Particle Acceleration in Solar Flares and Escape into Interplanetary Space

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``Solar Sources of Impulsive Solar Energetic Particle Events"

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We review the physics of particle acceleration and kinematics under the particular aspect of their escape and propagation into interplanetary space. High-energetic particles associated with solar flares or CMEs can be generated (1) in the coronal flare site with subsequent escape into interplanetary space, or (2) in CME-associated shocks in interplanetary space itself. Here we consider only the first option.

Contents of talk :

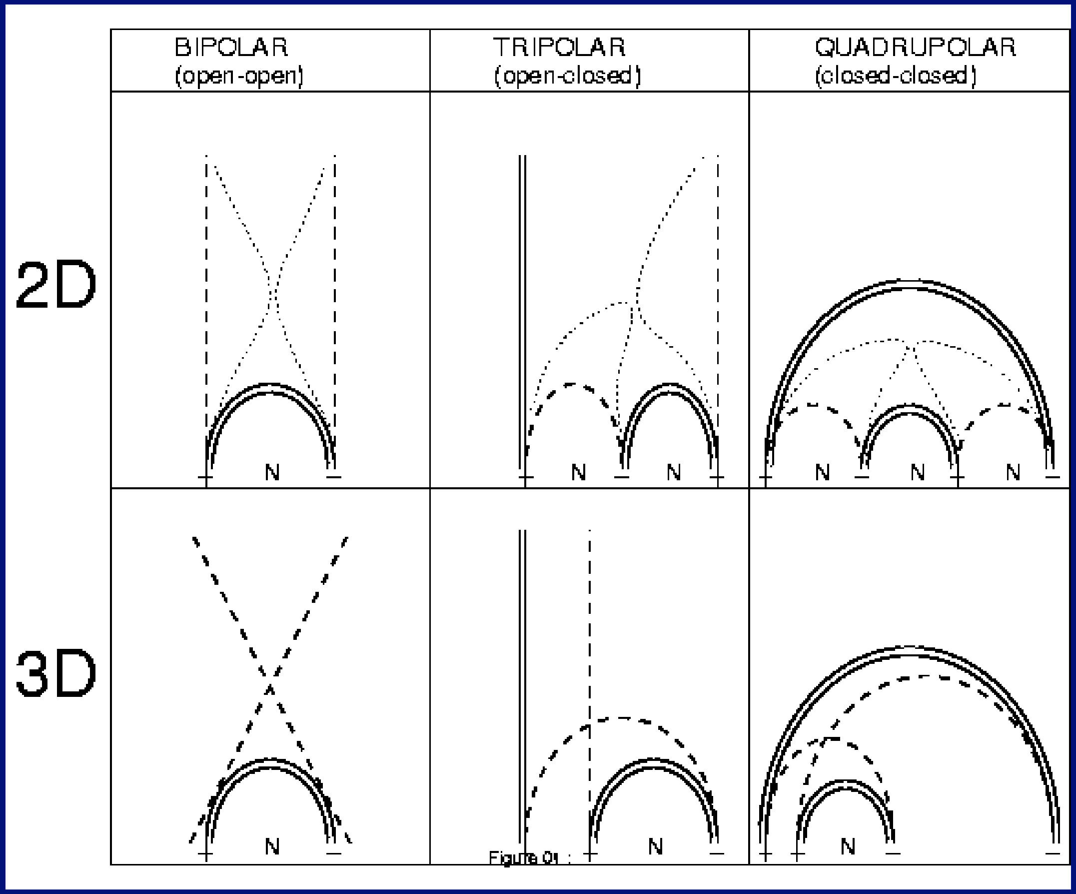
Particle Acceleration in Solar Flares and Escape into Interplanetary Space

1) Magnetic Topology of Acceleration Region
2) Altitude of Acceleration Region
3) Physics of Acceleration
4) Upward vs. Downward Acceleration
5) Access to Interplanetary Space

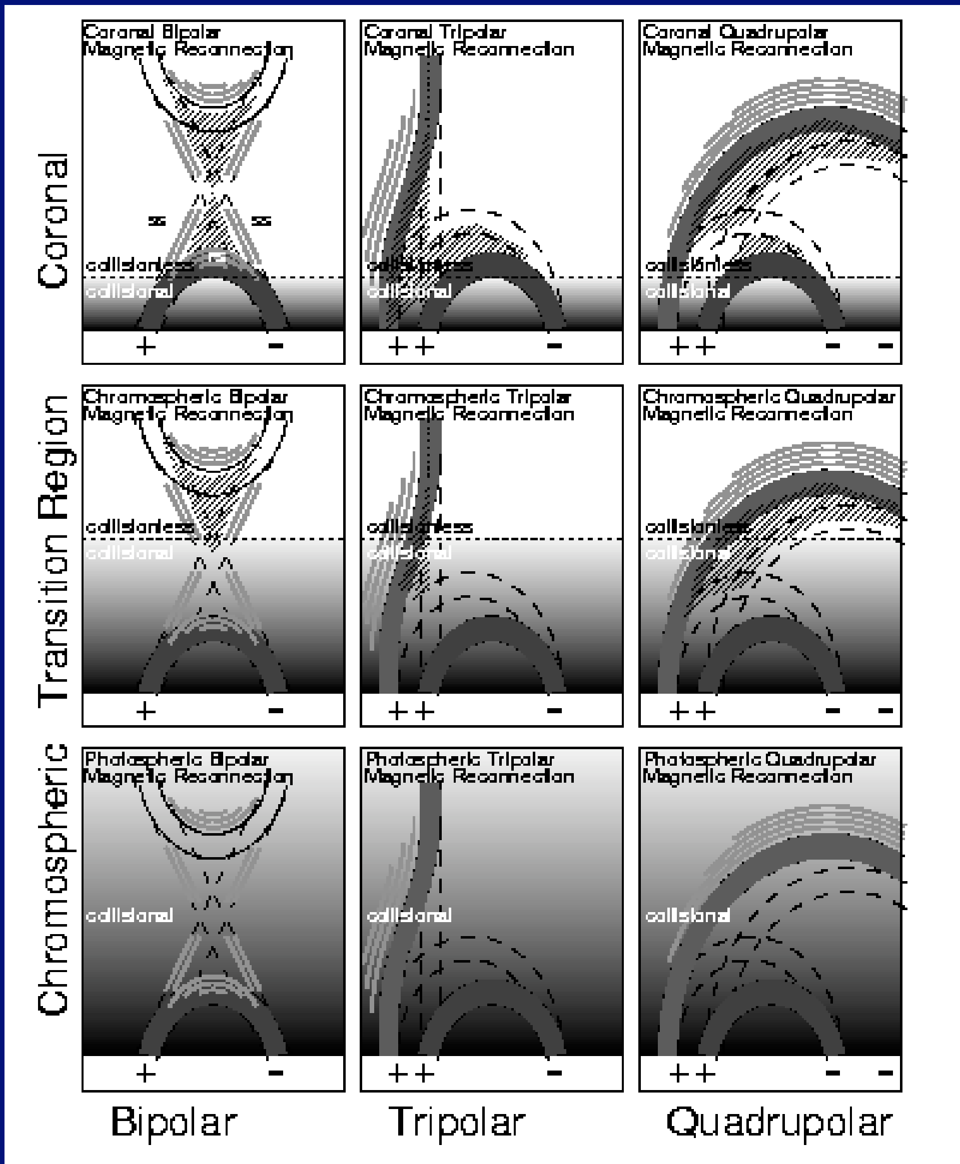
Refs : a) Aschwanden M.J. 2002, Space Science Reviews, Vol. 101, p.1-227
"Particle Acceleration and Kinematics in Solar Flares"
b) Aschwanden M.J. 2004, PRAXIS Publishing, Chichester, UK
& Springer, Berlin, 850p, (in press)
"Physics of the Solar Corona. An Introduction"

Books online: http://www.lmsal.com/~aschwand/

1) MAGNETIC TOPOLOGY OF ACCELERATION REGION



The basic configurations of X-type magentic reconnection topologies in solar flares entail combinations between open and closed field lines : bipolar, tripolar, and quadrupolar cases, in 2D and 3D.



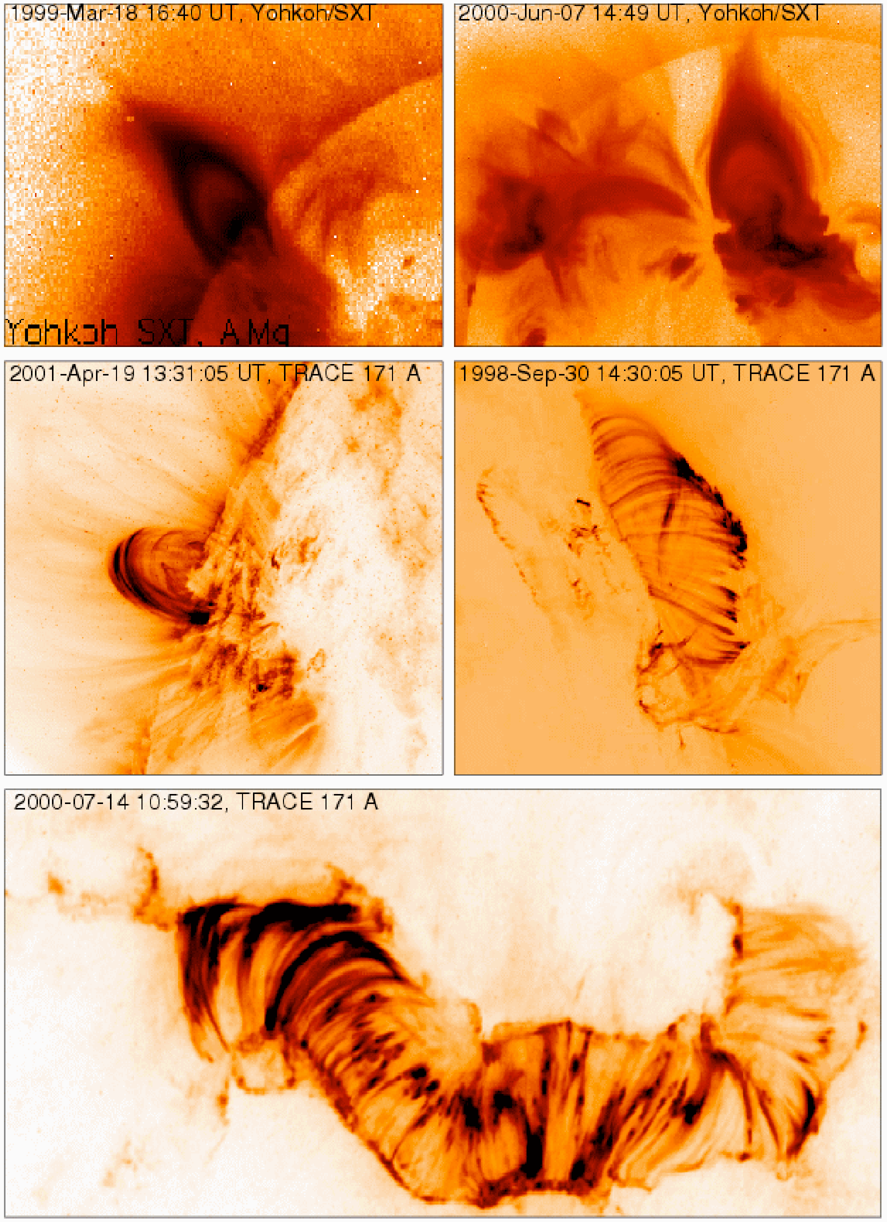
Force on accelerated particles :

$$m\frac{dv}{dt} = q\left(E + \frac{v}{c} \times B\right)$$

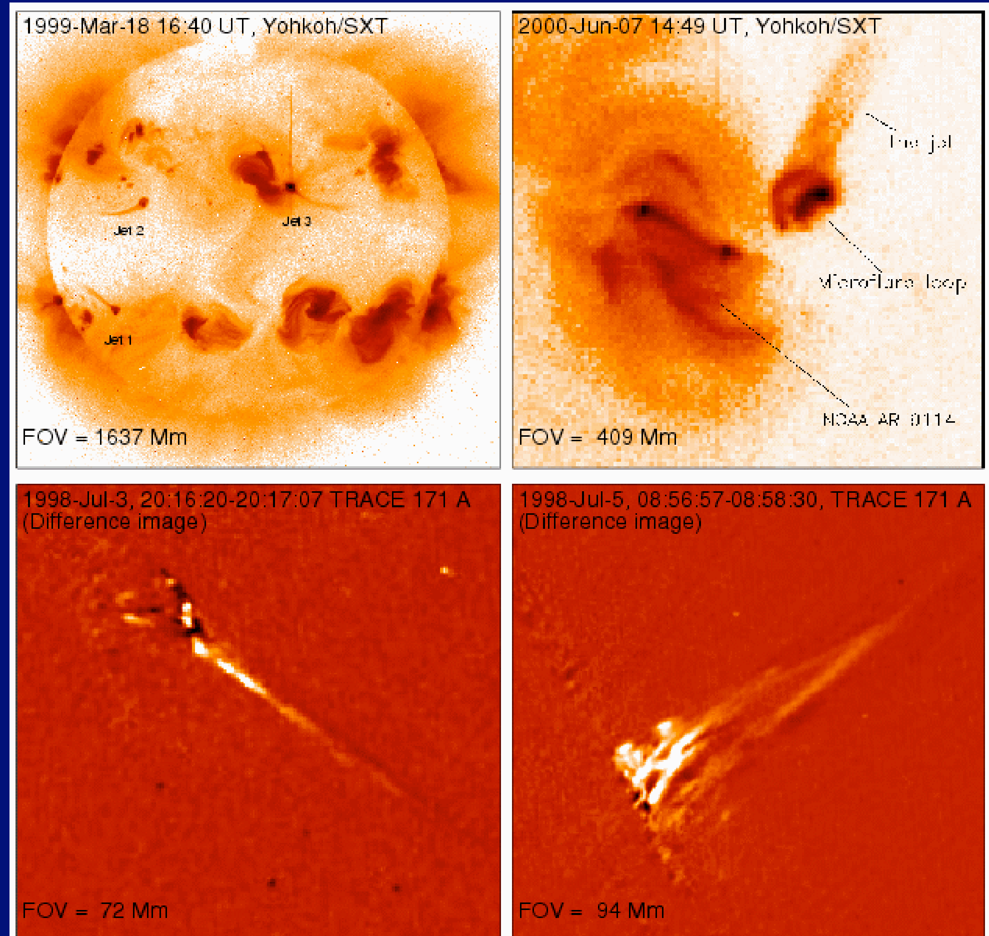
Energy gain from shortened (relaxed) force-free field line:

$$\Delta W = \int_{cusp} [B^2(s)/8\pi]ds - \int_{force-free} [B^2(s)/8\pi]ds$$

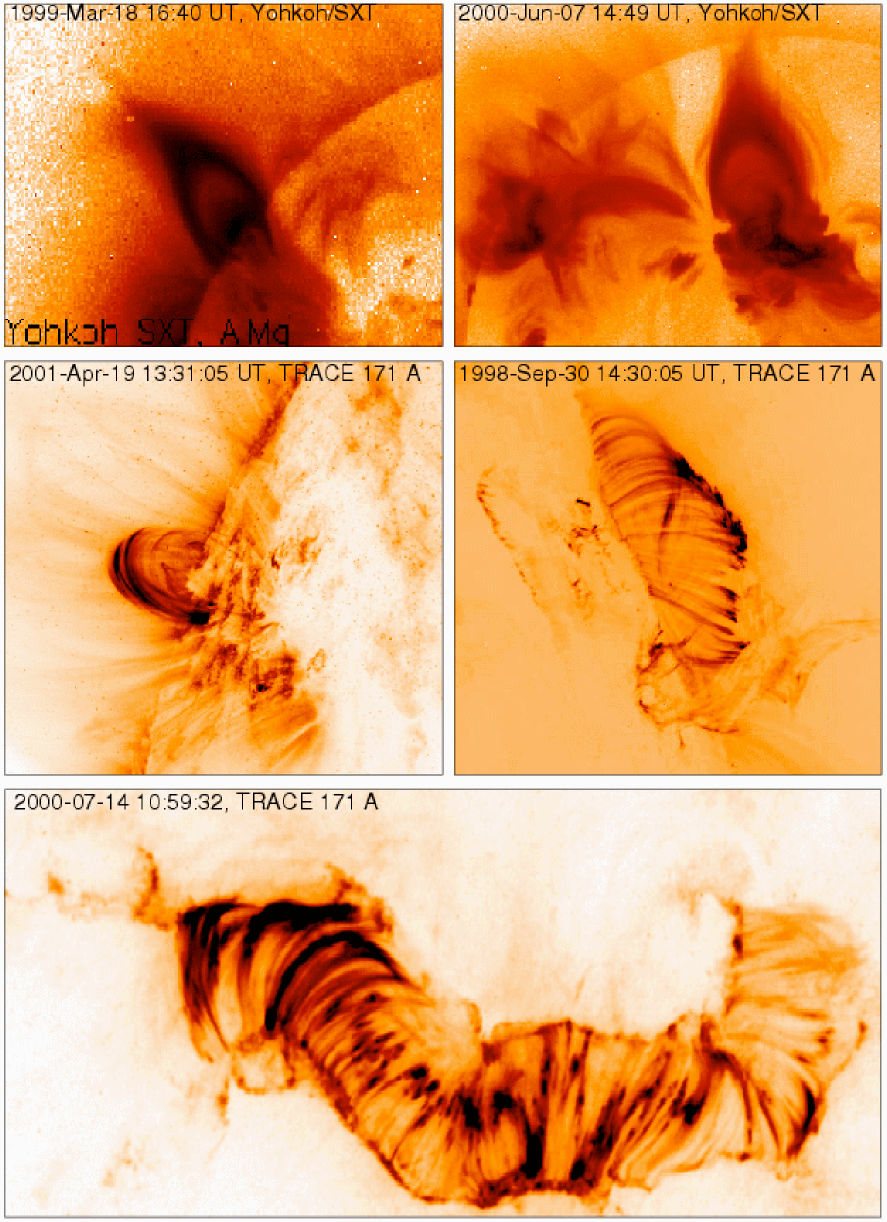
Acceleration regions are expected in locations where newly reconnected field lines relax into a force-free configuration.

