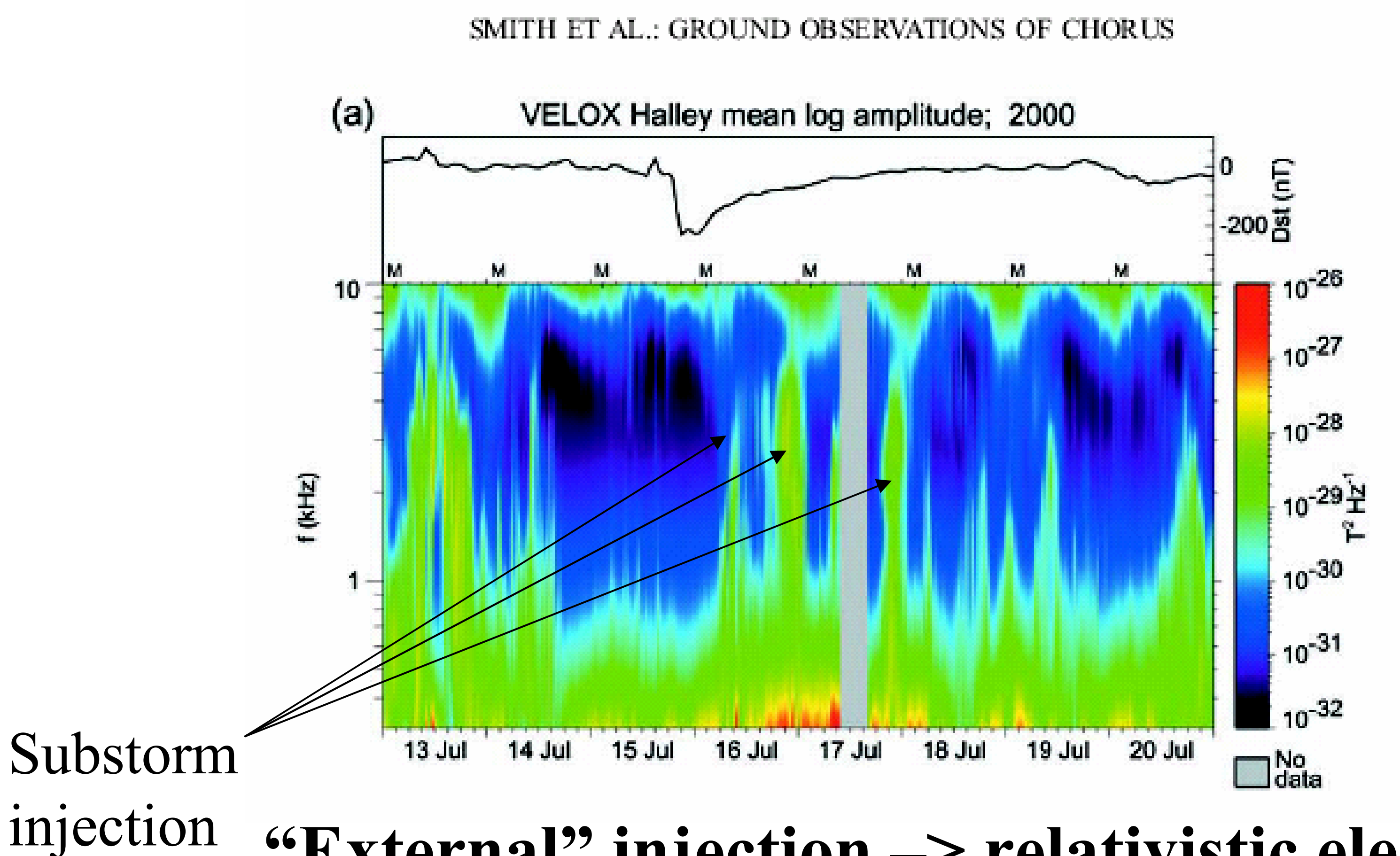


(Meredith)

Strong correlation between kHz oscillations and relativistic electron enhancement