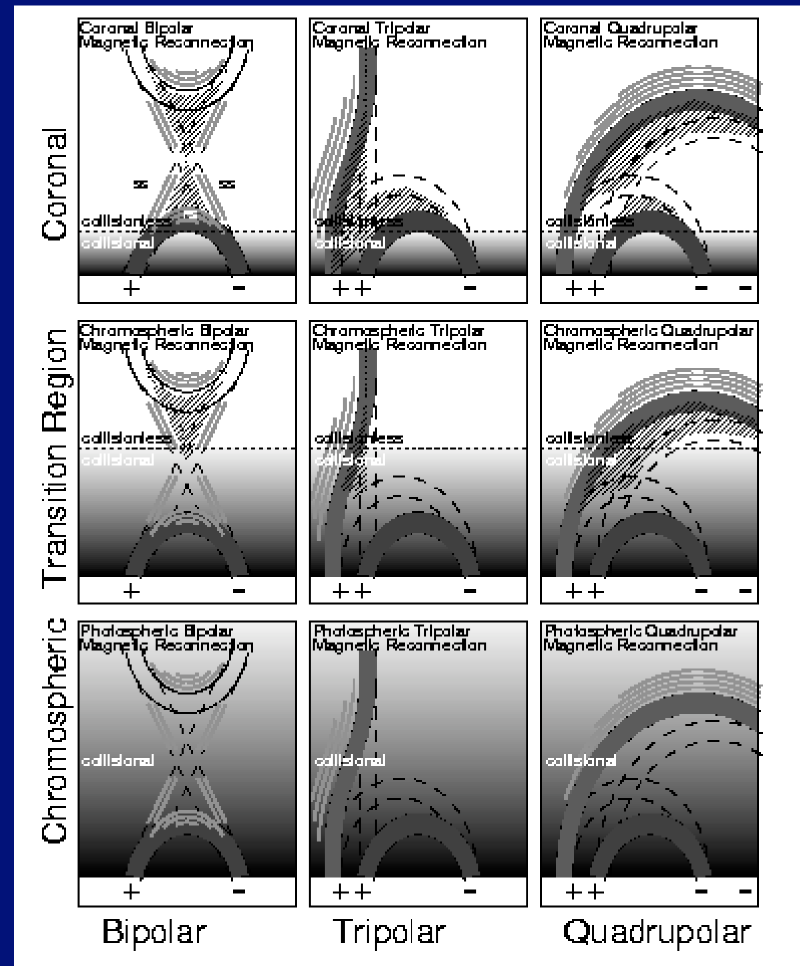


Bipolar topologies



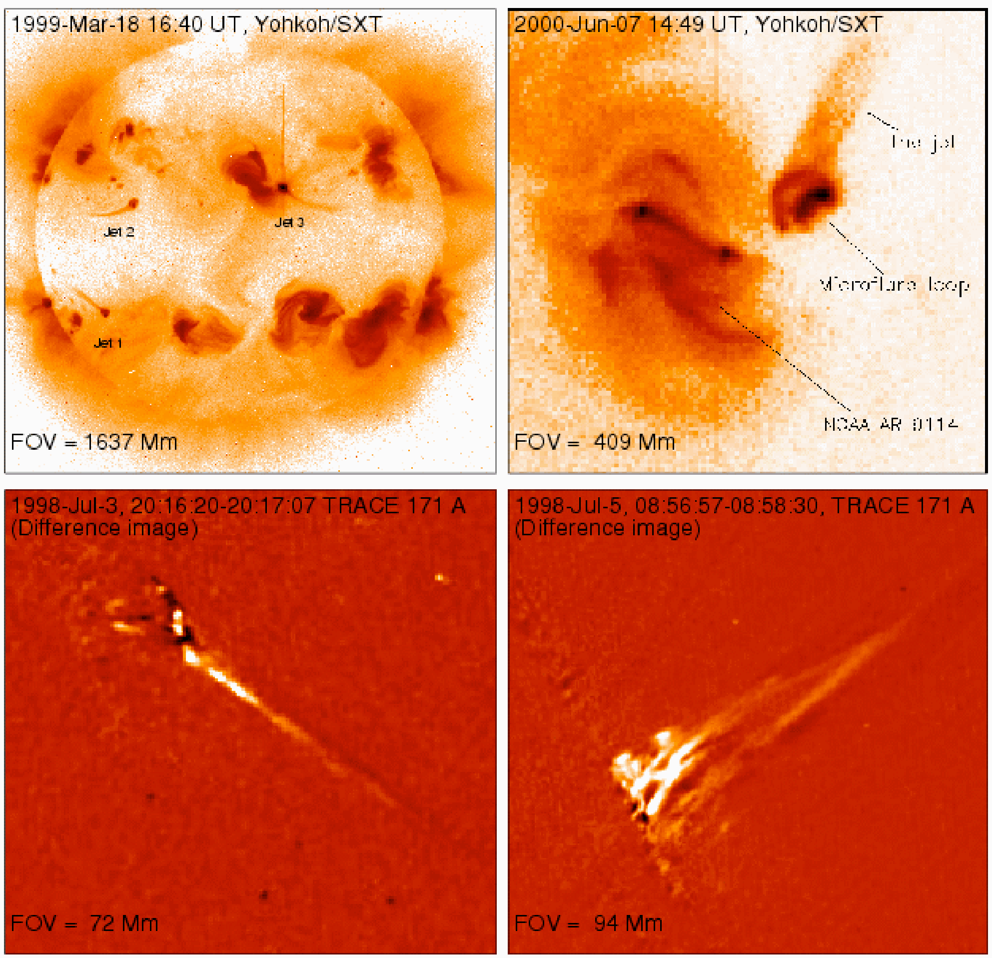
Tripolar topologies

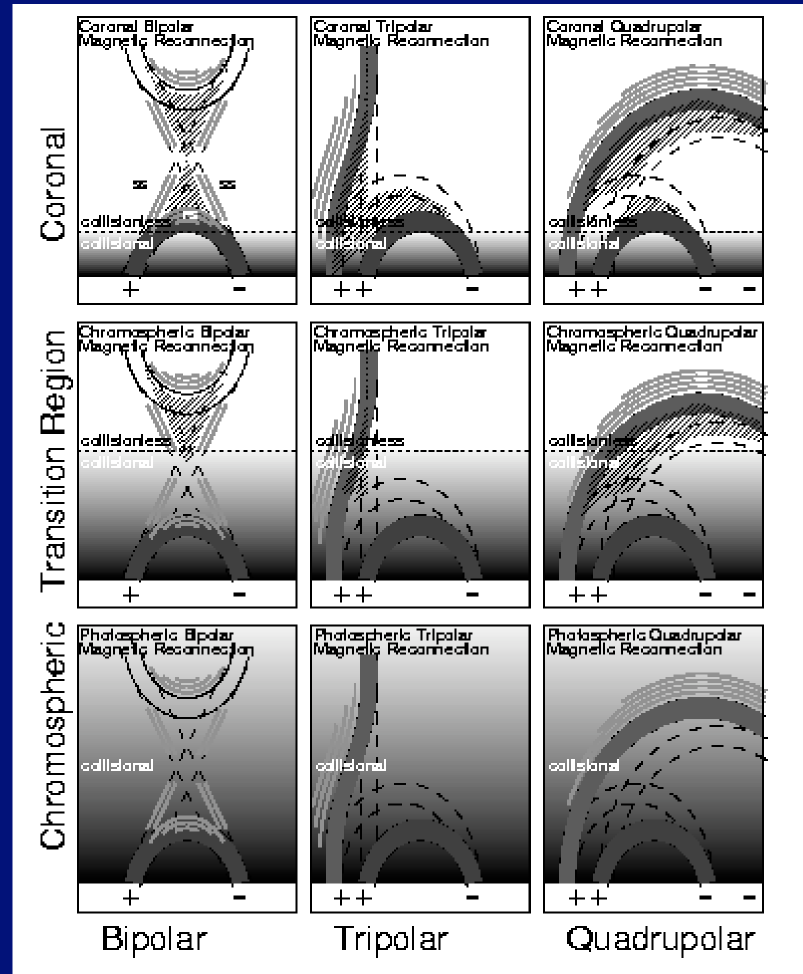




Kopp-Pneuman model (CSHKP)
Tsuneta

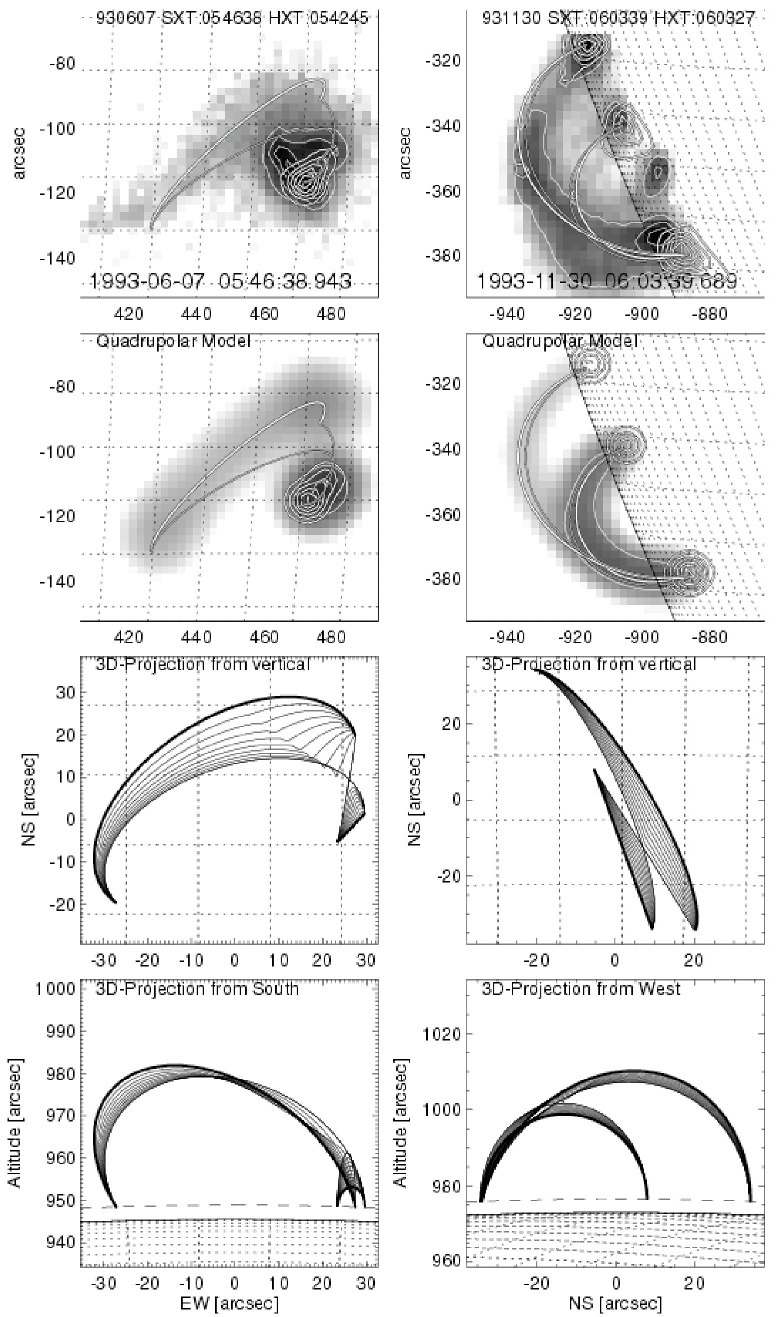
Bipolar topologies

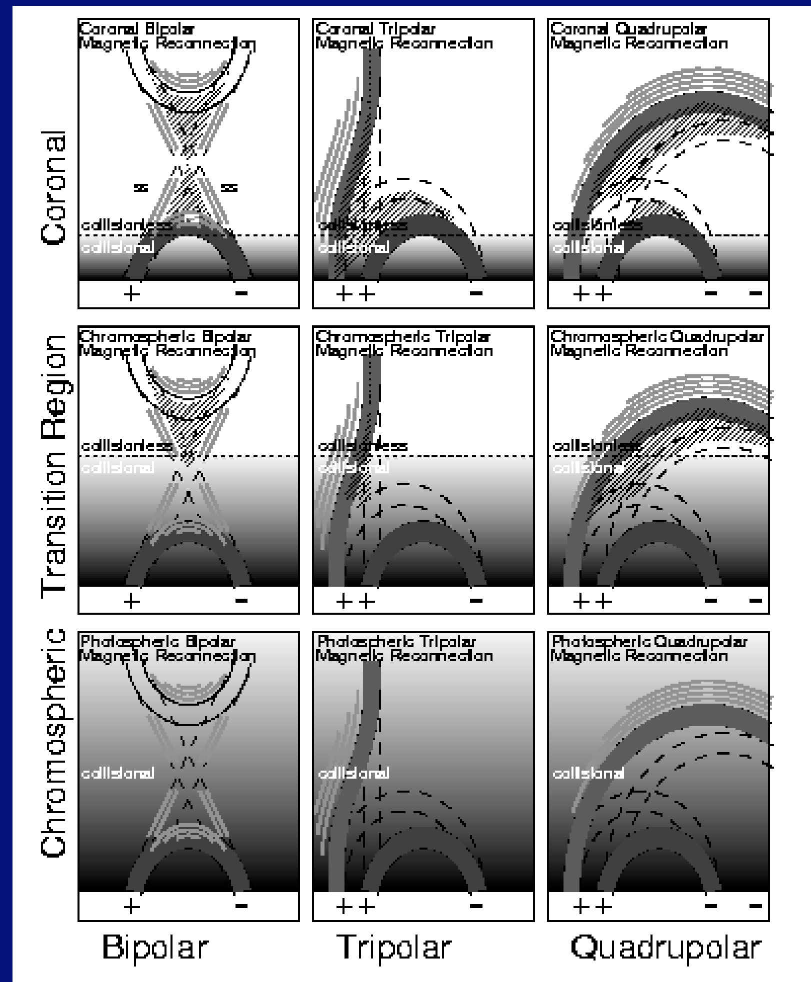




Tripolar topologies

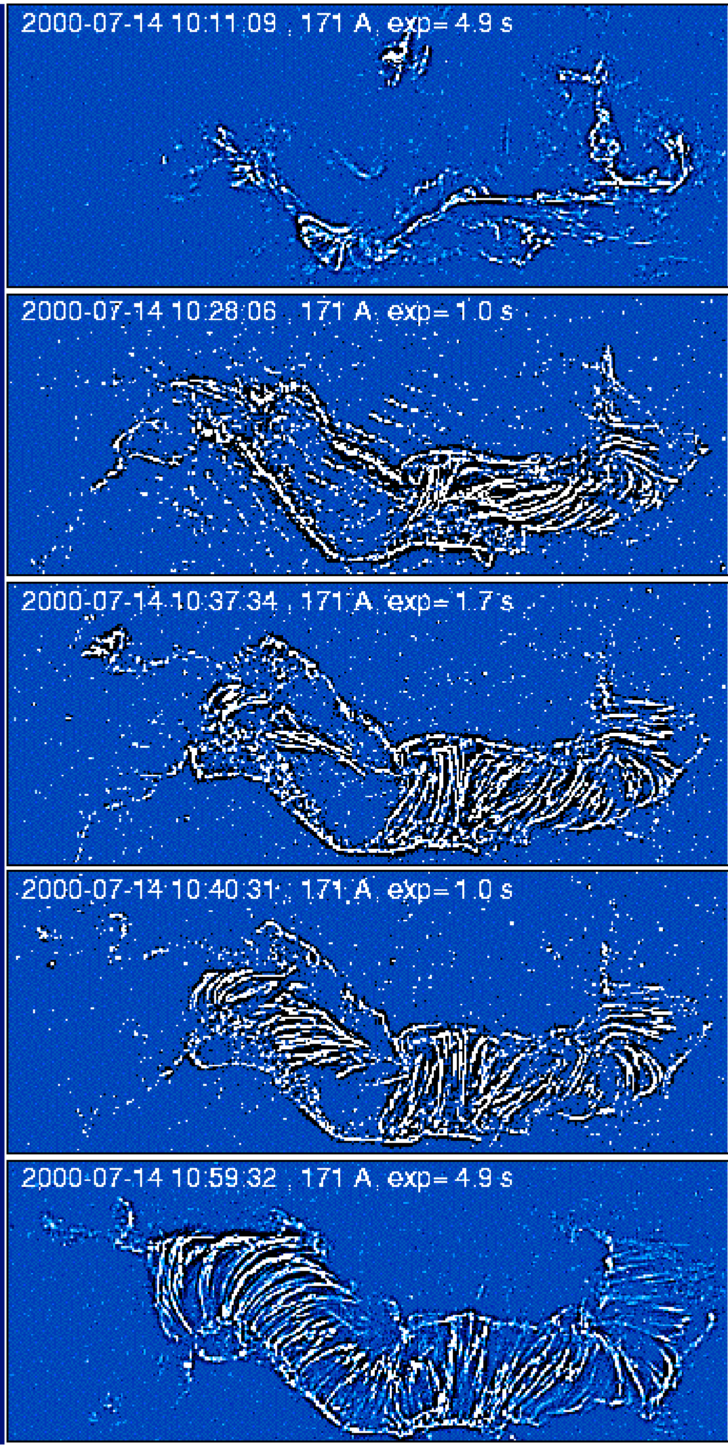
Emerging flux model
Heyvaerts-Priest-Rust 1977
Soft X-ray jets (Shibata)

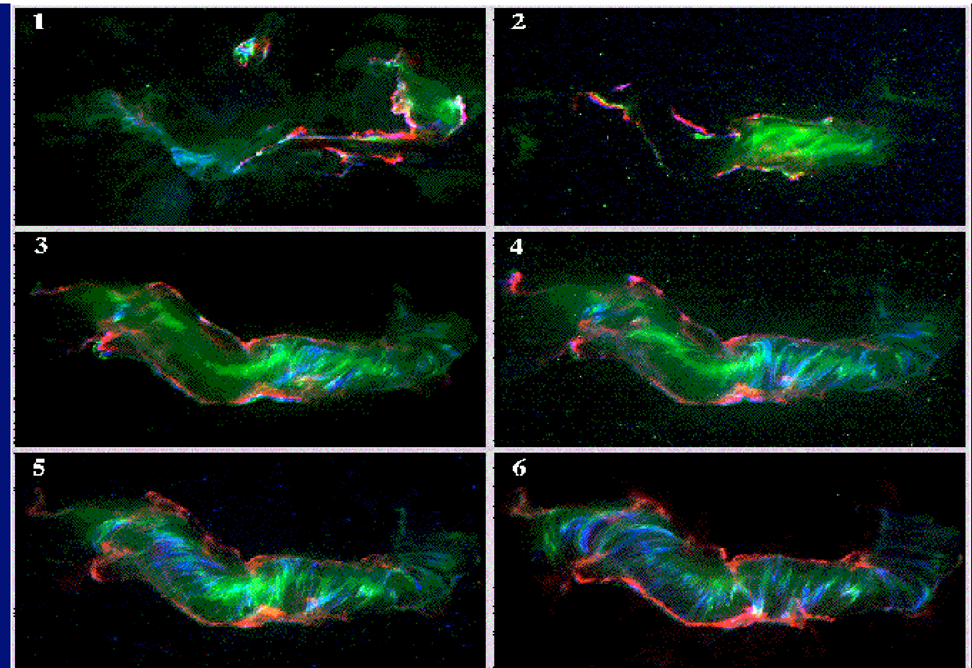


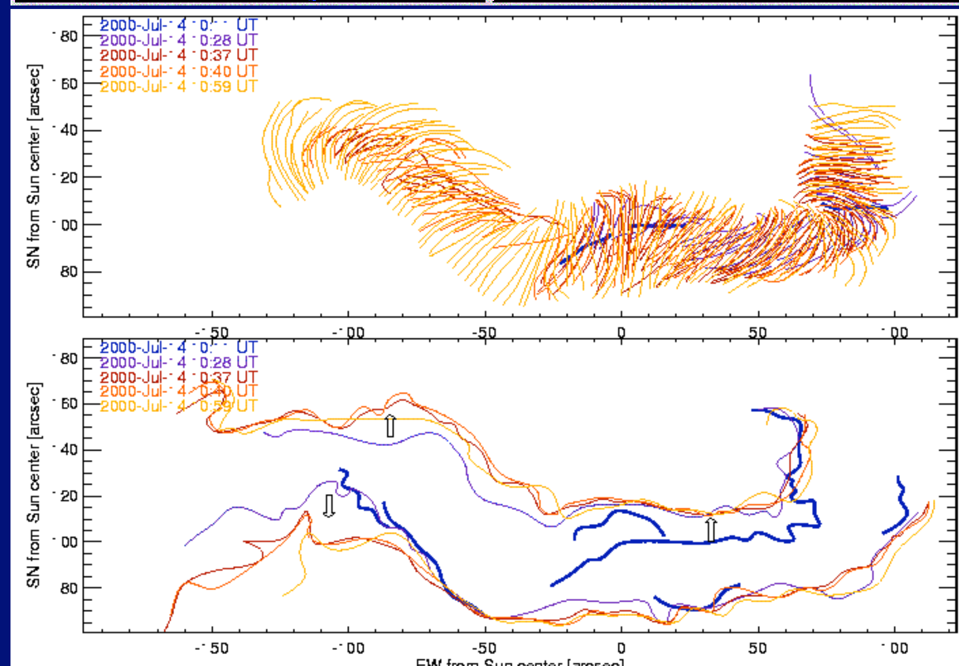


Magnetic flux transfer (Melrose)
3D flare geometry:
Hanaoka, Nishio, Aschwanden

Quadrupolar topologies





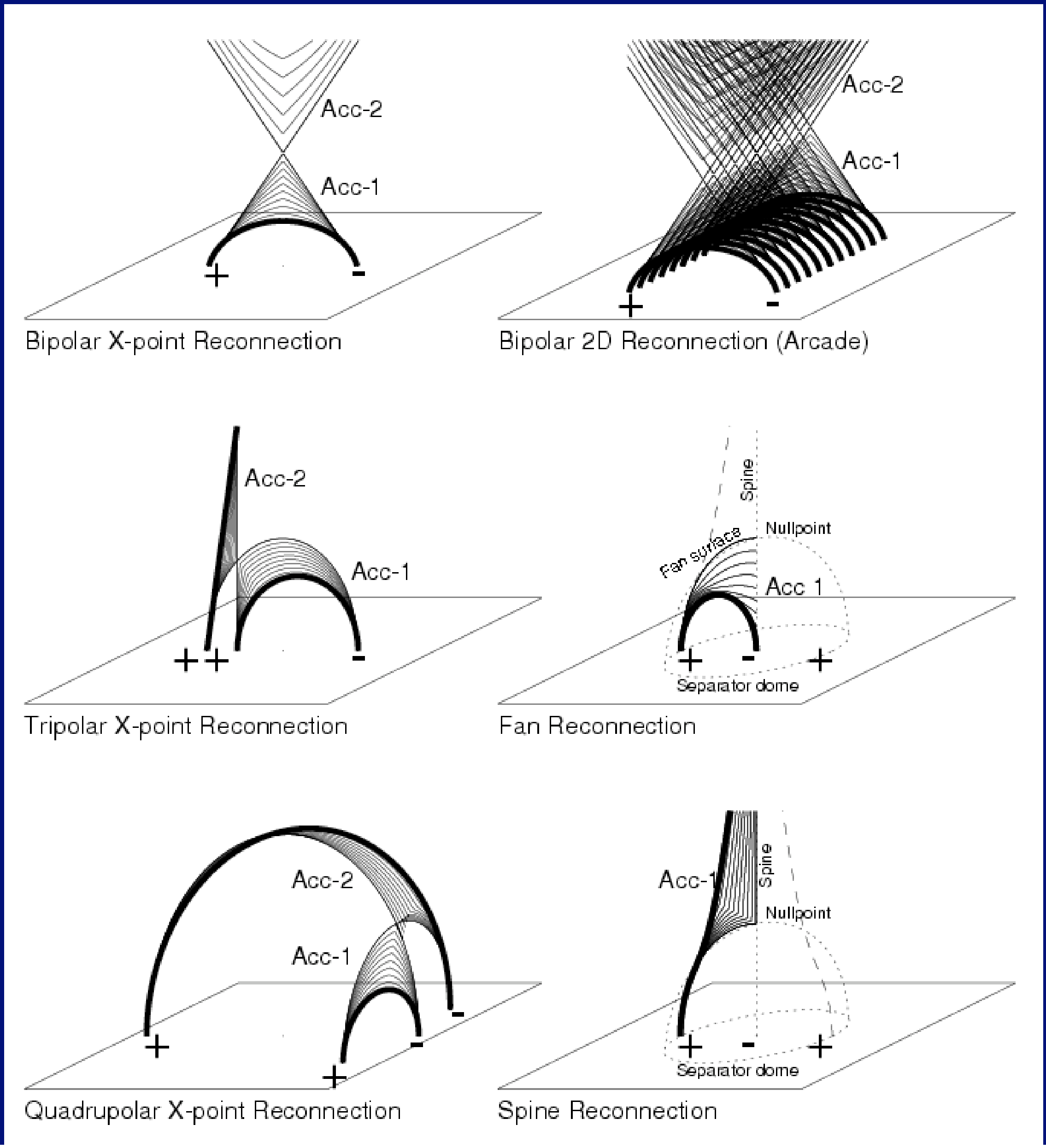


Bastille-Day flare, 2000-Jul-14

Clue 1:

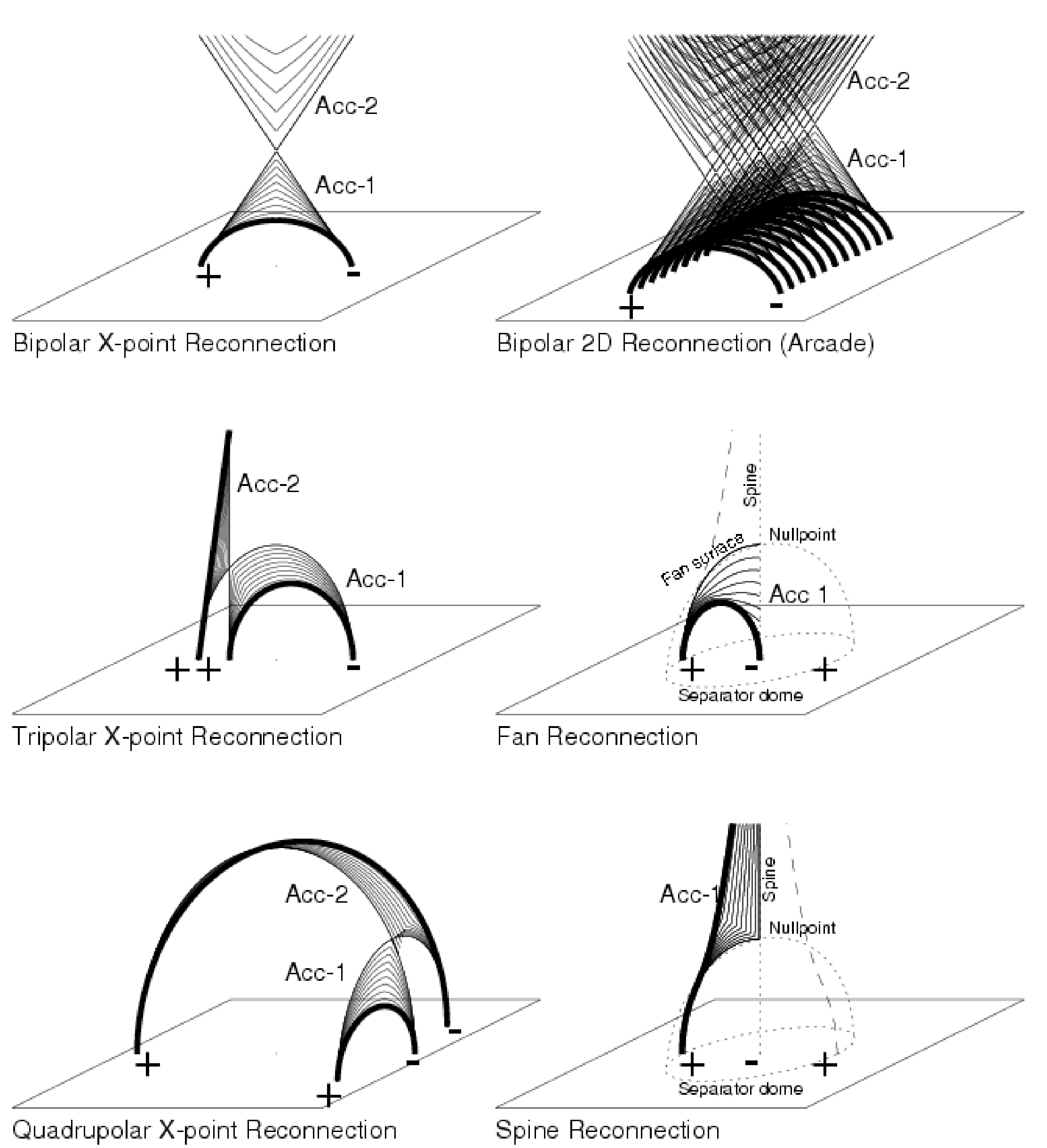
For escape into interplanetary space we need the involvement of open post-reconnection field lines, which is the case for bipolar and tripolar reconnection, but not for quadrupolar reconnection !

2) ALTITUDE OF ACCELERATION REGION



Volume of field-line shrinking (relaxation) after magn. Reconnection defines geometry of acceleration region :

- -cusps
- -double cusps
- -jets
- -curved hyperboloids
- -spines

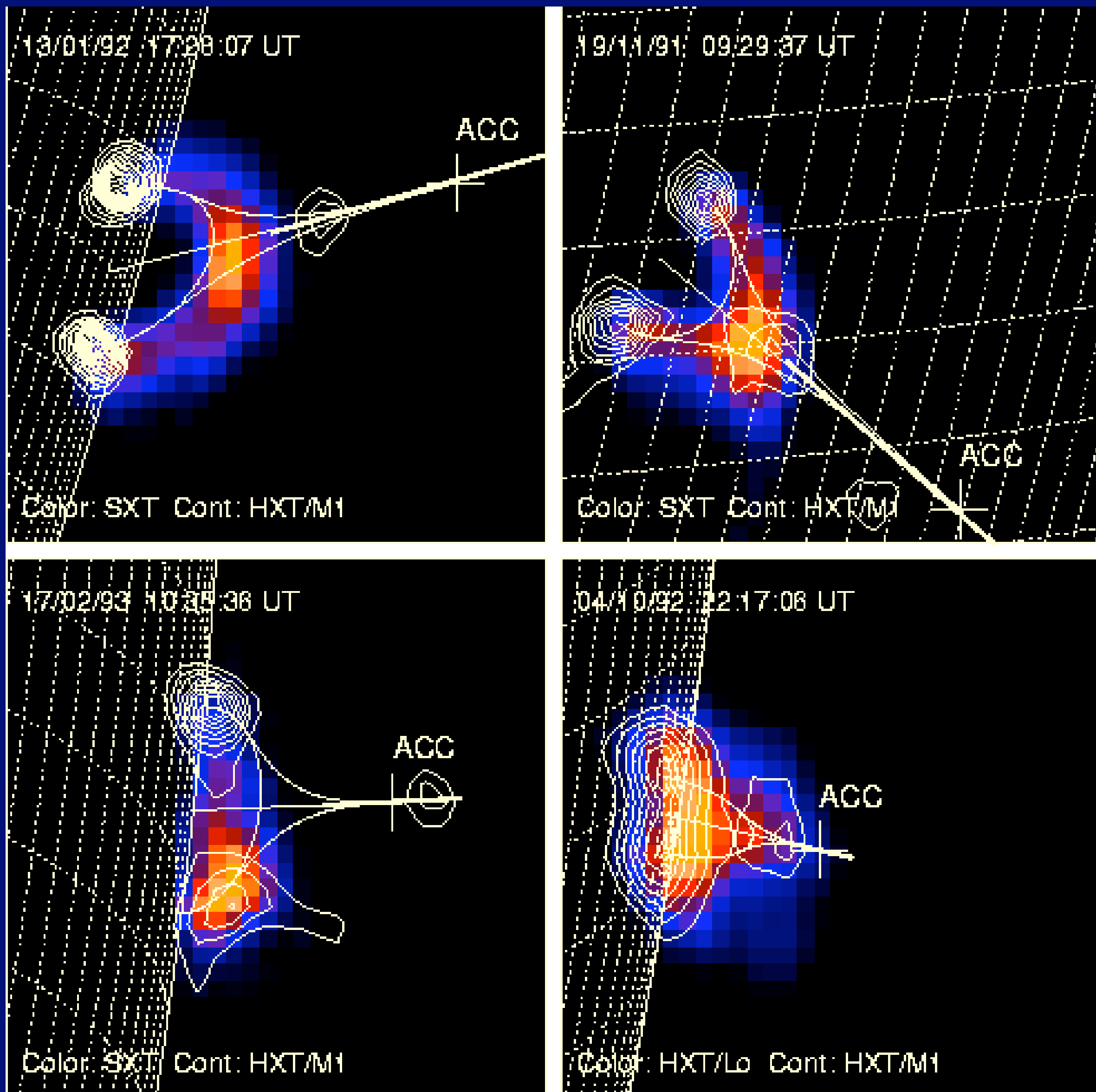


Shrinkage ratio :

length of pre-reconnection
to post-reconnection
field line

= electron time-of-flight
distance to soft X-ray
flare loop half length

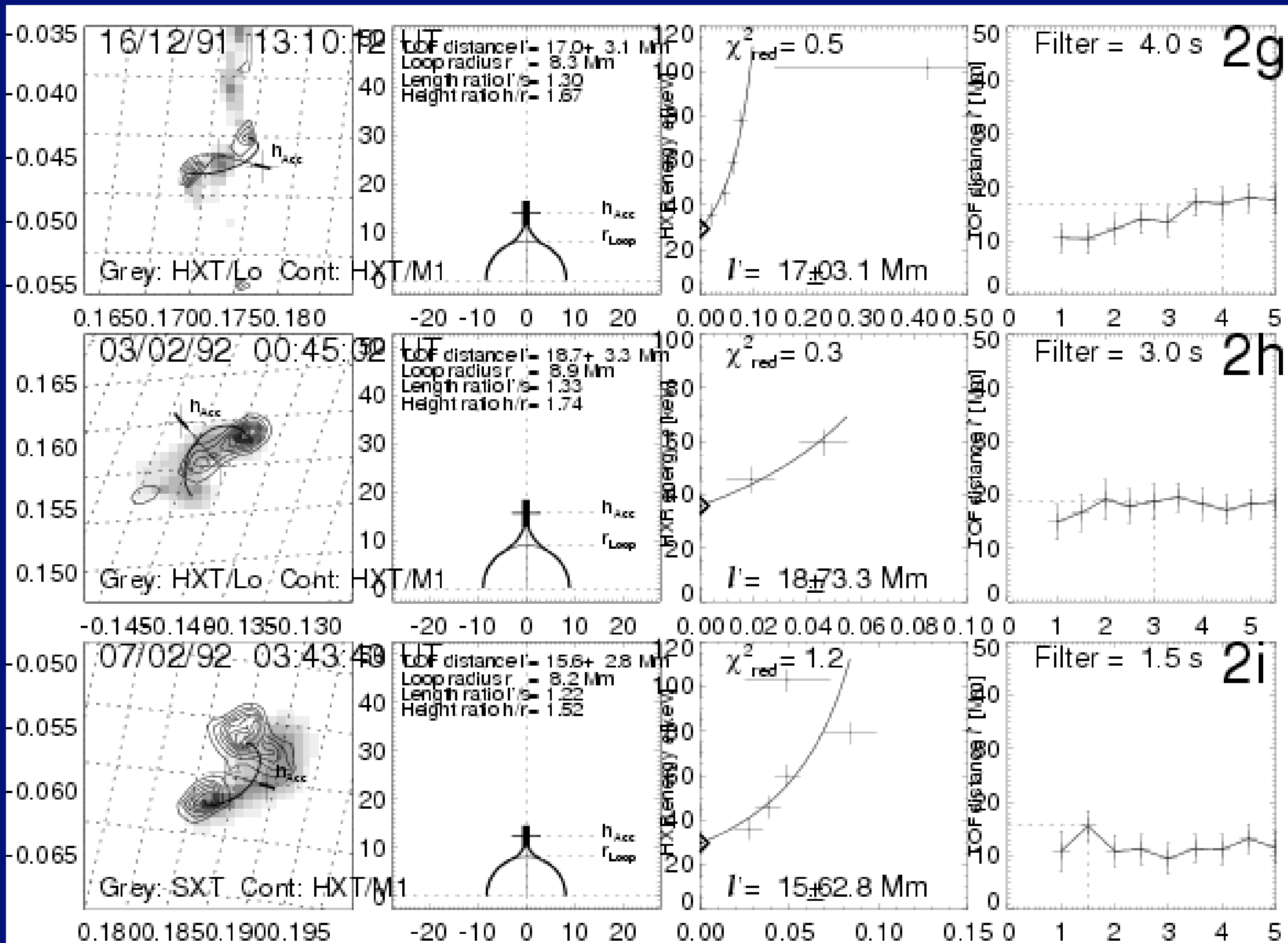
bipolar: L/s > 1.0
tripolar: L/s > 1.0
quadrupolar: L/s = 1.4-1.6
3D fan: L/s = 2.0



Measurements of
ratio of
electron time-of-flight
distance L to
flare loop half length s

L/s = 1.43 +/- 0.30
(Aschwanden et al. 1996)

L/s = 1.6 +/- 0.6
(Aschwanden et al. 1998, 1999)

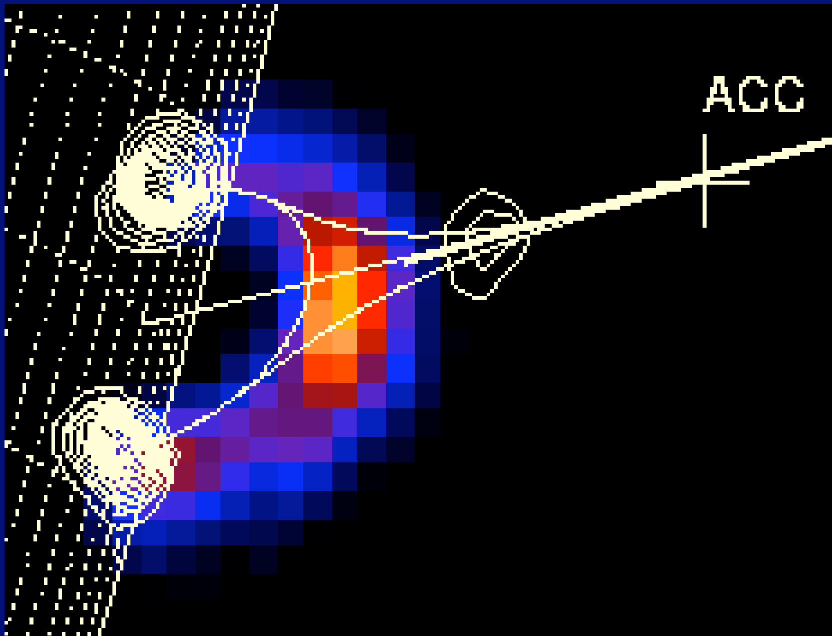


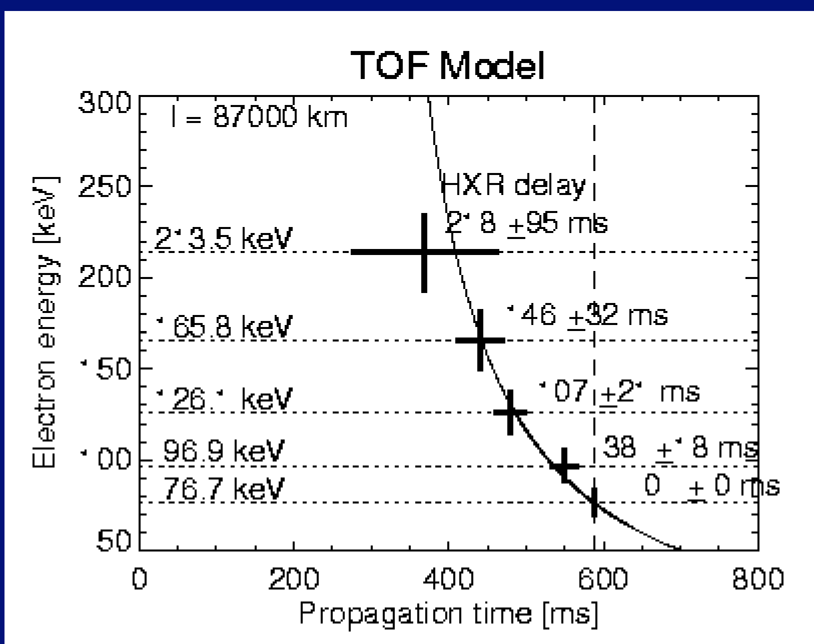
Measurement of electron time-of-flight distance :

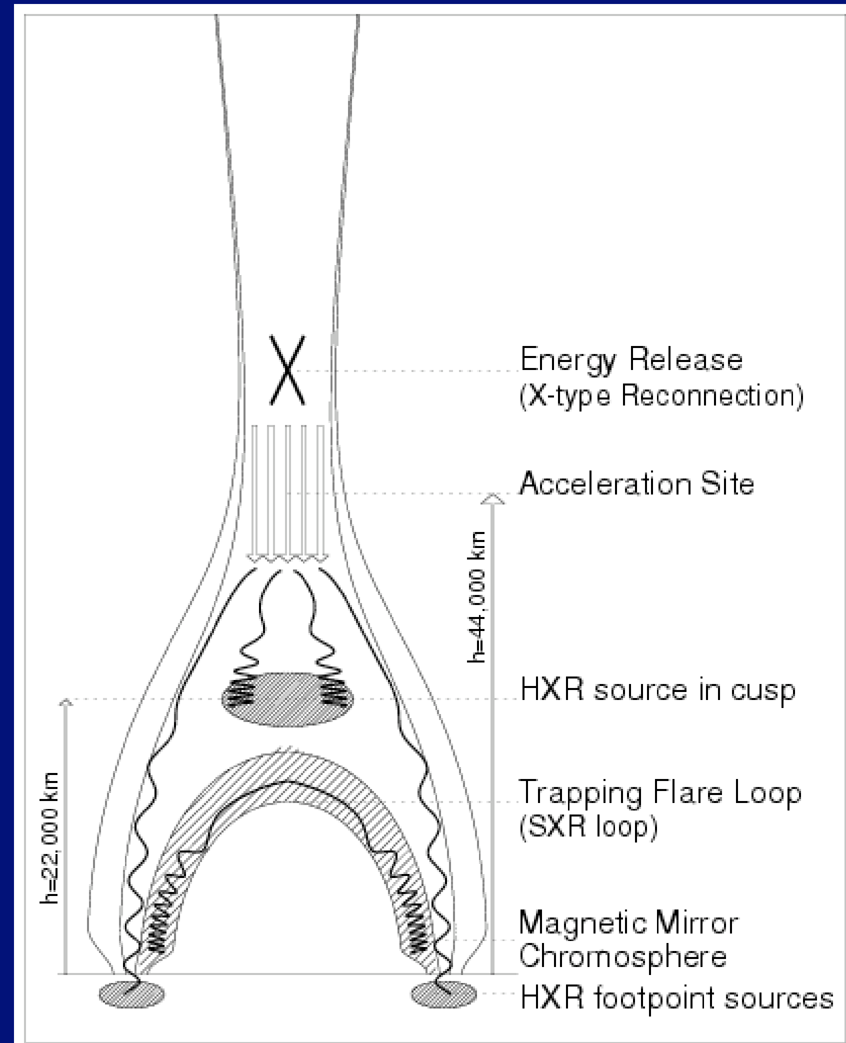
-velocity dispersion from hard X-ray energy-time delay t=L/v

-pitch angle correction (v_parallel/v = cos α)

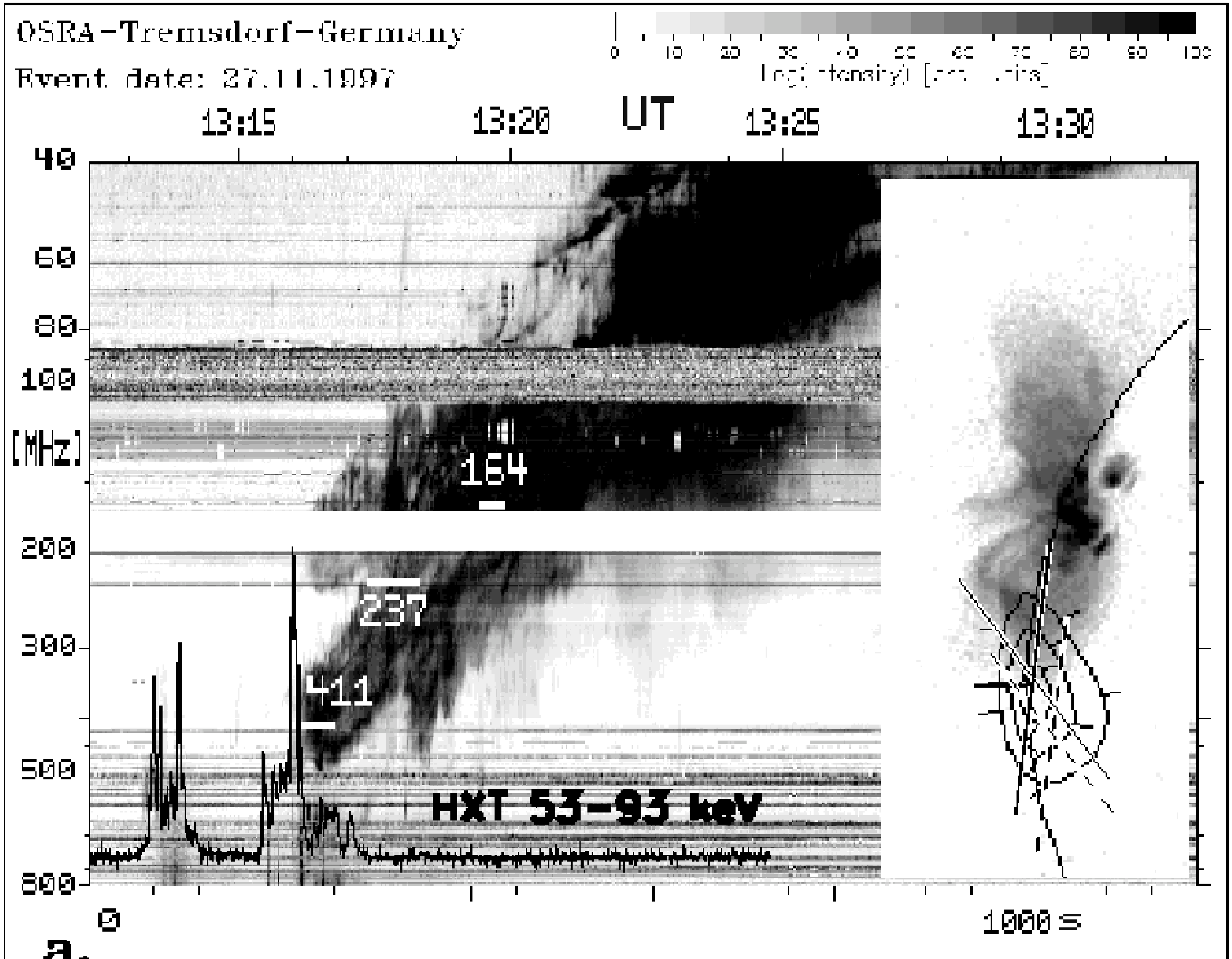
-magnetic field line twist correction (L_projected/L_TOF)







Reconstruction of height
of electron acceleration region
in Masuda flare: L/s ~ 1.5-2.0
(Aschwanden et al. 1996)