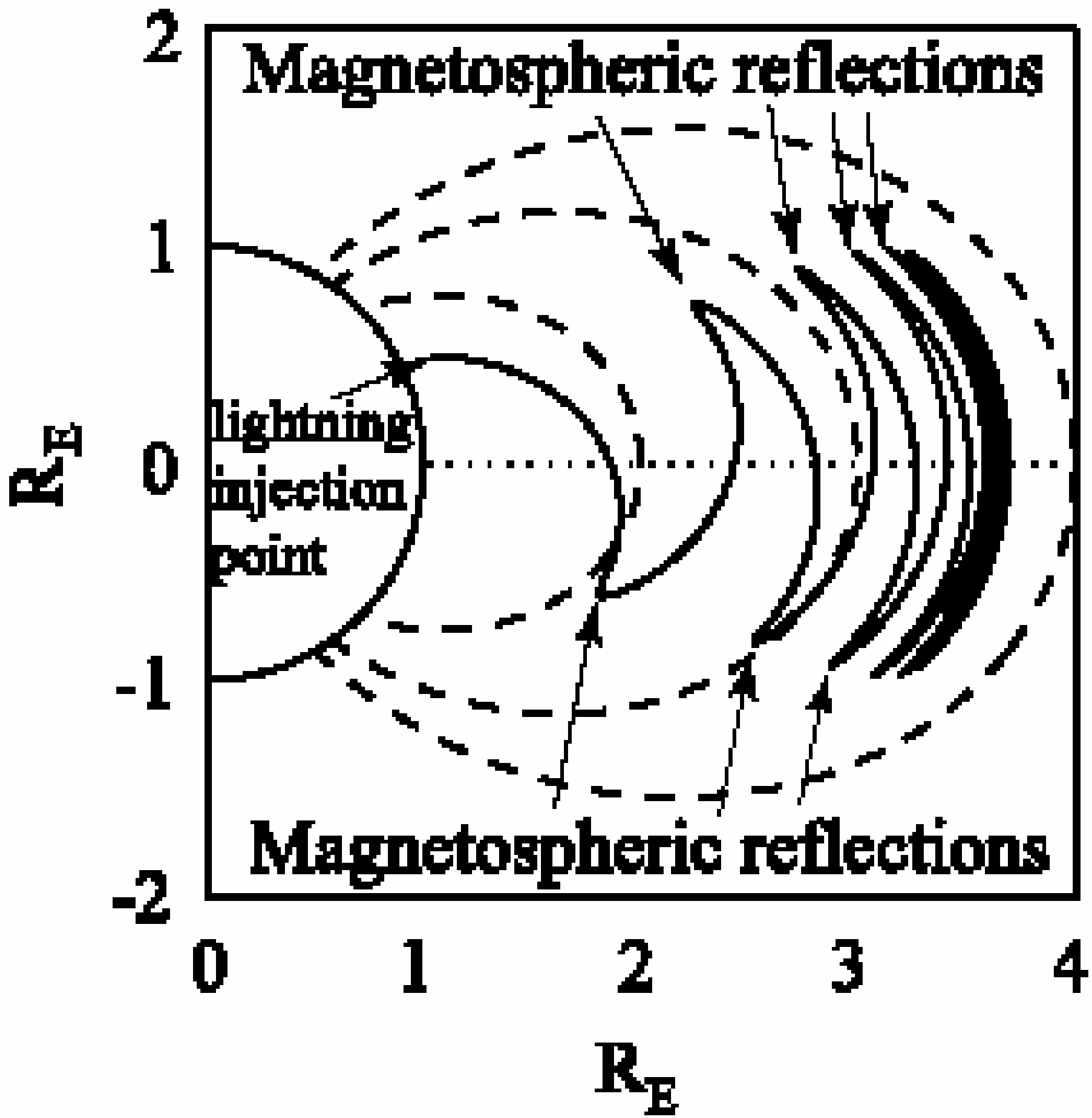
Waves observed on ground

Signatures on ground of chorus waves: strongly related to geomagnetic substorm, energization of electrons and precipitation (loss of the radiation belts) in the recovery phase of the magnetic storm