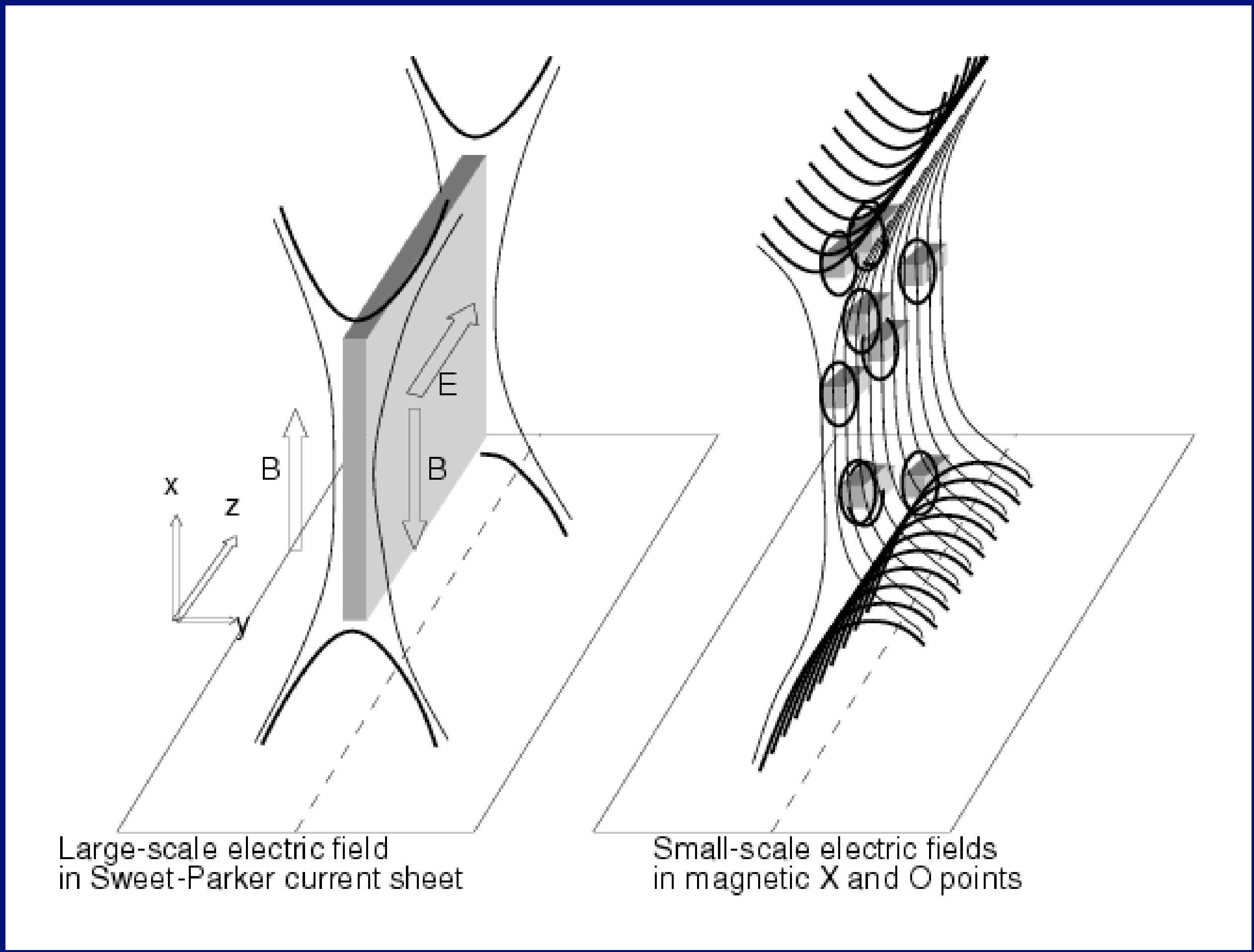


Type II was localized in lower corona (Nancay),
far below CME bowshock at 5 solar radii (Klein et al. 1999)

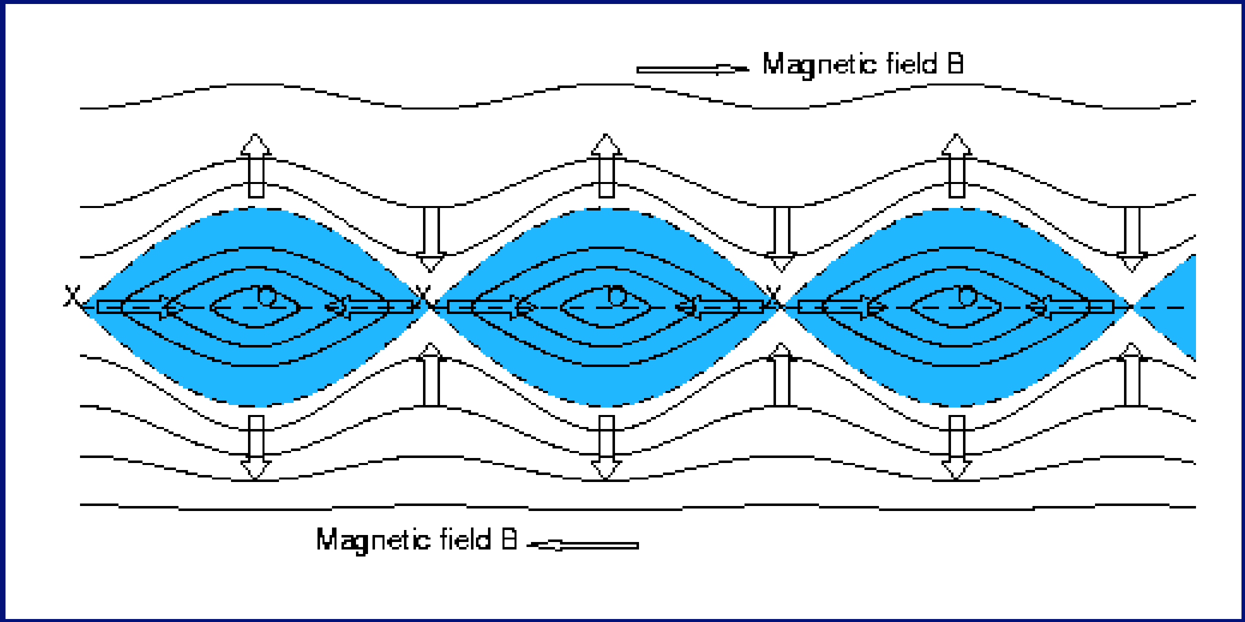
Clue 2:

The altitude of flare acceleration sites is about a factor of ~1.5 times the height of flare loops, so h_acc ~ 5000-35,000 km. This height range corresponds to h_acc < 0.05 R_sun. If the origin of energetic particles is traced back to larger distances from the Sun (e.g. with from the velocity dispersion over the Sun-Earth distance), they are likely to be accelerated in CME shocks, and not in flare reconnection sites.

3) PHYSICS OF ACCELERATION



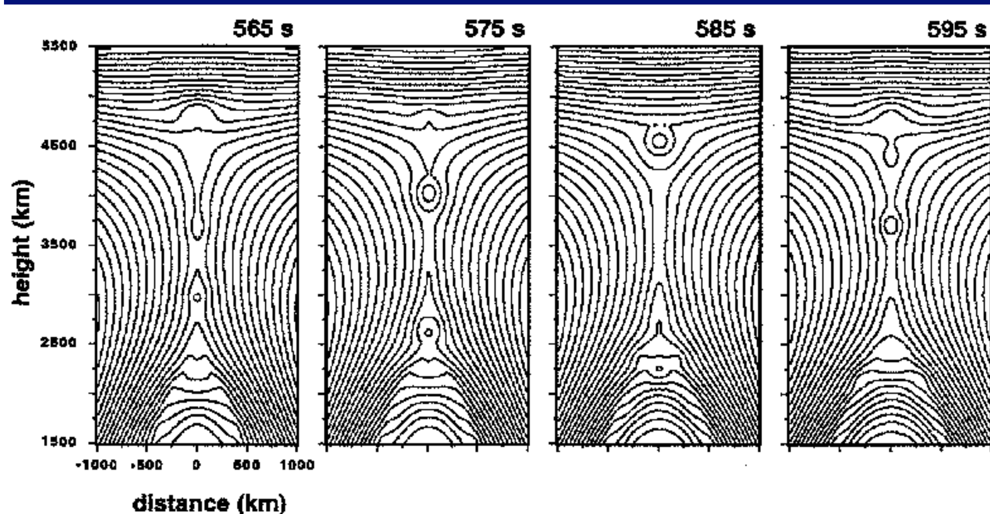
Fast (subsecond) time structures of hard X-ray and radio pulses in solar flares suggest small-scale, fragmented, bursty magnetic reconnection mode.

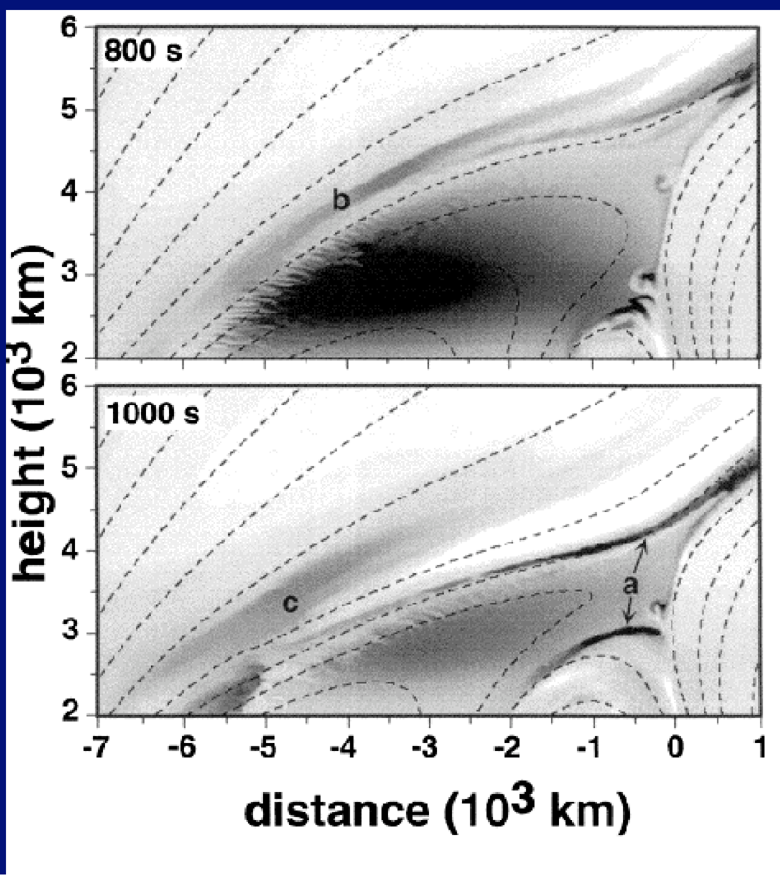


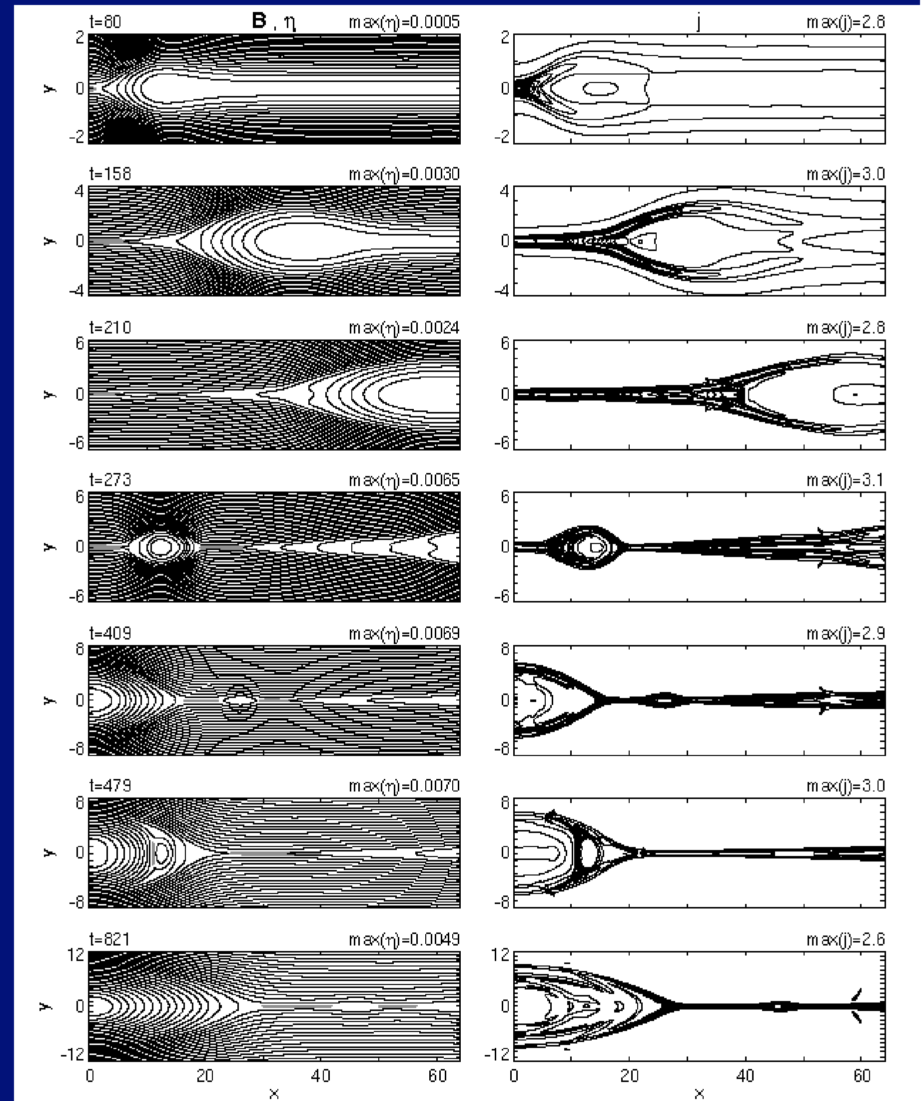
Magnetic island formation by tearing mode instability
(Furth, Killeen, & Rosenbouth et al. 1963)

Magnetic X-point and O-points form →
coalescence instability (Pritchett & Wu 1979)

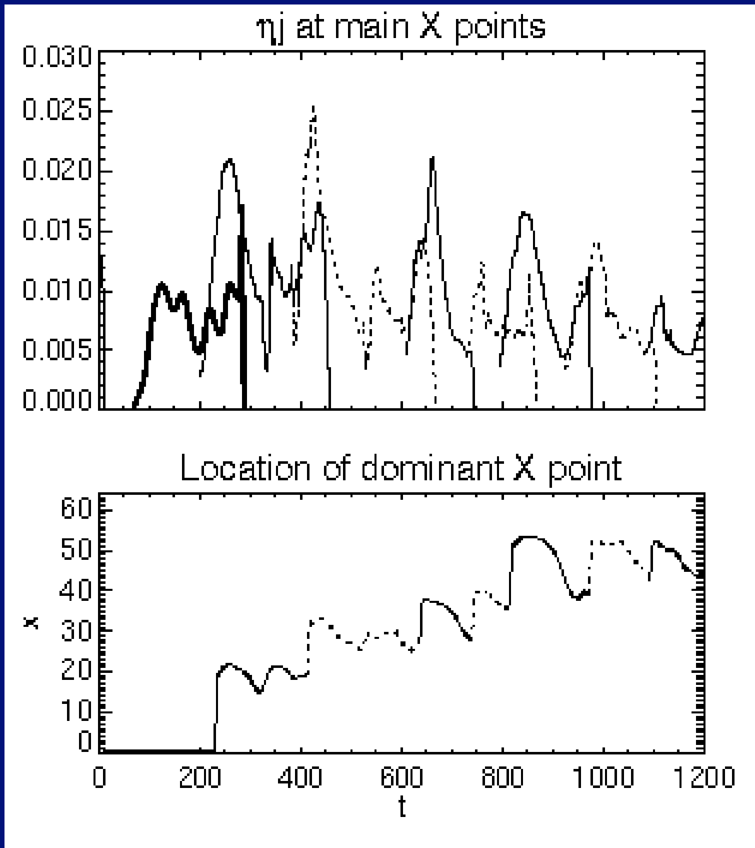
Magnetic island formation + coalescence instability →
regime of impulsive bursty reconnection
(Leboef et al. 1982; Tajima et al. 1987; Kliem 1998, 1995)

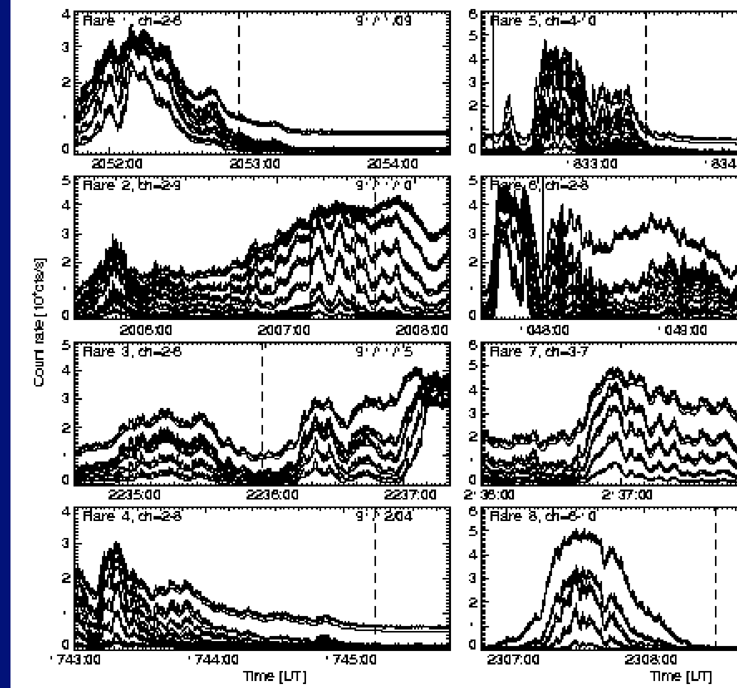


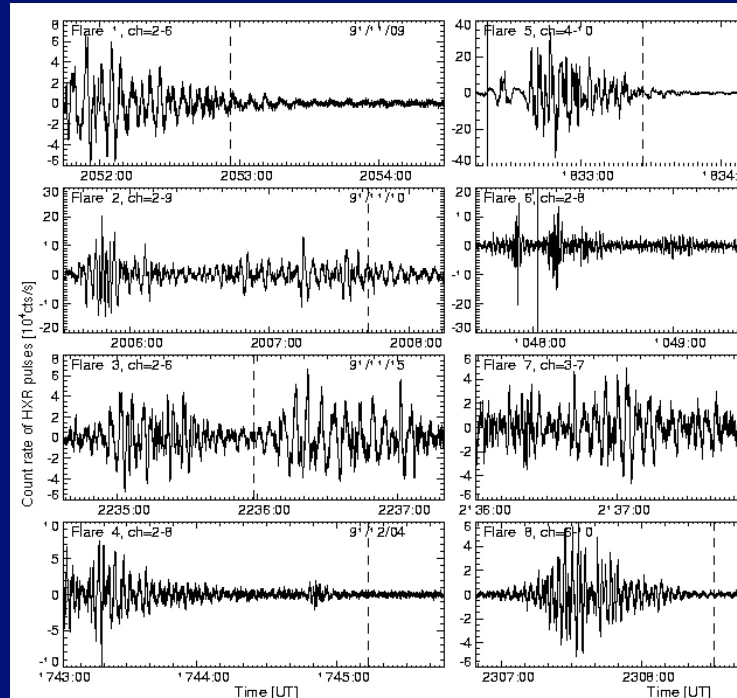




Karpen et al. 1995, 1998
Schumacher & Kliem 1997
Kliem et al. 1995, 1998
Kliem, Karlicky, & Benz 2000

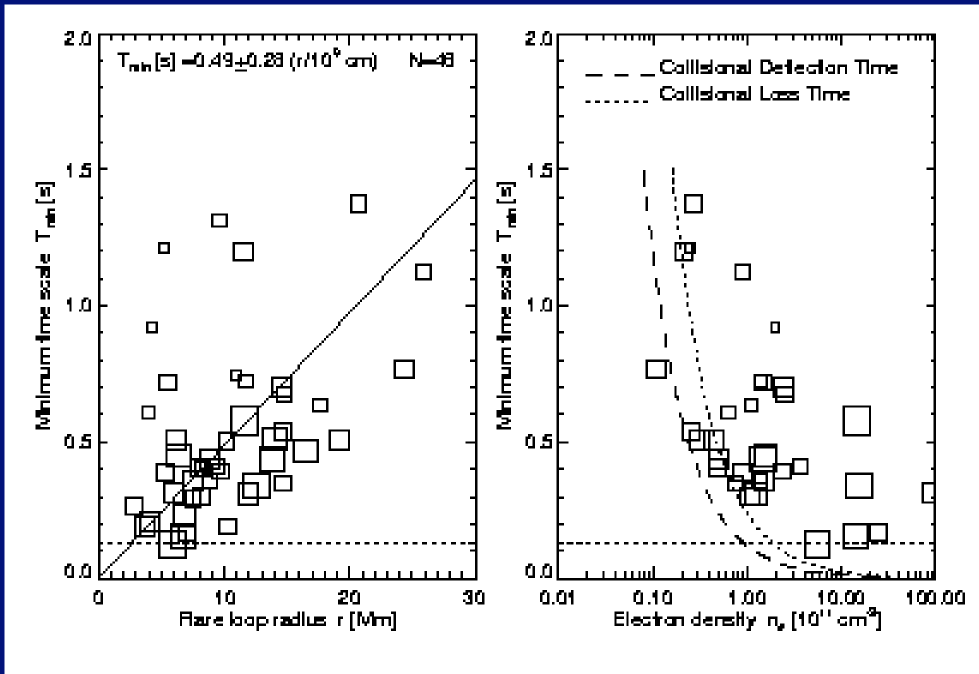


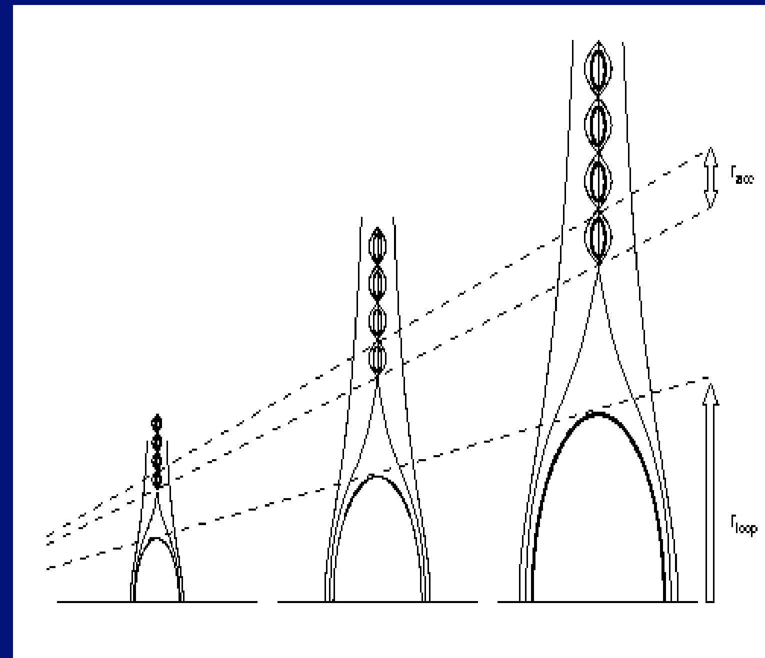




Electric field at X-point in impulsive bursty reconnection mode
(Kliem et al. 2000)