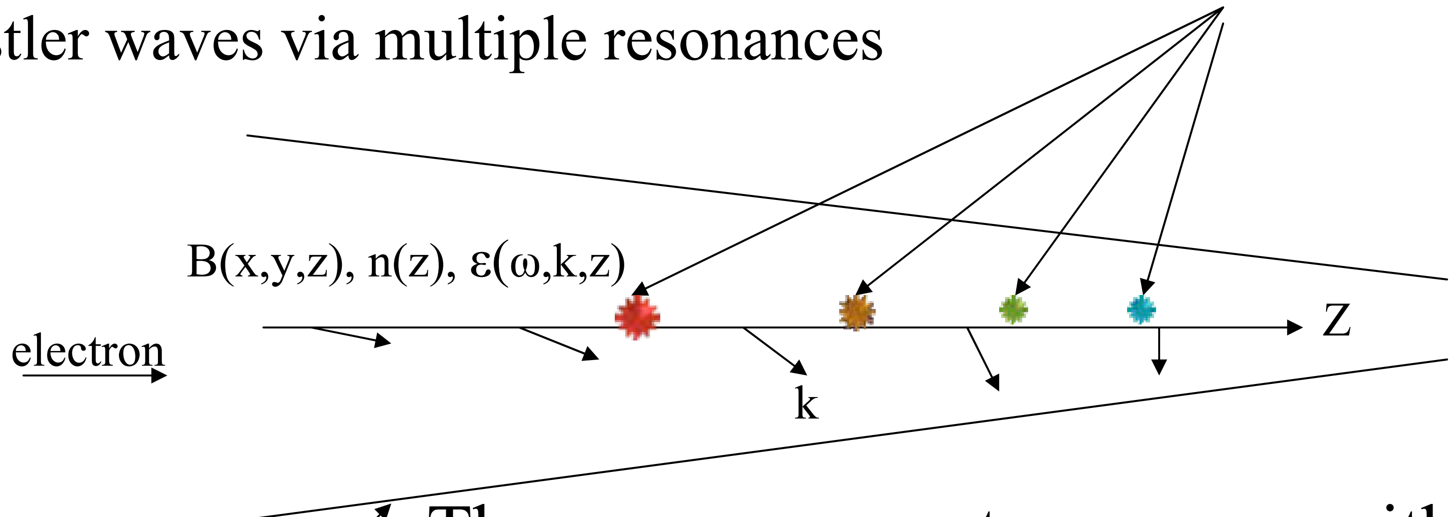
“External” injection –> relativistic electrons

Whistler ray trajectories – Bortnik et al 2004



Geometric optics for whistler propagation

Electrons gyrate along the field line and interact with the oblique whistler waves via multiple resonances



Inhomogeneous magnetic field

The wave propagates as a ray with a changing wavenumber due to varying density/magnetic field;

an electron interacts with the wave via numerous resonances along its path

$$\mathbf{k_{||} v_{||} - \omega = n\ \Omega/\gamma}$$

Electron characteristics

$$\delta f(v) \sim J_n(k_\perp \rho) \exp [\, i\, (k_{||}\, z - (\omega - n\Omega/\gamma)t)\,]$$

Resonance: Doppler shifted frequency=n*gyrofrequency/γ

The effect at higher/anomalous harmonics is more pronounced for the more energetic electrons.

Non-isotropic lower energy electrons excite waves which diffusively energize the high energy electrons

Computational Procedure

The background plasma is determined by the background density n(x) and magnetic field **B**(x).