Hard X-ray pulses resulting from accelerated electrons dt ~ 0.1-0.3 s
(Aschwanden et al. 1996)

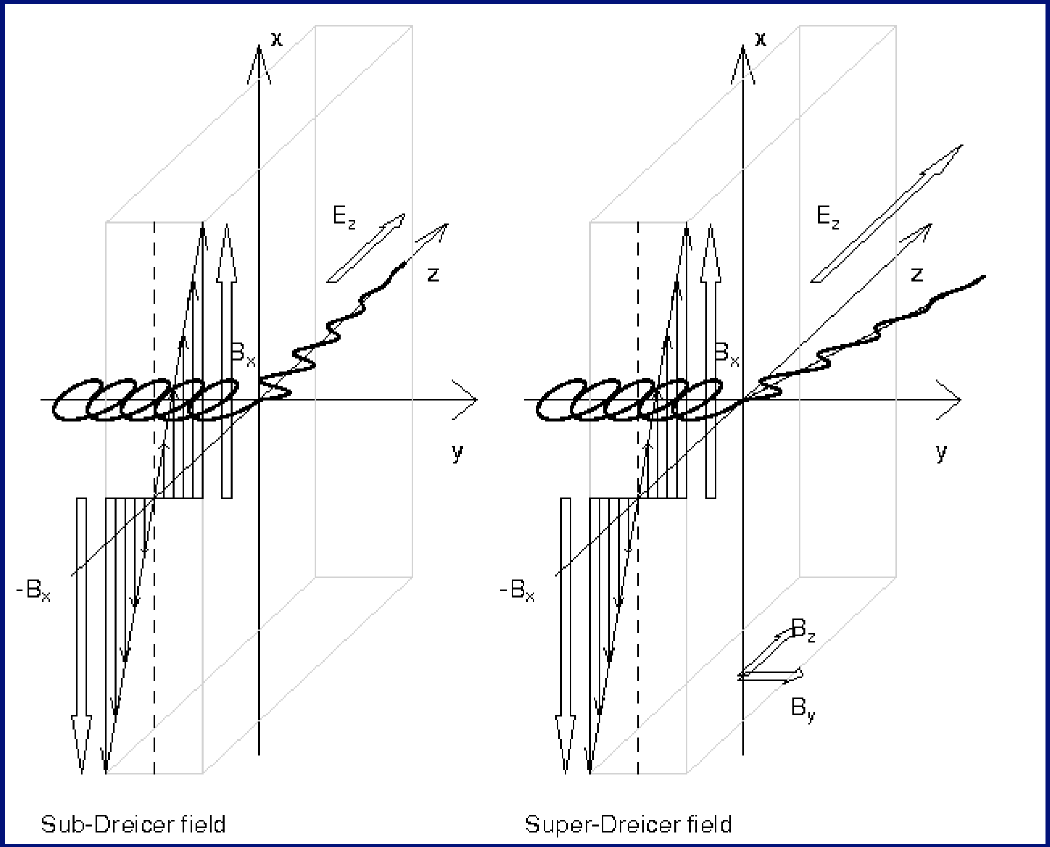




Observations show a scaling law between Hard X-ray pulse durations and flare loop size : T_pulse ~ 0.5 s [r_loop/10 Mm]
→scale invariance of magnetic reconnection region

(Aschwanden et al. 1998)

Lower limit of pulse durations: collisional deflection time



a) Electric DC field acceleration :

-Sub-Dreicer field needs too large current sheets

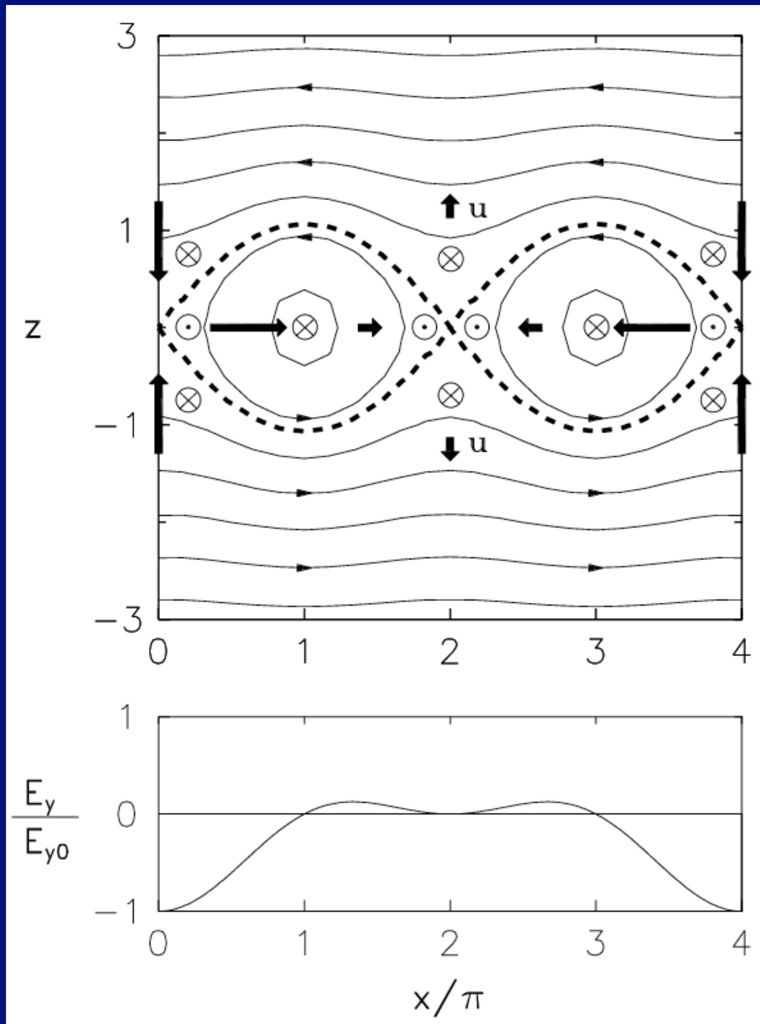
(Holman 1985; Tsuneta 1985)

-Super-Dreicer field applicable in magnetic islands

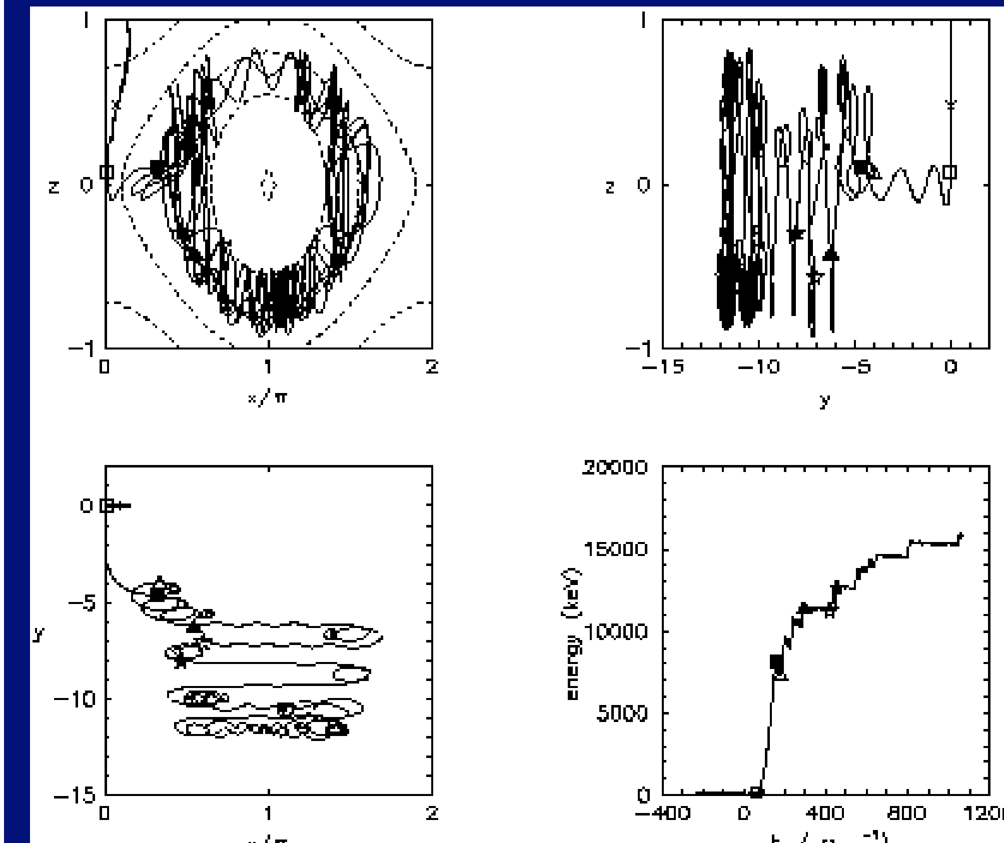
(Litvinenko 1996)

-Generalization to dynamics of filamentary current sheets

(Tajima et al. 1987; Kliem 994)



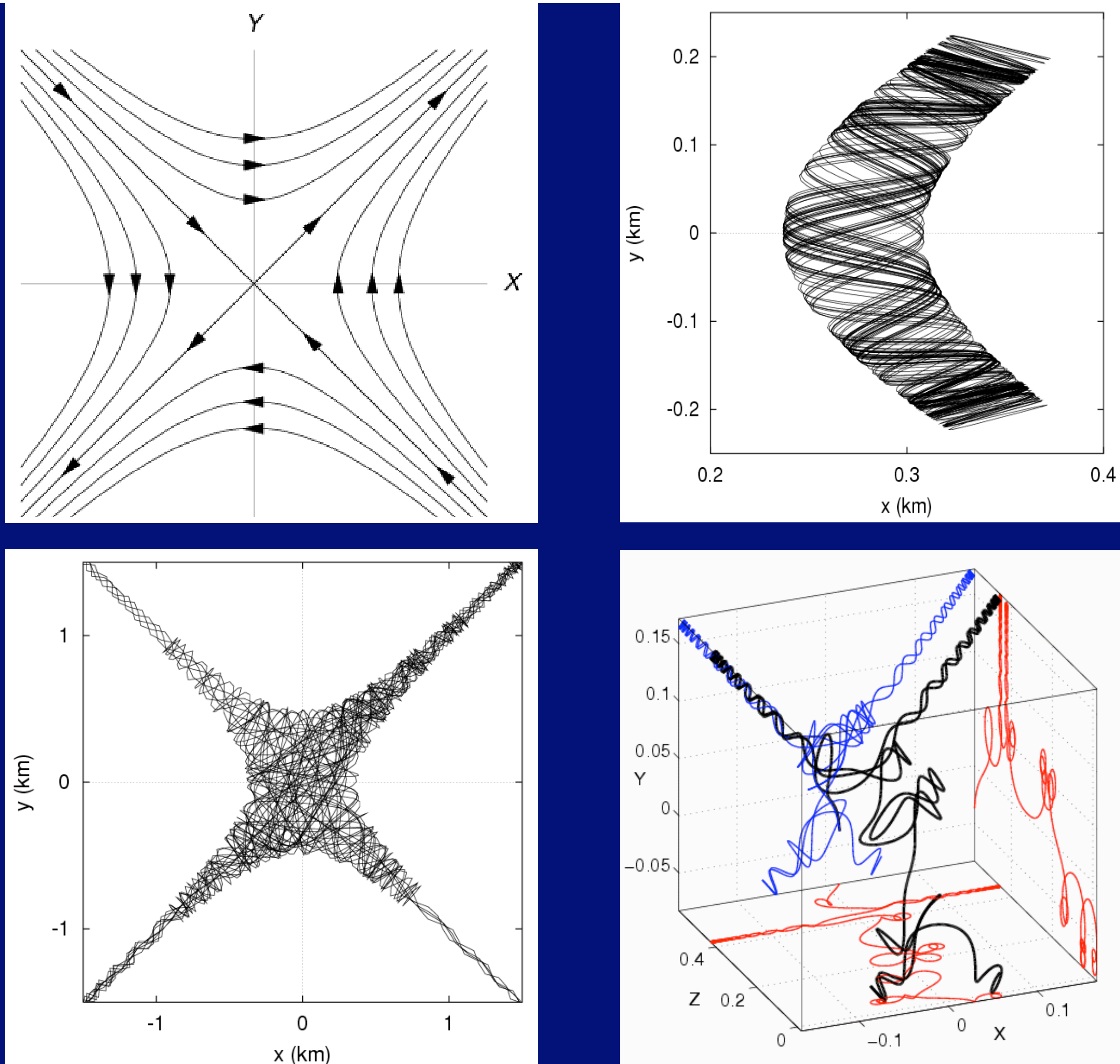
(Kliem 1994)



Convective electric field : E_conv = - u/c × B

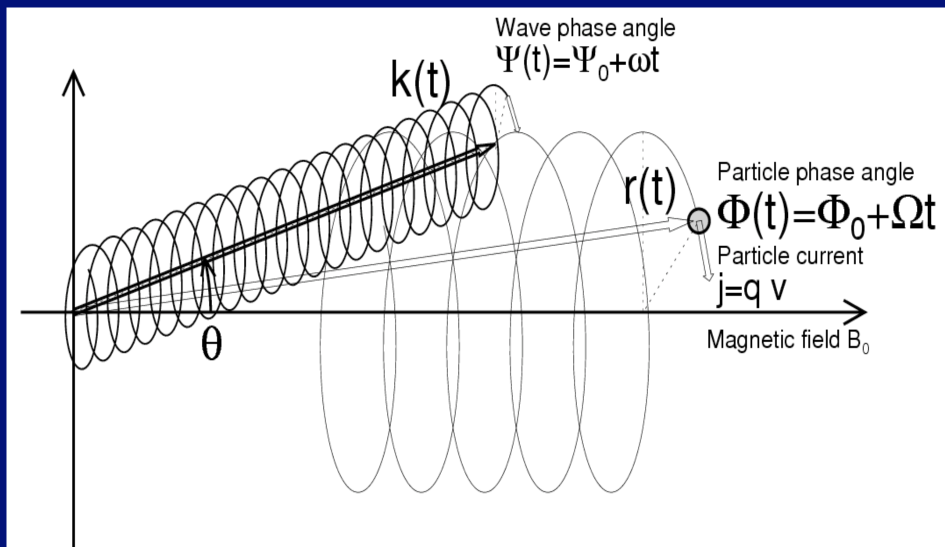
(convective flow speed u ~ (0.01-0.1) v_A

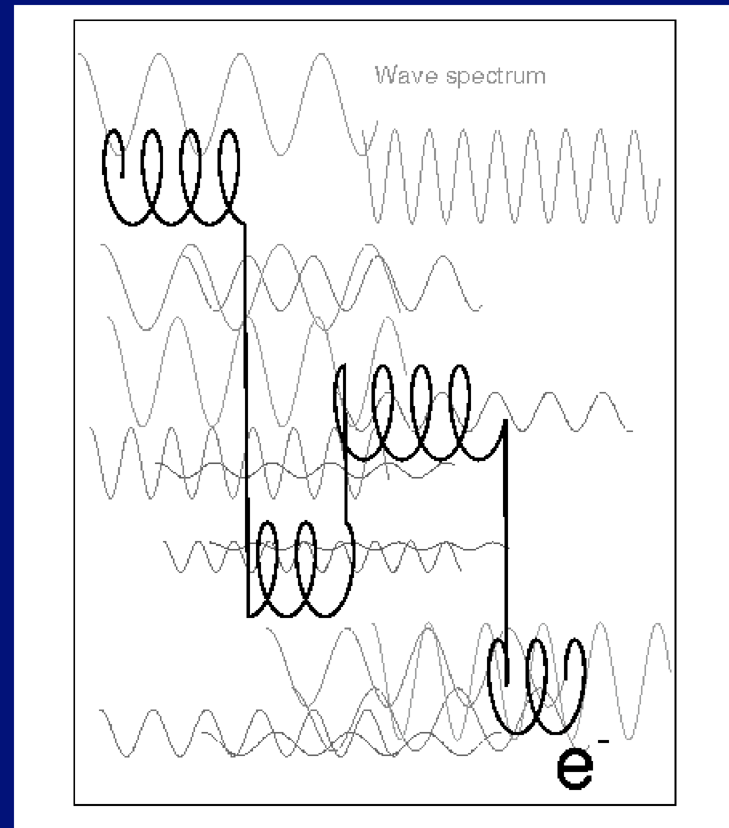
Particle orbit near magnetic O-point in magnetic island shows largest acceleration kick due to ∇B-drift next X-point



Particle acceleration near X-point (chaotic orbits)

(Hannah et al. 2002)

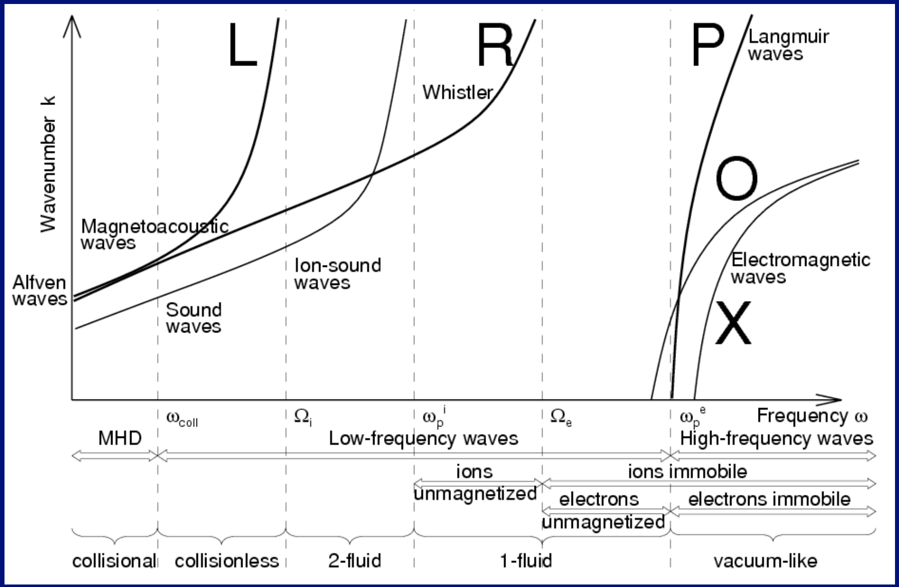


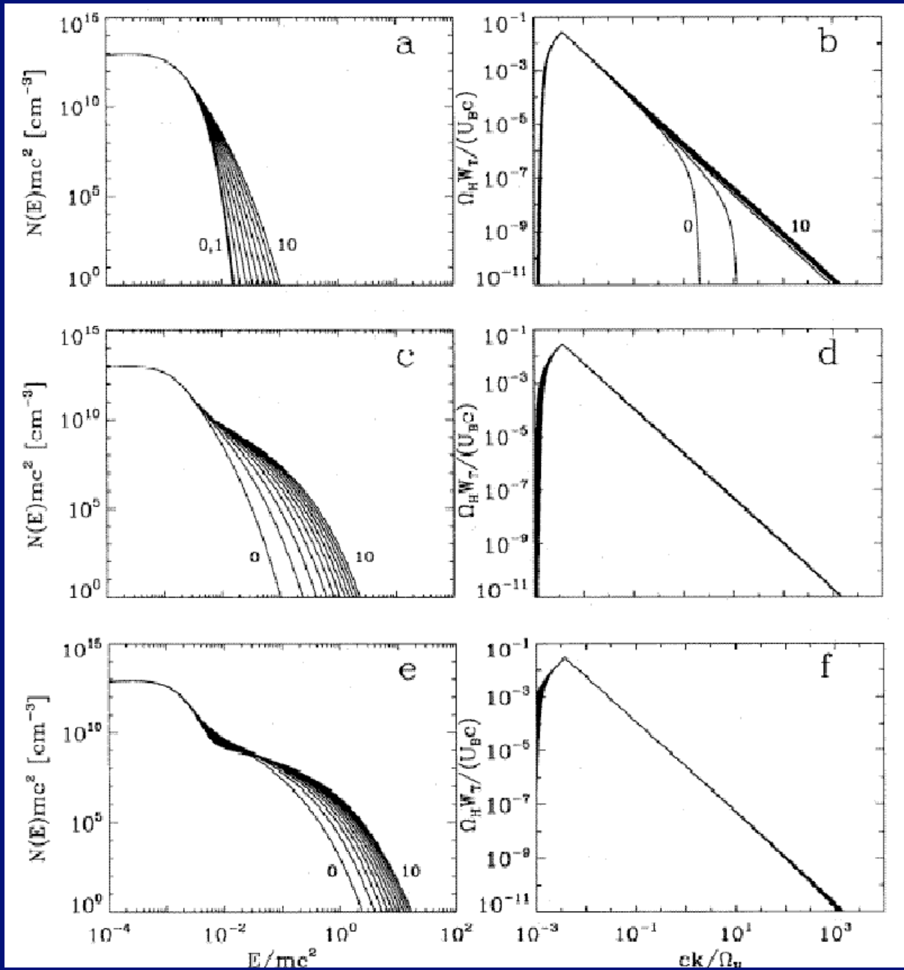


b) <u>Stochastic acceleration</u>

- Wave turbulence spectrum (Kolmogorov, Kraichnan)
- Particle randomly gains energy by wave-particle interactions (Doppler gyroresonance condition)