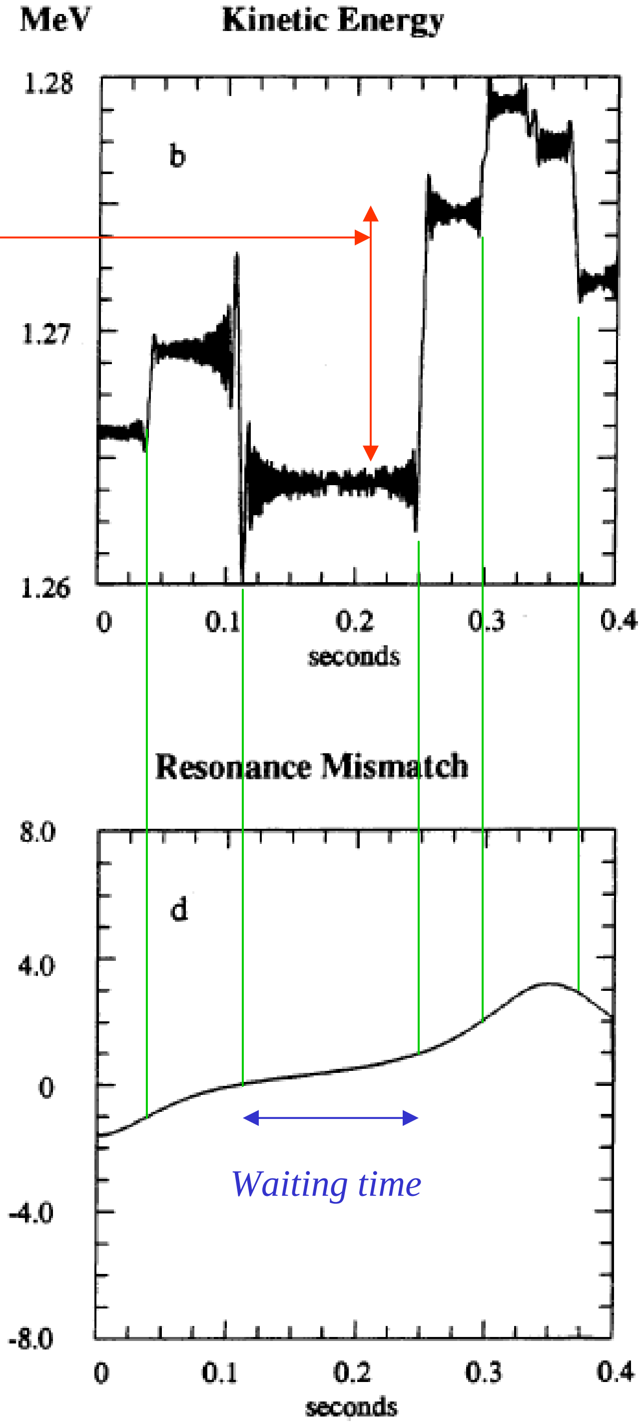
Inhomogeneous field model:

$$B_x(\mathbf{x}) = -B_o\, z\, x / L^2$$

$$B_y(\mathbf{x}) = -B_o\, z\, y / L^2 \qquad \text{div } \mathbf{B}=0$$

$$B_z(\mathbf{x}) = B_o\,(1 + z\, z / L^2)$$

Dispersion relation is solved LOCALLY, at the position of the electron, with the resulting eigenvectors of the electric and magnetic fields.



$$\nu = \frac{\omega - k_{\parallel}(x,t)\ v_{\parallel}(x,t)}{\Omega(x,t)}$$

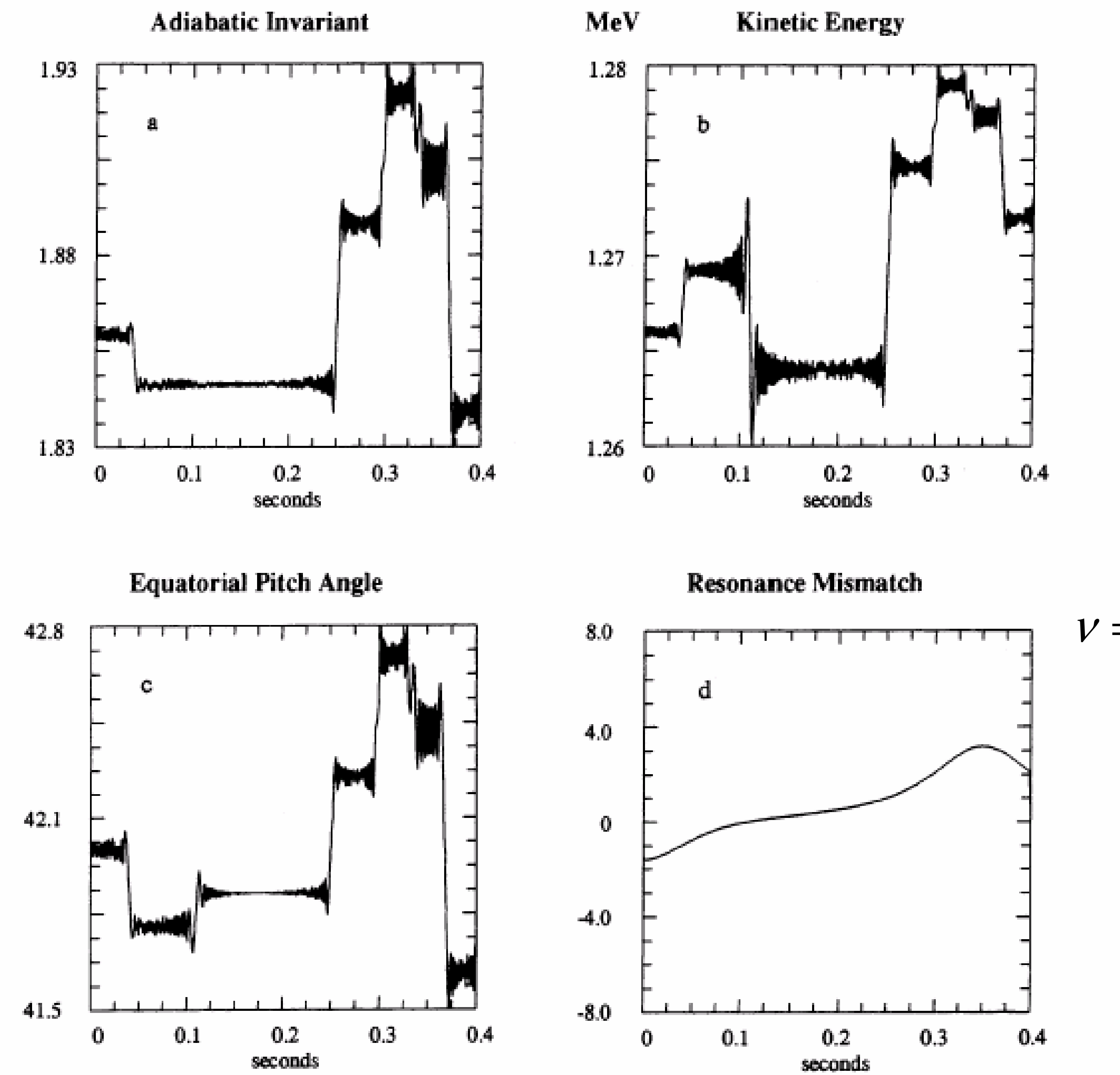
ν=n

The crucial ingredient in the energization stems from the ability of an electron to interact with many wave modes as it propagates/bounces along the inhomogeneous magnetic field.

Non-isotropic lower energy electrons excite waves which diffusively energize the high energy electrons

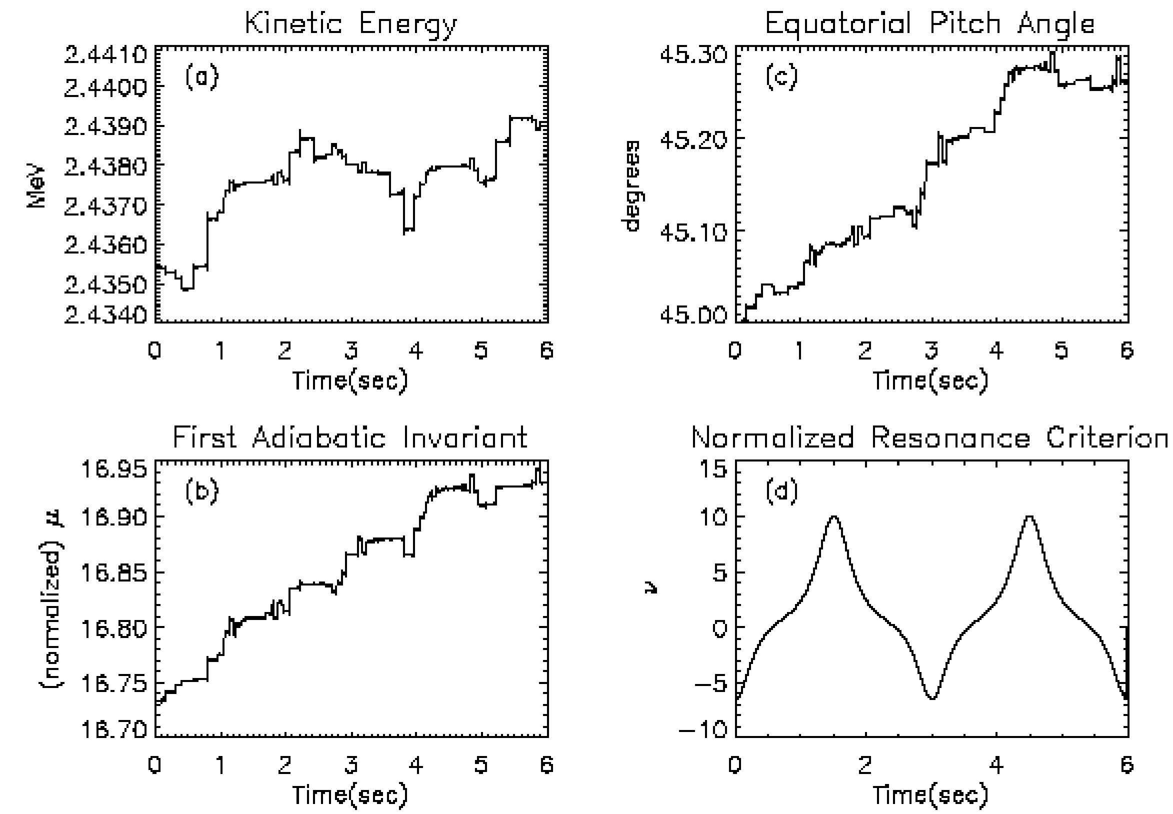
The whistler wave changes its phase velocity along its propagation.