$$\boxed{\omega - s\Omega / \gamma - k_{\Uparrow} v_{\Uparrow} = 0}$$



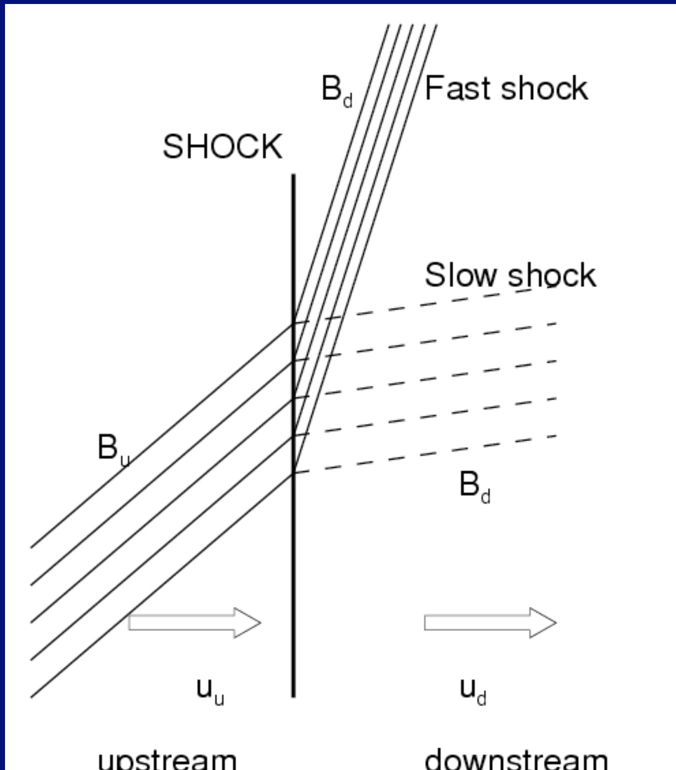


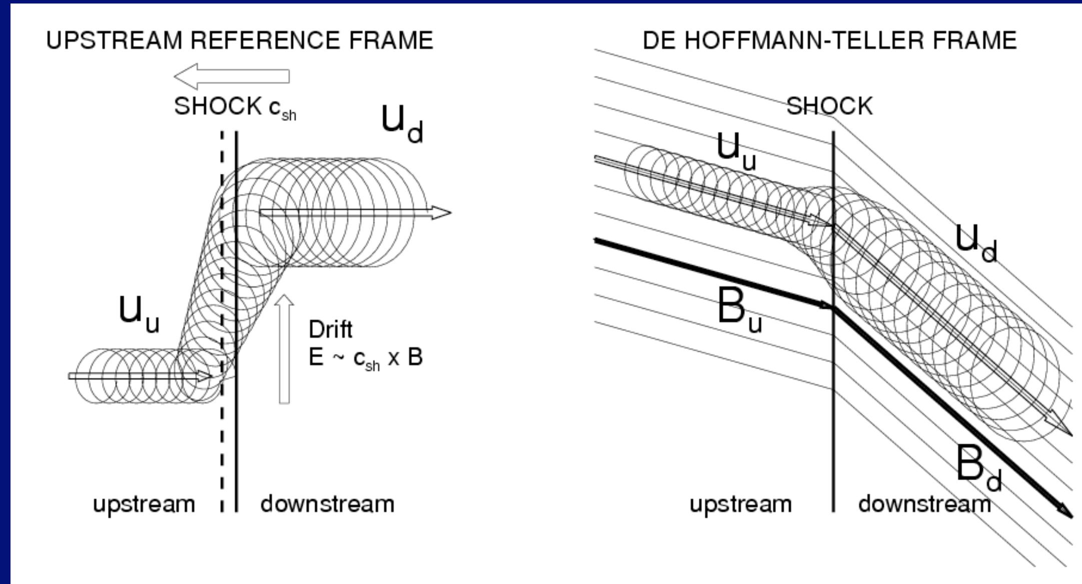
Miller etr al. 1996

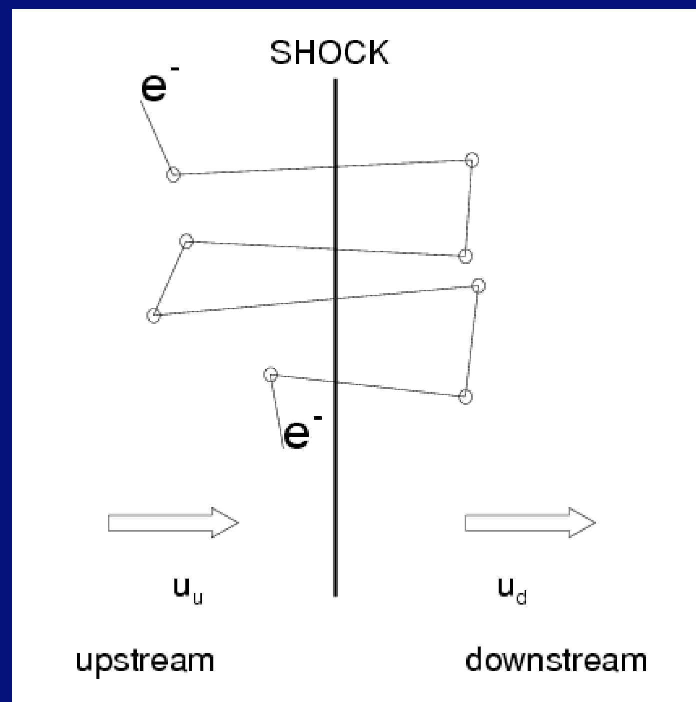
-Electron acceleration by whistler waves $\boxed{\Omega_p << \omega < \Omega_e}$

-Ion acceleration by Alfven waves $\boxed{\Omega_H \sim k_{\Uparrow} v_{\Uparrow}}$

-Enhanced ion abundances in flares reproduced by stochastic acc.
(C, O, Ne, Mg, Si, Fe, but some problems with He3/He4)

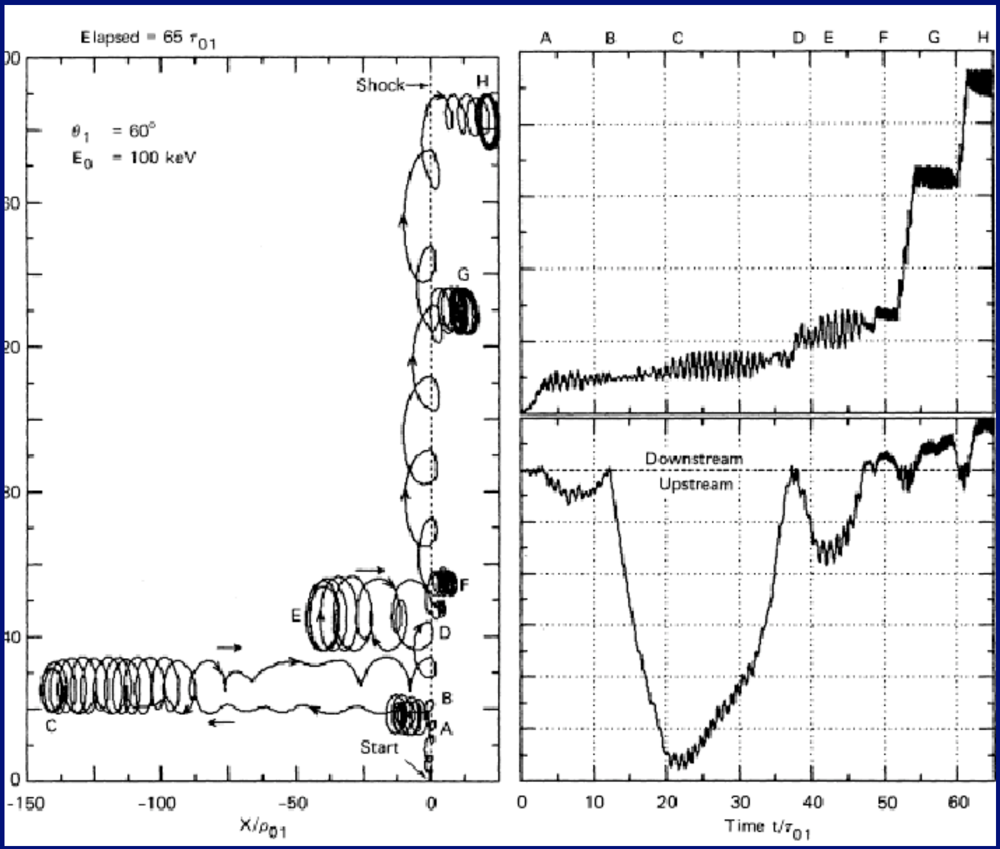






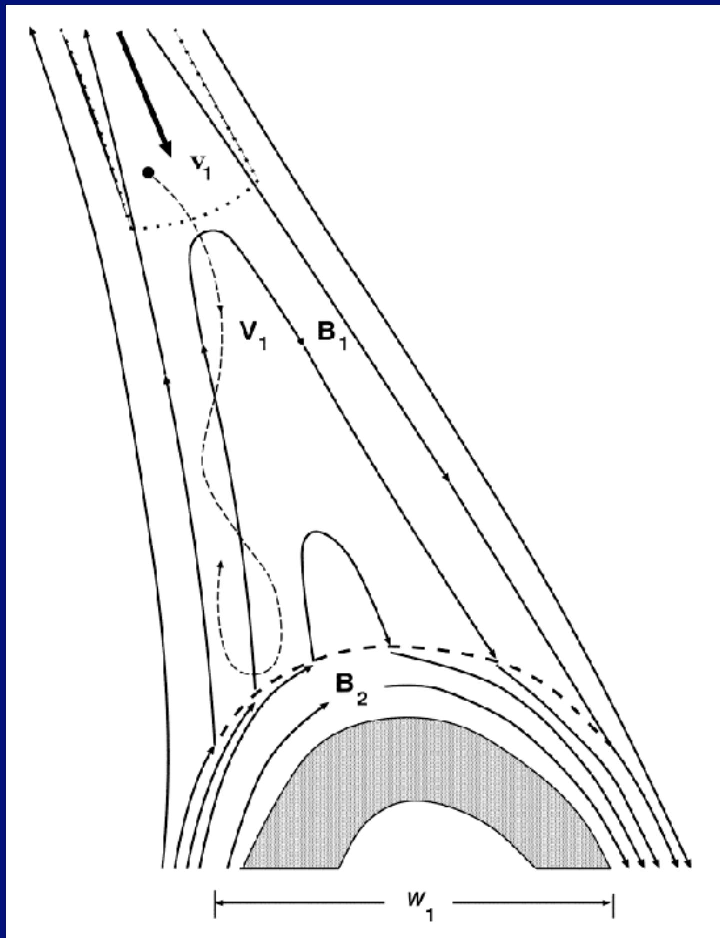
c) Shock acceleration

-First-order Fermi acceleration
(electric field E=-(v_sh/c)xB
in deHoffman-Teller frame)
-Diffusive (second-order Fermi)
(multiple shock crossings)

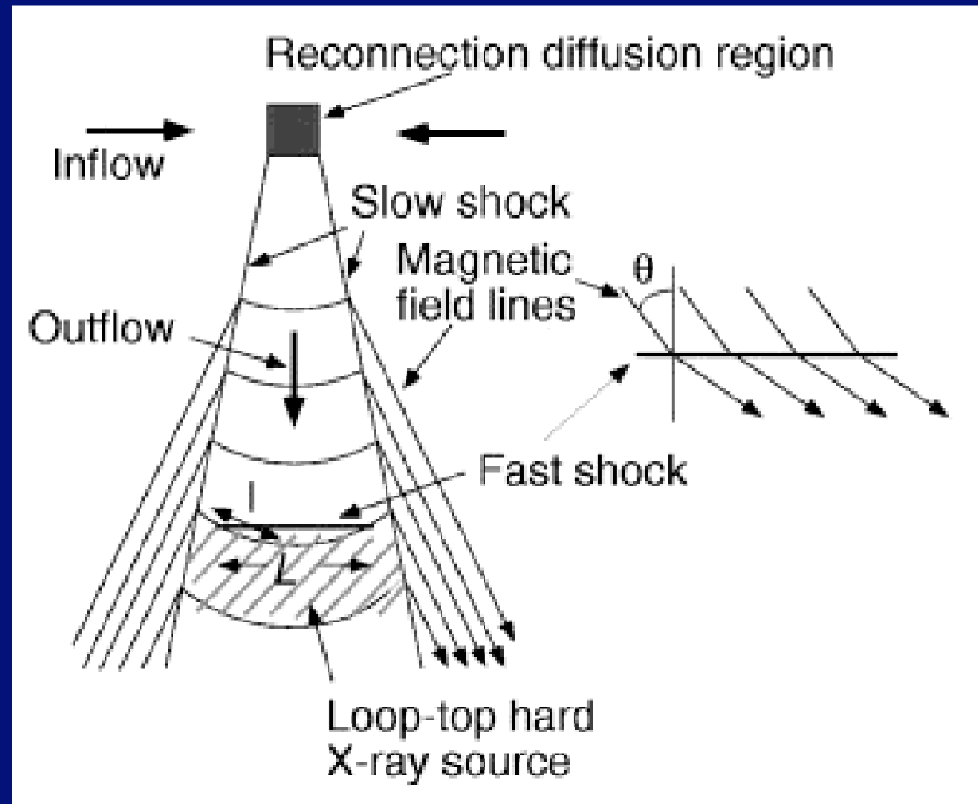


Particle orbit undergoes diffusive shock acceleration
in a quasi-perpendicular shock (60 deg)
by multiple crossings of the shock front
with magnetic mirroring upstream the shock front (x<0)

Decker & Vlahos (1986)



Somov & Kosugi (1997)



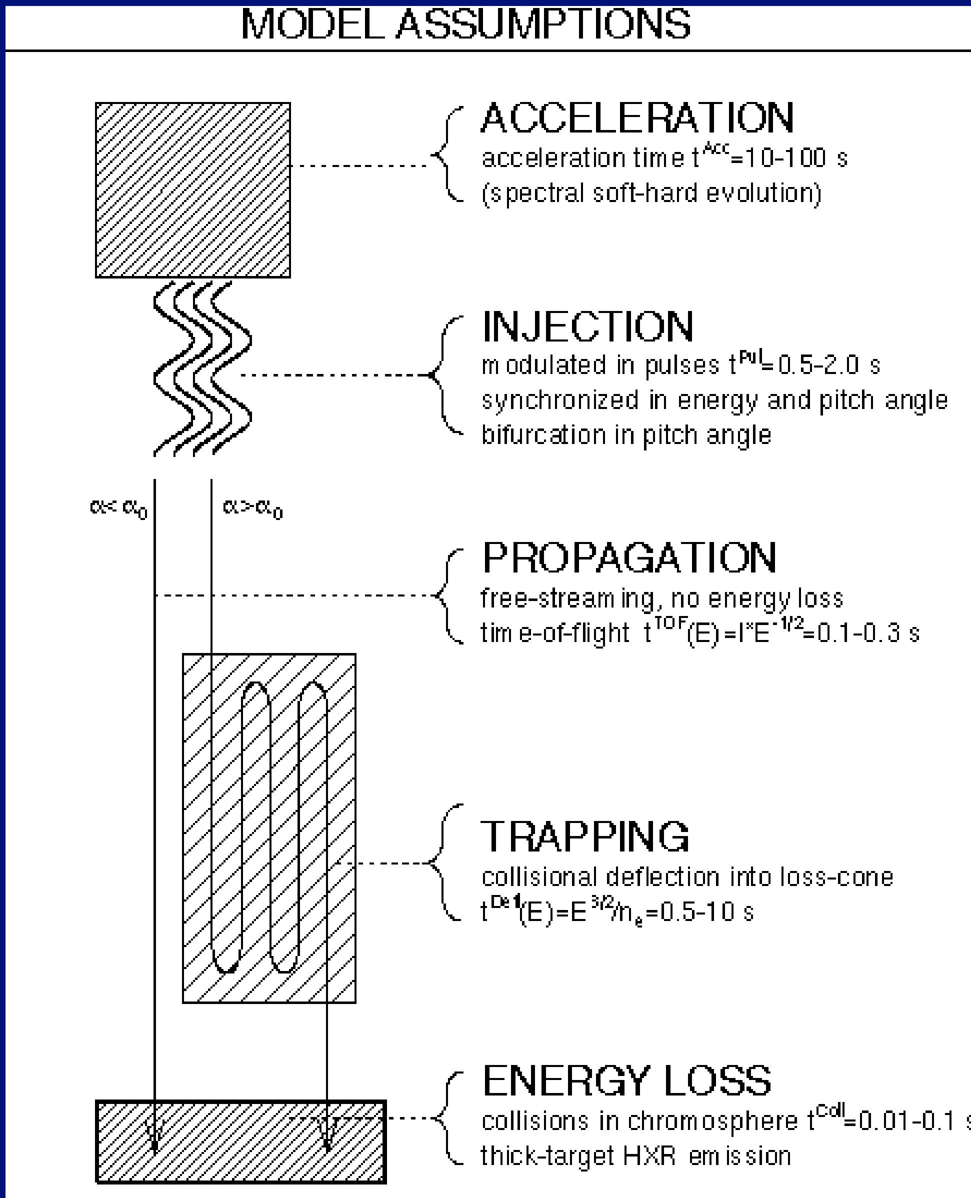
Tsuneta & Naito (1998)

<u>Applications of shock acceleration to solar flares :</u>

-First-order Fermi in mirror trap in flare loop cusp

-Fast shock in reconnection outflow above flare loop

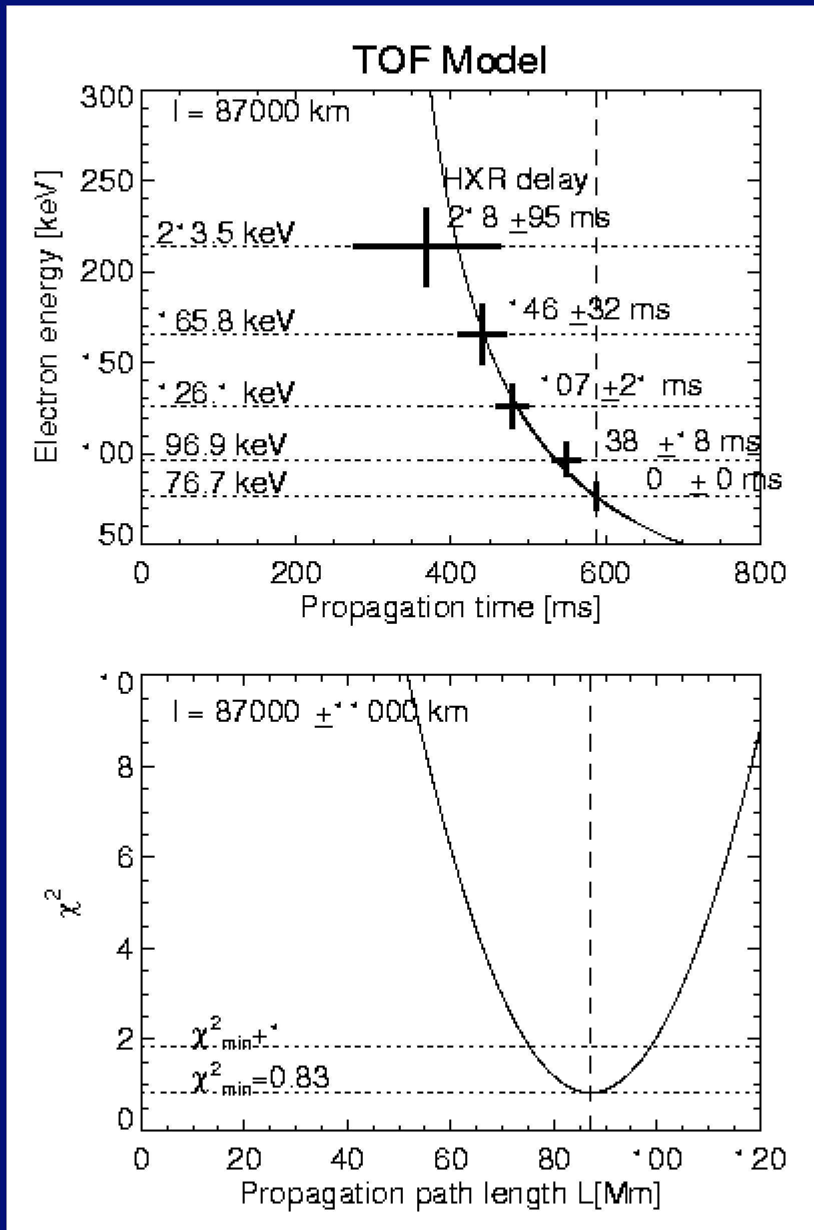
-Type II as shock front signature in interplanetary space



PARTICLE KINEMATICS:

Each particle transport process has its characteristic energy-dependent timing that can be used for diagnostic

- -acceleration dE/dt > 0
- -injection [pitch angle, α(t)]
- -time-of-flight t(E) ~ t/v(E)
- -trapping: collisional deflection
  time t(E) ~ E^3/2 / n_e
- -energy loss:
  t_loss << t_TOF



Electron time-of-flight
(velocity dispersion)