Short time evolution

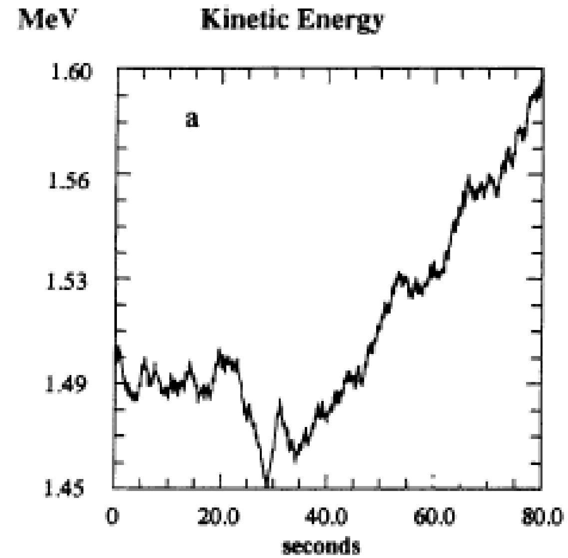


$$\nu = \frac{\omega - k_{\parallel}(x,t)\ v_{\parallel}(x,t)}{\Omega(x,t)/\gamma(x,t)}$$

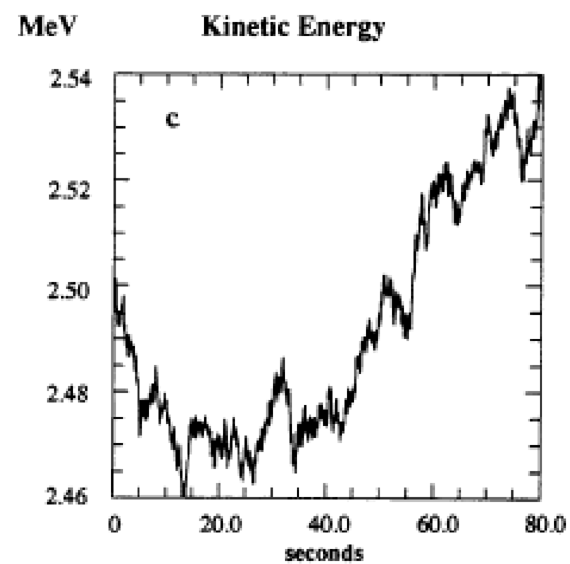
Medium term evolution



Realization of energy modifications - whistler wave interaction



Does the time dependent data describe a Brownian motion?



Each resonant energy change forms a random variable

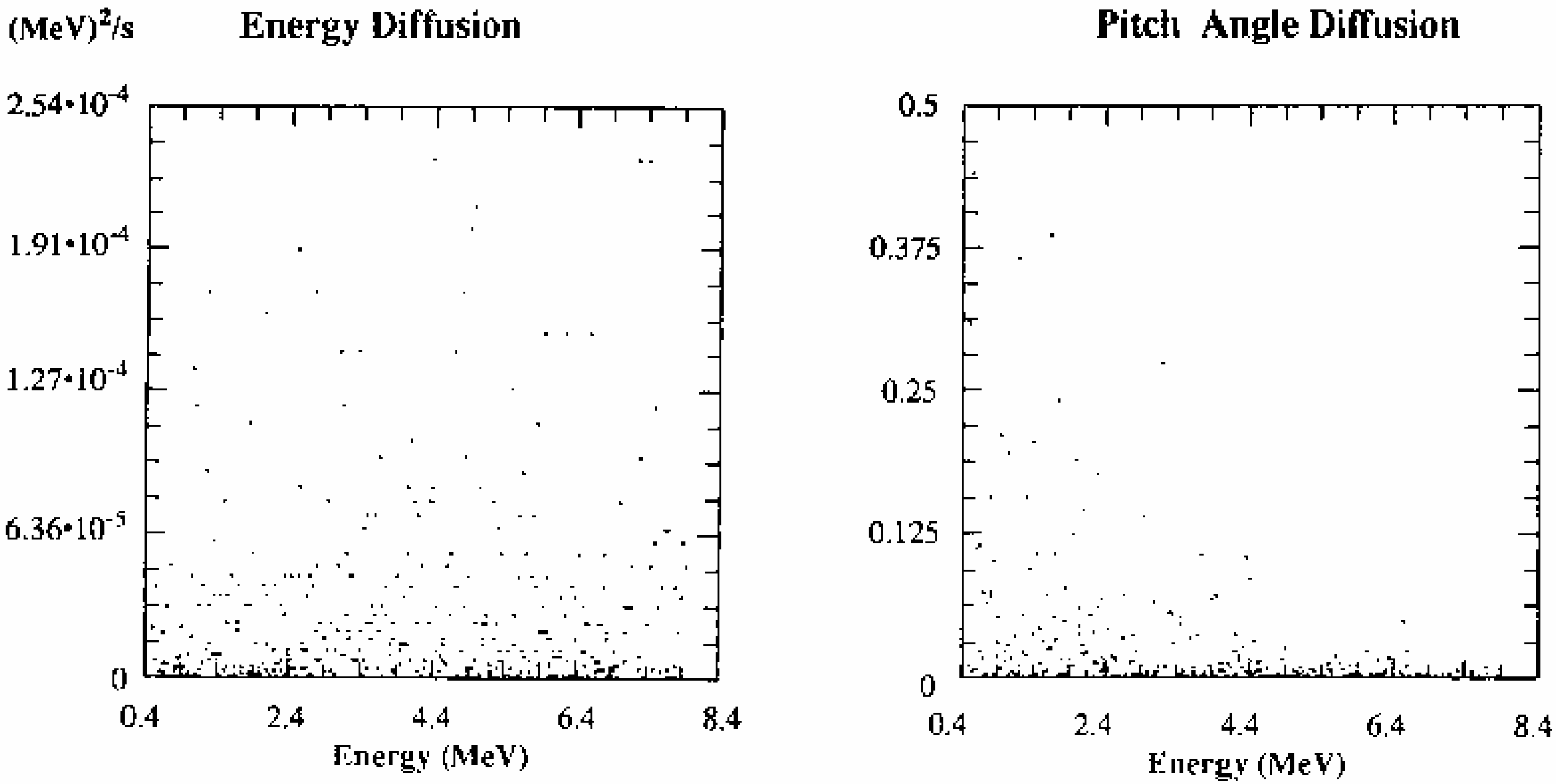


Fig. 3. Diffusion in energy and in pitch angle for several hundreds of electrons as a function of the initial energy

Whistler diffusion time scale increases with electron energy and is much faster than magnetospheric ULF or solar Alfvenic time scale

For 5 mV/m ➔ ➔ 100 keV/ minute

Scenario

Reconfiguration of an inhomogeneous (magnetospheric, solar, astrophysical) magnetic field results in injection of anisotropic (in pitch angle) energy electrons, which emit oblique whistlers and **bootstrap** *their tail. Magnetospheric electrons are accelerated over 10s minutes to MeV energies and are trapped on closed field lines. Solar electrons are accelerated over ~1 minute to MeV energies and reach open field lines due to the propagating CME shock. Astrophysical energization is extremely fast due to the relativistic injection energy. Energization time scale decreases with wave intensity and with the injected electron energy; the process is enhanced accordingly:*

magnetospheric ==> *solar* ==> *astrophysical applications.*

SUMMARY

Solar electrons appear at numerous characteristic forms, relating to several physical processes. Type III and the HXR emitting seem to be well correlated and timed. The delayed, often quasi relativistic, although appearing in conjunction with CME liftoff, are energized behind the magnetically unstable CME via an efficient bootstrap mechanism. Similar process is confirmed at the magnetosphere and may play an important role in astrophysical plasmas.