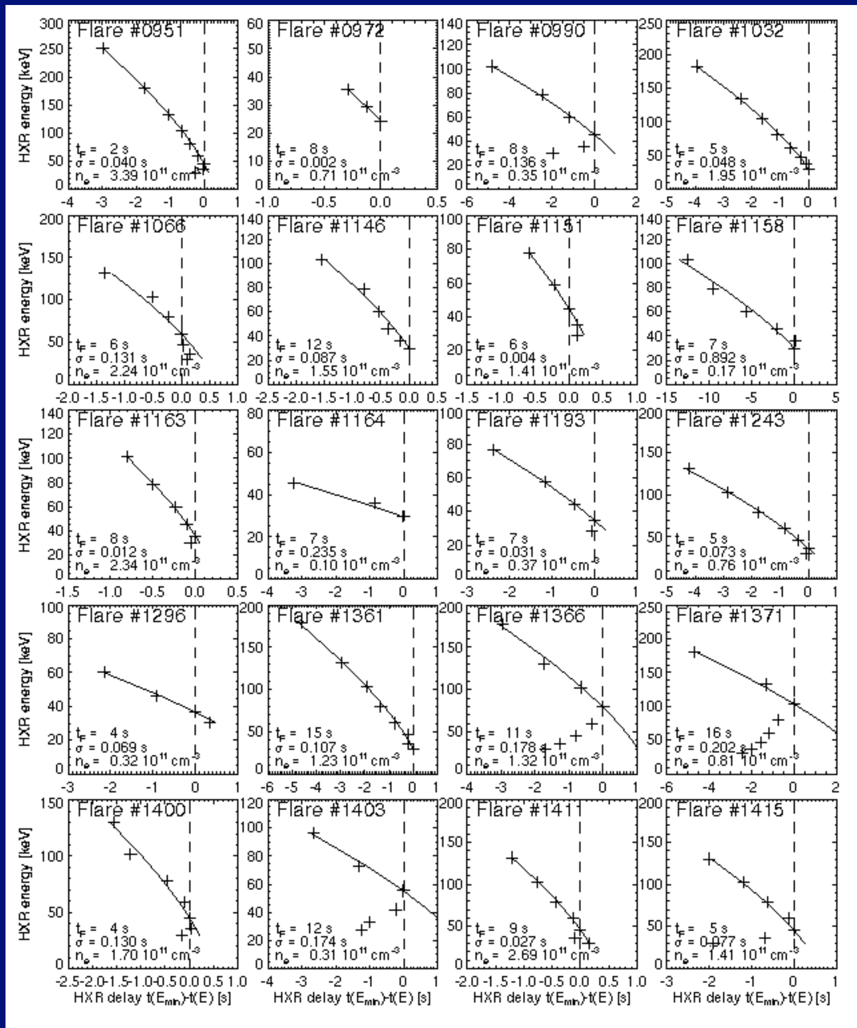
$t_1 - t_2 = L/v_1 - L/v_2$

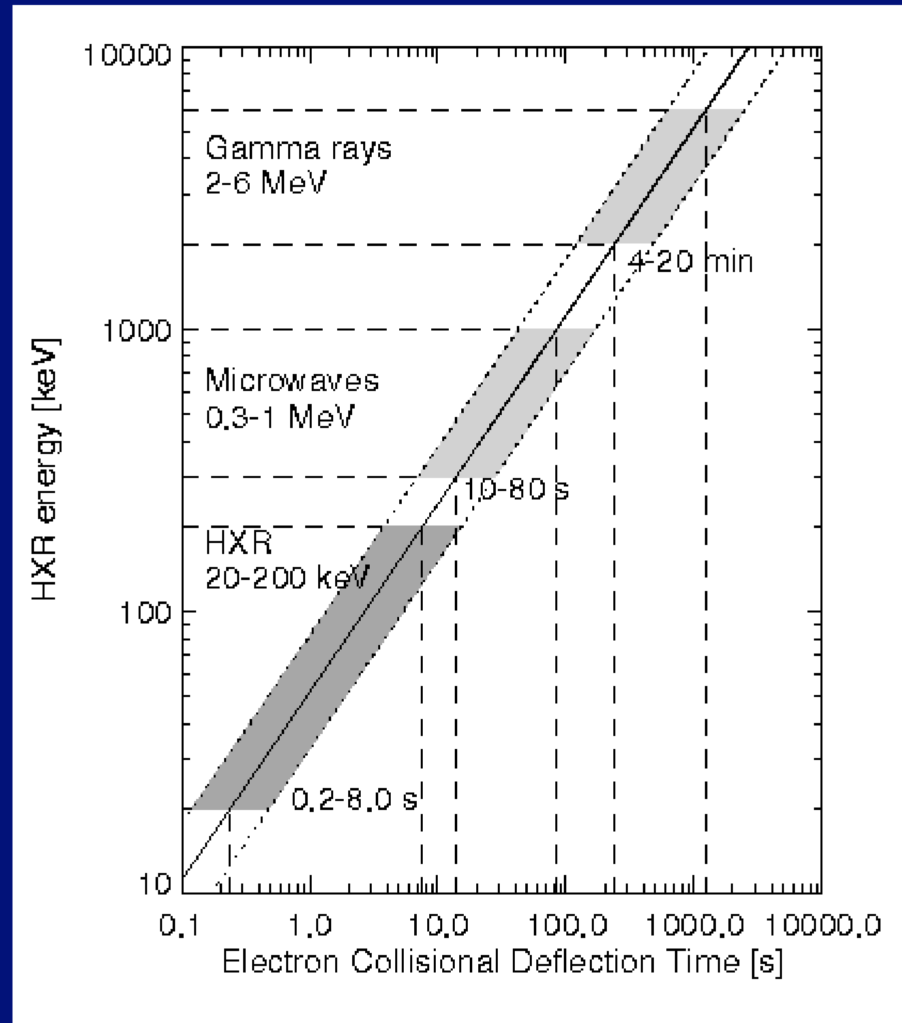
$v(E) = c\ [\ 1 - 1/\gamma^2]^{1/2}$

$E_{HXR} \sim 0.5\ E_{kin}$

pitch angle correction

magnetic field twist corr.

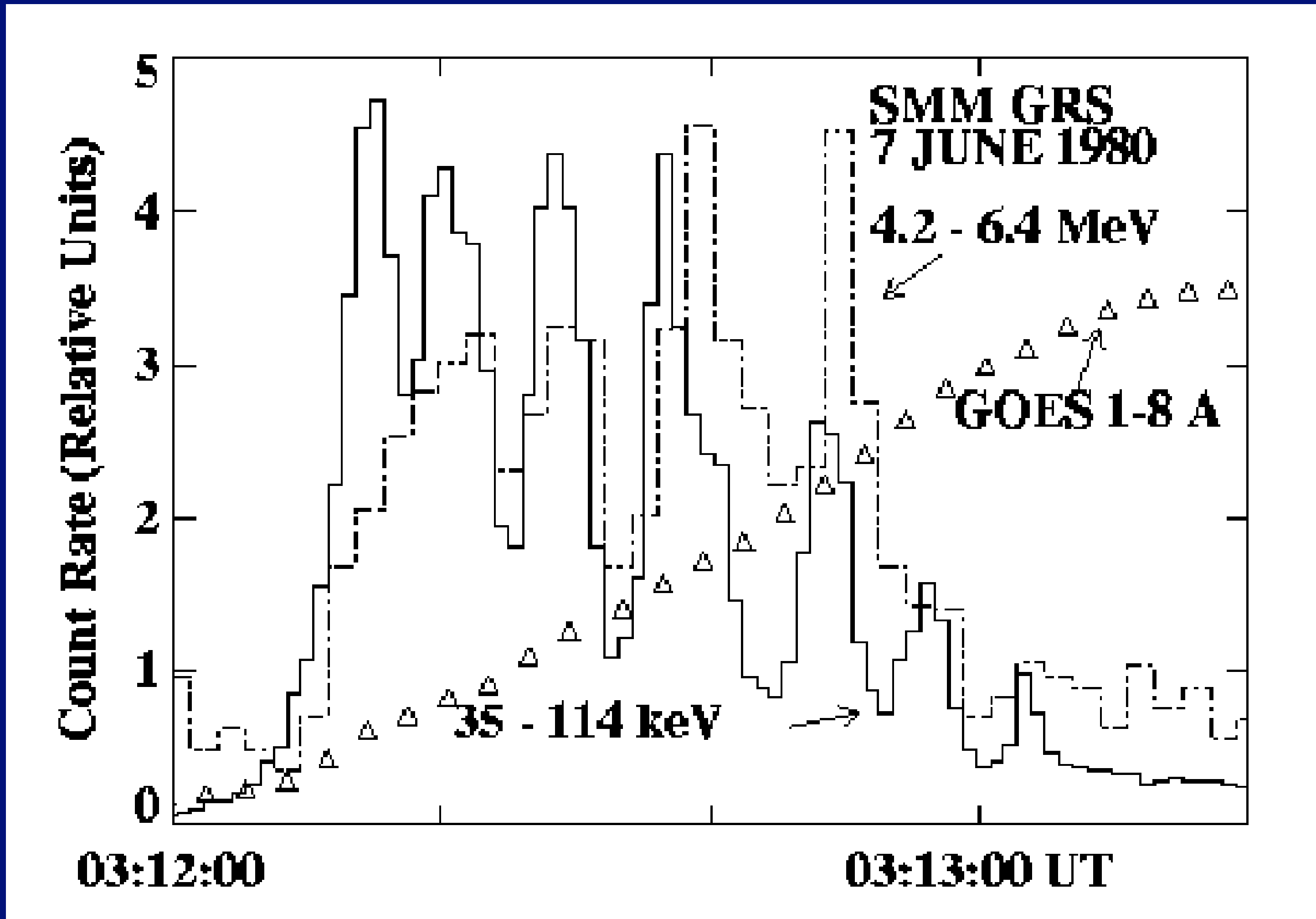




Electron trapping:

Weak-diffusion limt : collisional deflection time

t_trap (E) ~ E^3/2 / n_e → n_e ~ 10^10-10^12 cm-3



Electron vs. ion acceleration :

- gamma ray pulses delayed with respect to hard X-rays by few sec
- time-of-flight difference between ions and electrons dt=L/v_e-L/v_I (v_i ~ v_e/42)

Clue 3:

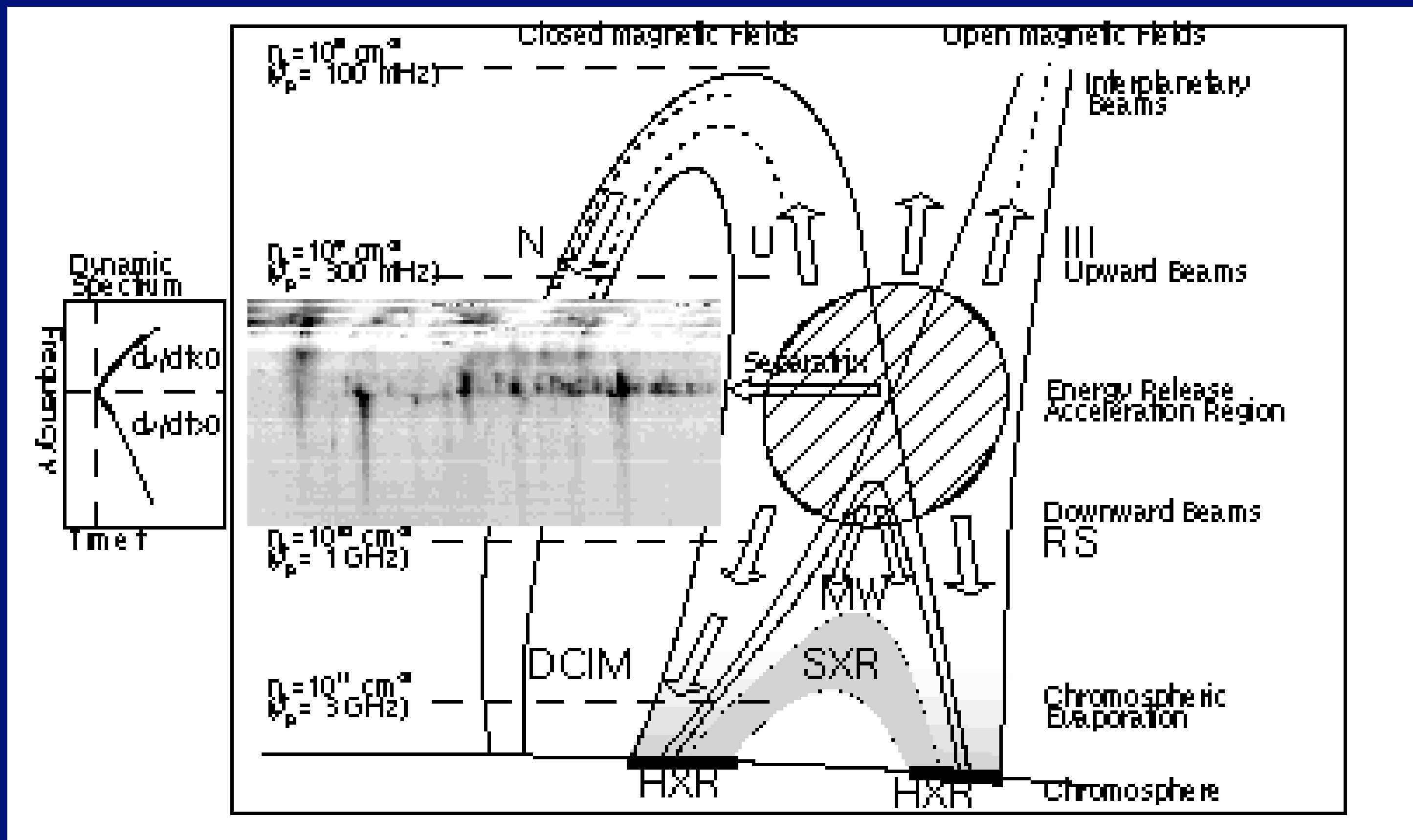
The vertical symmetry of magnetic reconnection regions warrant simultaneous acceleration in upward and downward direction. This applies to all 3 basic acceleration mechanisms:

(a) electric DC field in reconnection X-point

(b) stochastic acceleration in wave turbulence in reconnection region

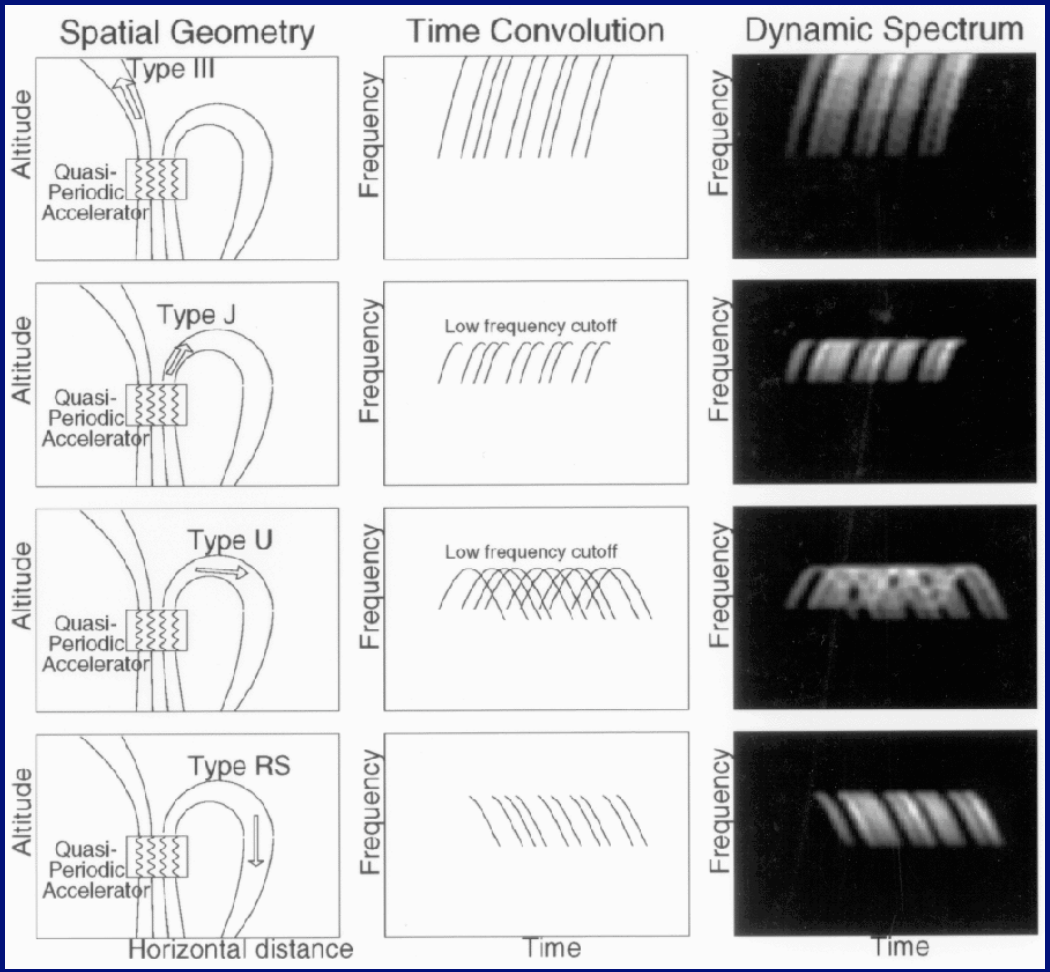
(c) fast shocks in Petschek magnetic reconnection configuration.

4) UPWARD VS. DOWNWARD ACCELERATION



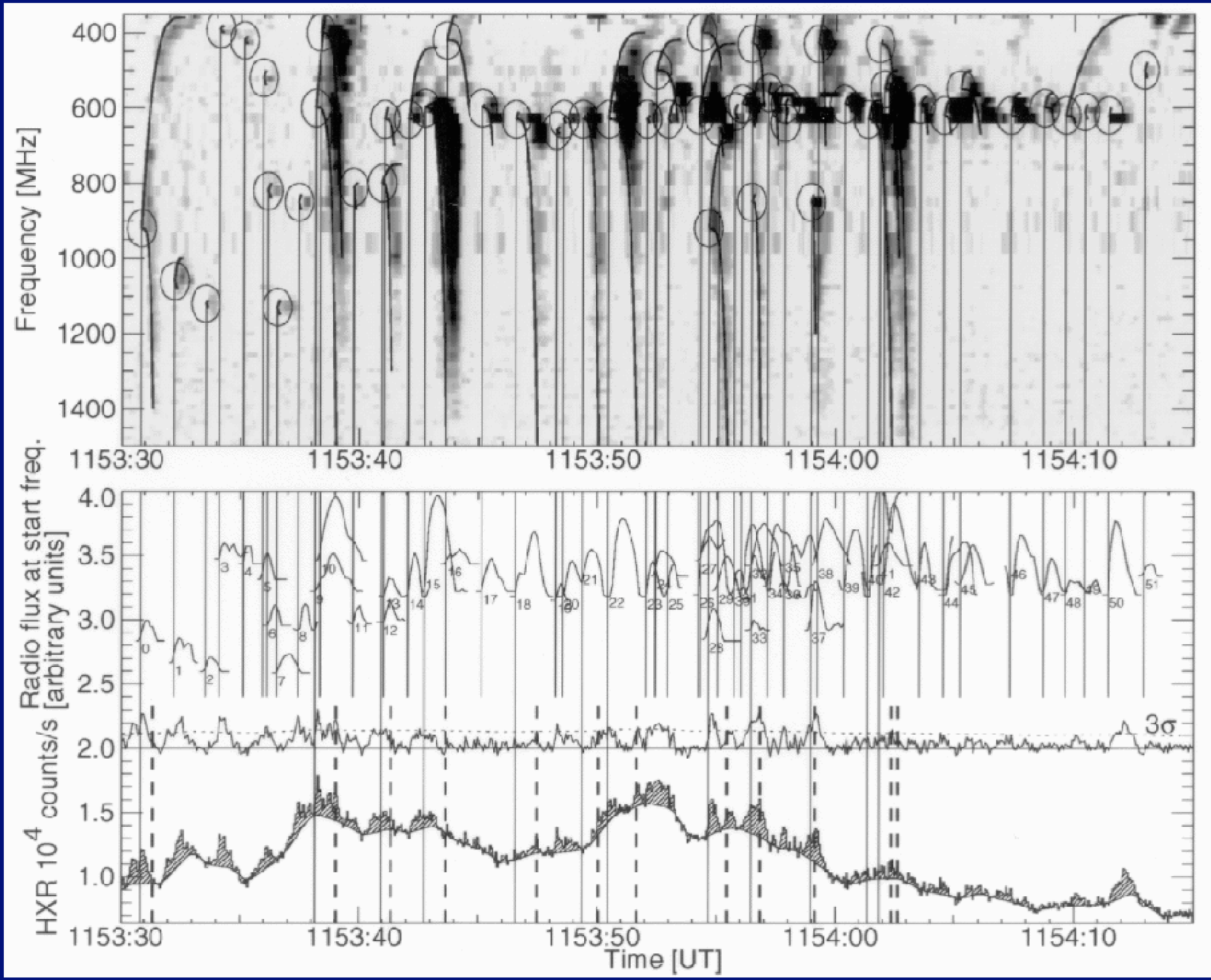
Radio: electron beams along open and/or closed field lines produce
plasma emission (radio type III, J, U, N, RS bursts)

Predictions: bi-directional beams (type III+RS pairs)
correlated pulses in radio (type III) and hard X-rays

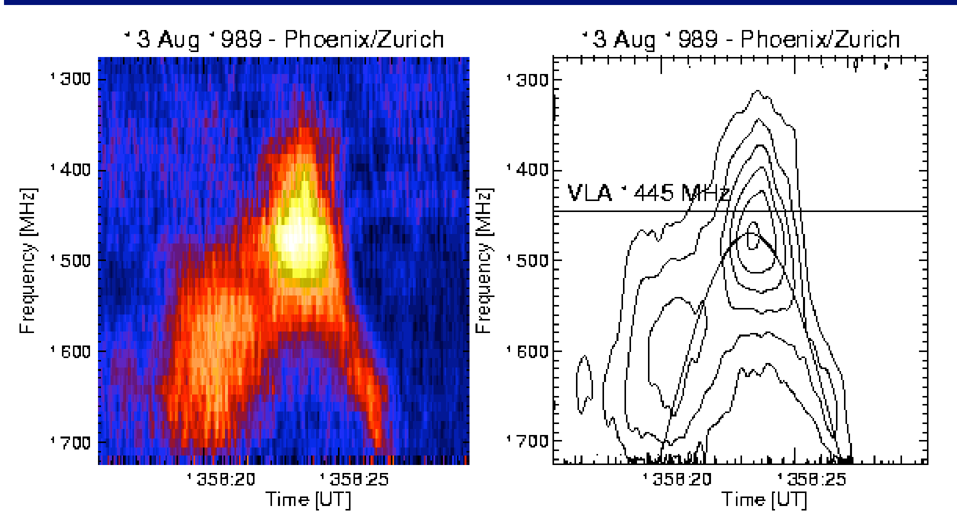


Electron beam trajectories diagnosis for radio dynamic spectra:

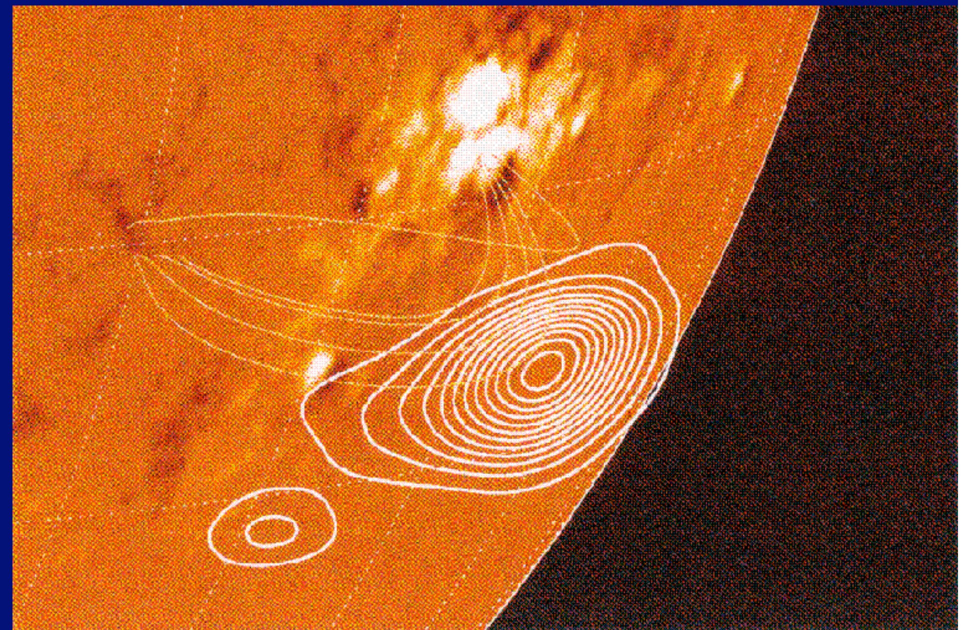
- open magnetic field lines (type III)
- closed magnetic field lines (type J, U)
- downward propagating electron beams (type RS)



Acceleration region bracketed by upward/downward electron beams:
→ triple correlations between radio type III, RS and HXR pulses



Aschwanden, Bastian, Benz, & Brosius (1992)



<u>Spatial reconstruction of electron beam propagation:</u>

-radio dynamic spectra: type U burst turnover frequency 1.445 GHz

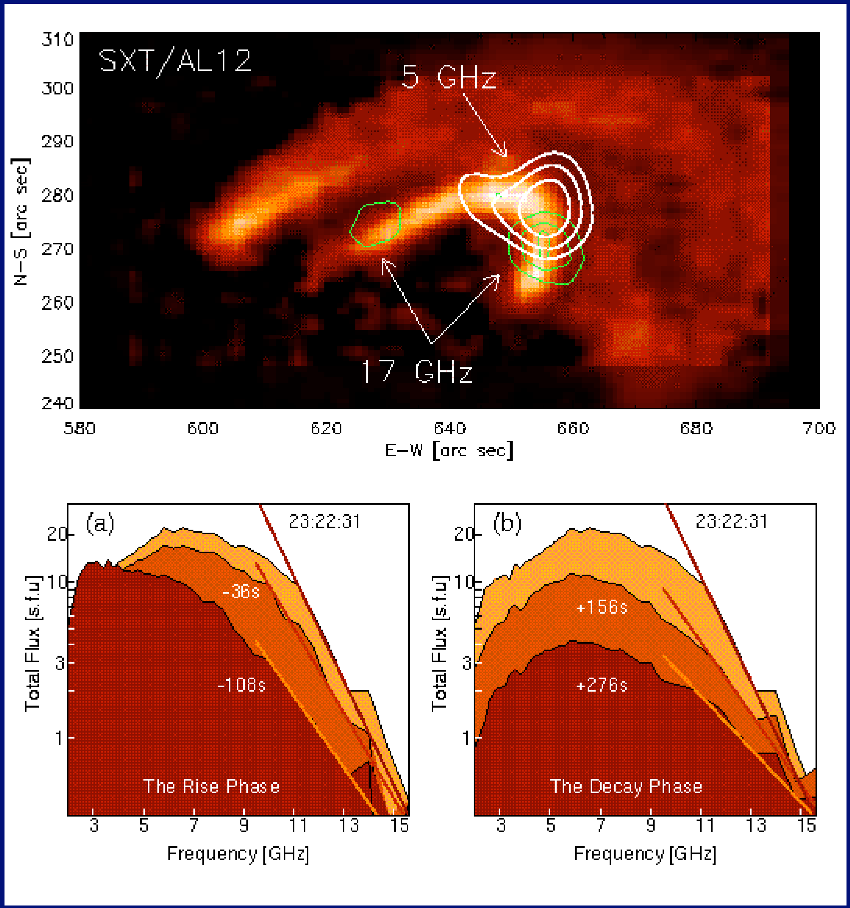
 → electron density n_e=(2*10^10 cm-3) at loop top

-radio image at 1.445 GHz (with VLA)

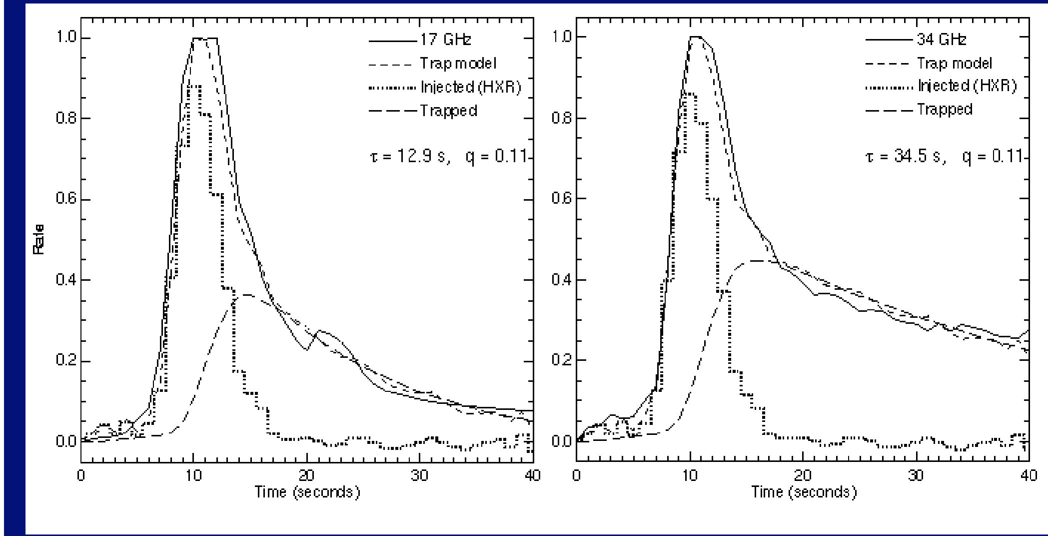
 → spatial location of loop top

-magnetic field extrapolation (KPNO)

 → footpoints and origin of electron beam acceleration



Lee & Gary (2000)



Kundu, White, Shibasaki et al. (2001)

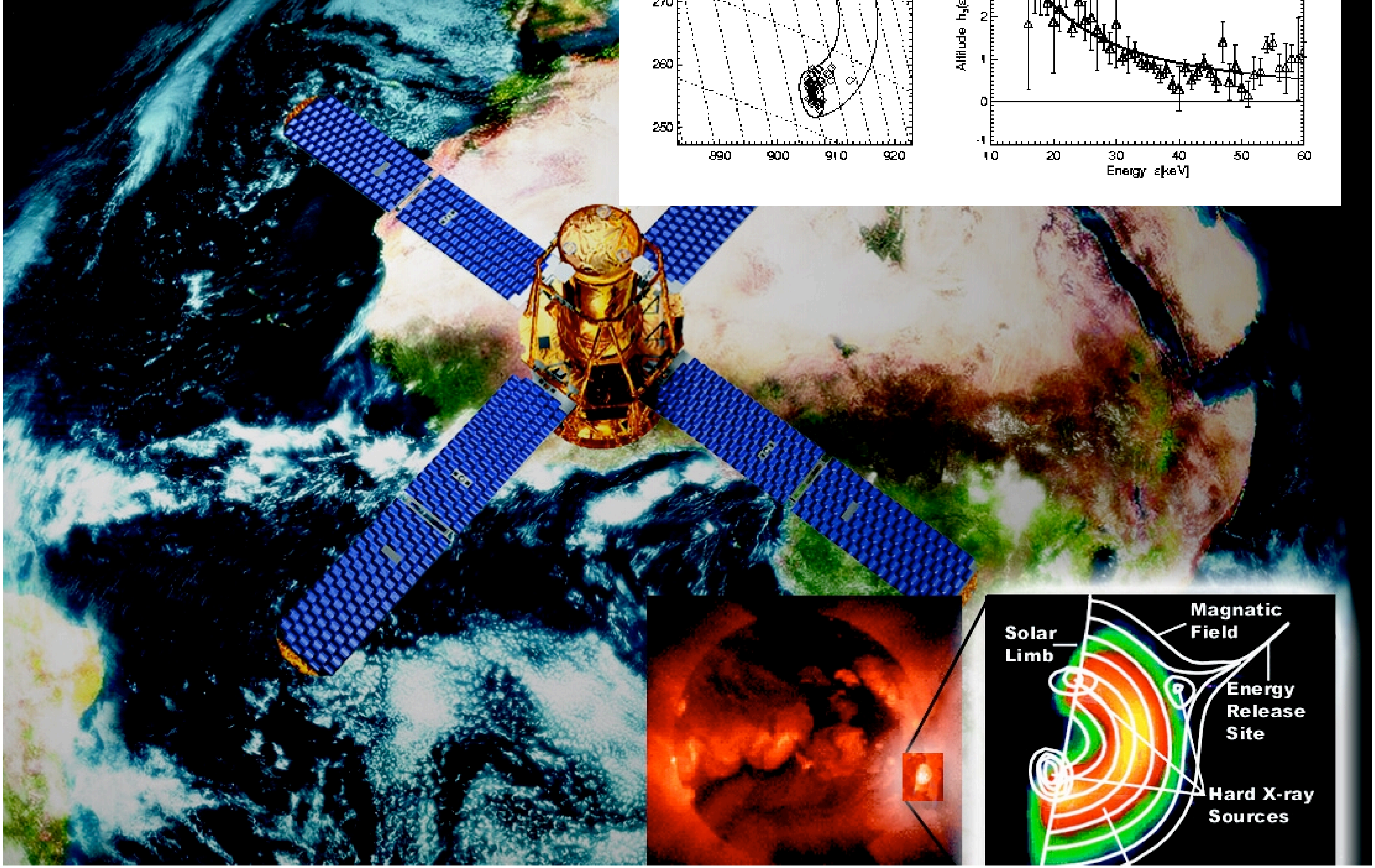
Gyrosynchrotron emission of trapped electrons :

→ pitch angle distribution of accelerated/injected electrons

Time profile components and e-folding deconvolution :

→ separation of directly-precipitating and trapped electrons (trap. time)

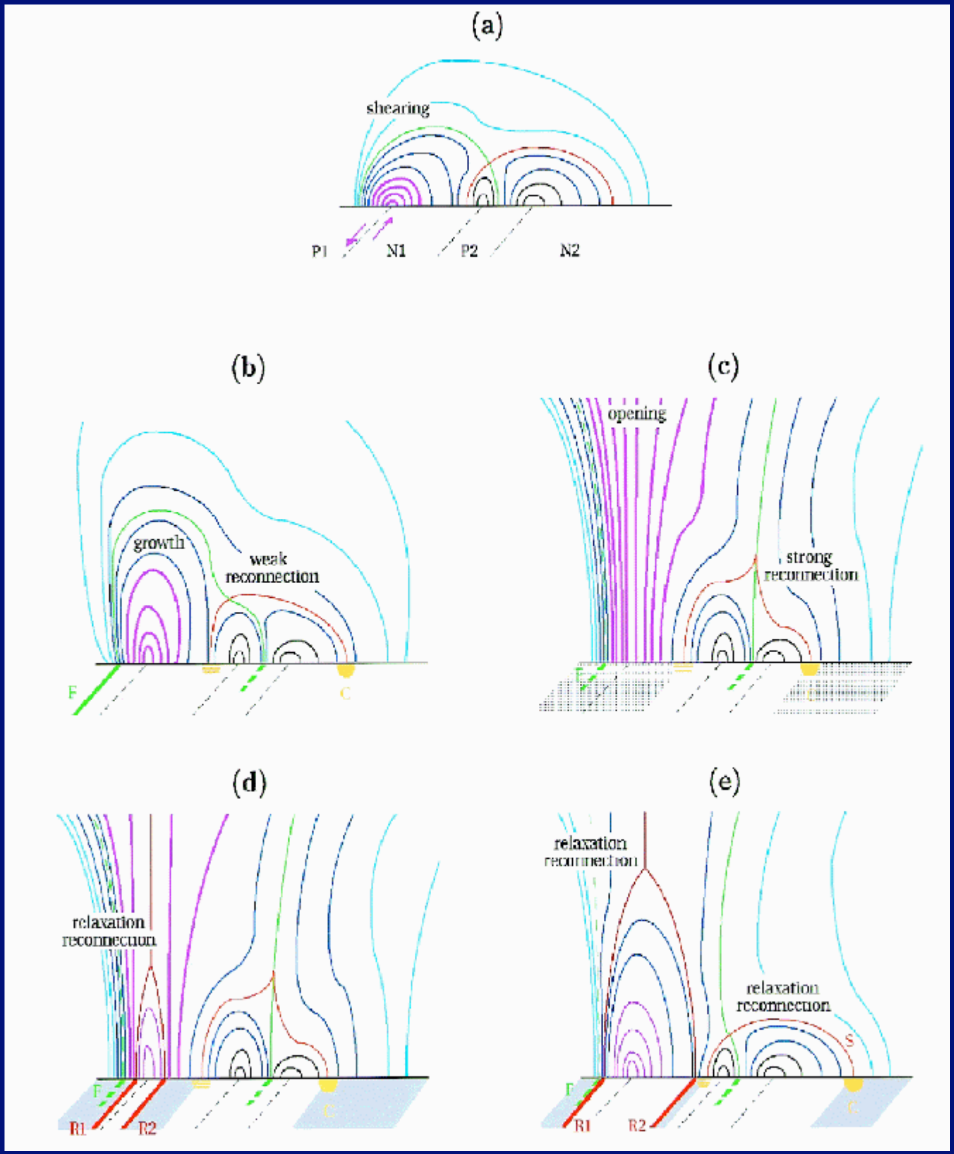
RHESSI results:
Height of hard X-rays h(E)
(Aschwanden, Brown & Kontar 2002)



Clue 4:

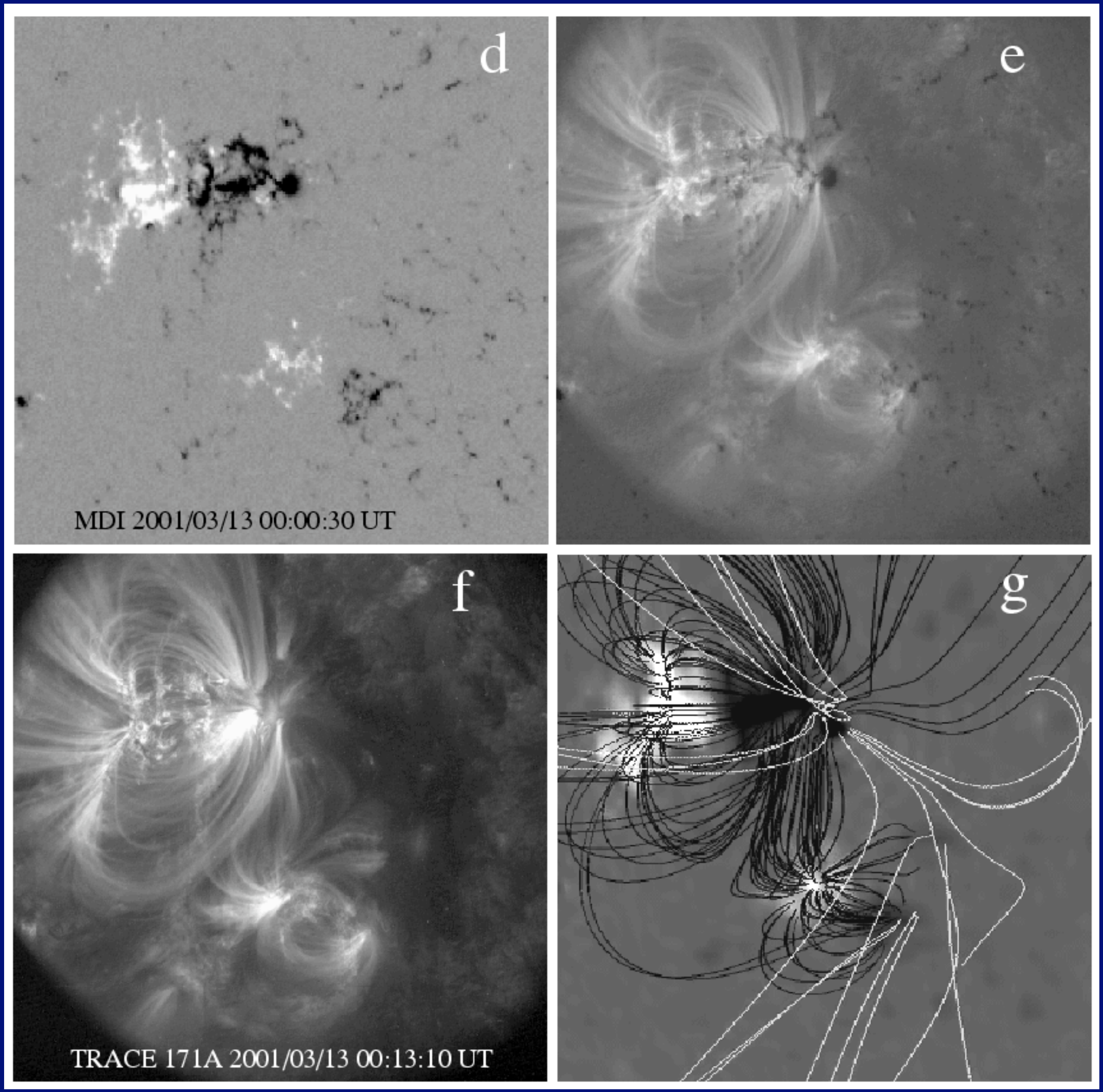
The vertical symmetry of magnetic reconnection regions warrant simultaneous acceleration in upward and downward direction. However, the outgoing magnetic field lines above magnetic X-points can be closed (type U-bursts), and thus do not necessarily warrant escape into interplanetary space. 15% of large flares suggest a completely confined magnetic configuration (radio-quiet flares: Simnett & Benz 1985).

5) ESCAPE INTO INTERPLANETARY SPACE



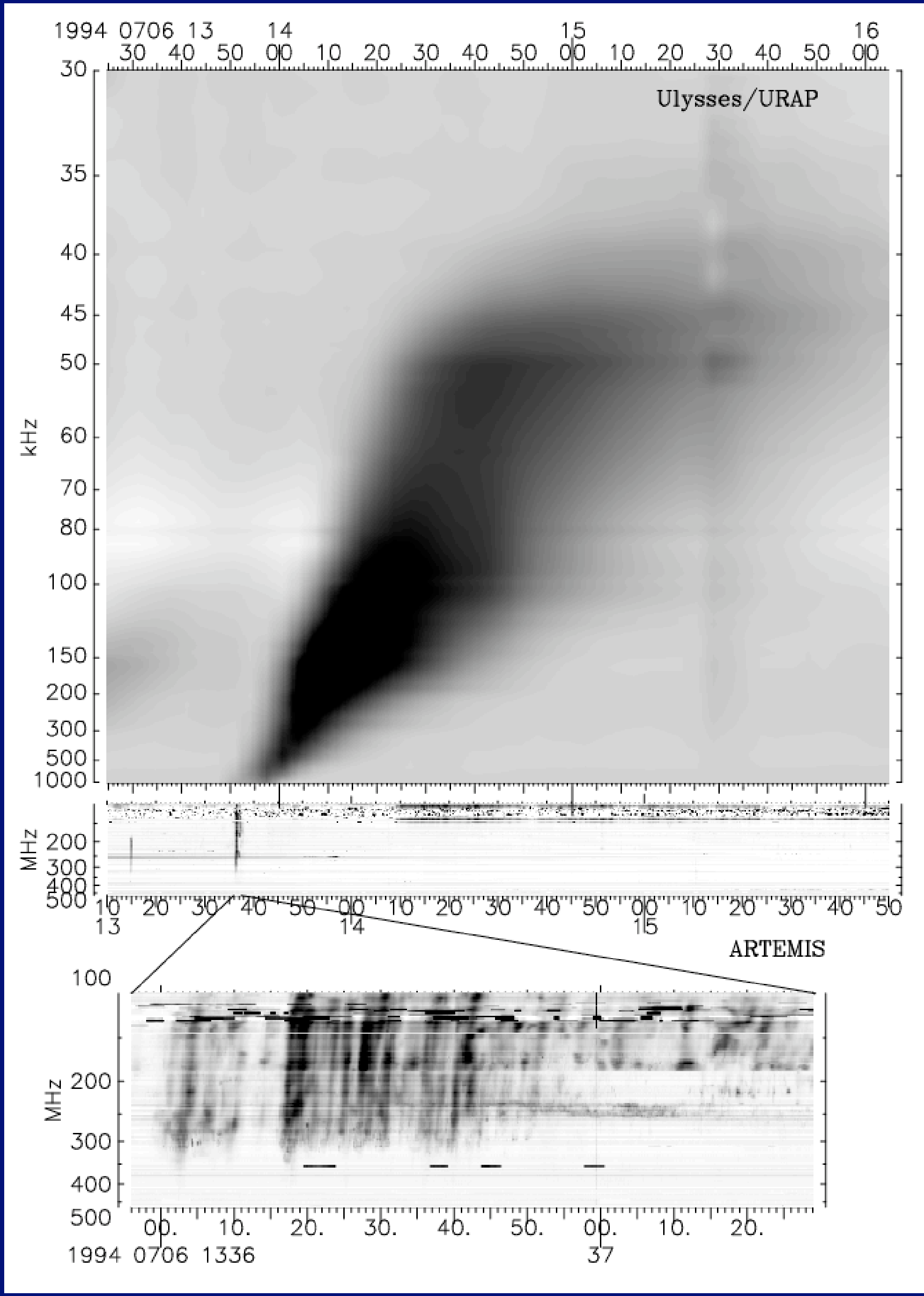
The escape of flare-accelerated particles into interplanetary is faciliated on one hand by temporarily opened fields during the magnetic reconnetion process.

For instance, during the "magnetic break-out model" (Antiochos et al. 1999), a temporary opening of a secondary arcade occurs during the reconnection process.



On the other hand, there are also pre-existing open field lines that allow particles to escape.

Schrijver & DeRosa (2003) Found from potential field extrapolations that a fraction of the IMF connects directly to plages of active regions (<10% in solar min. 30-50% at cycle max.)



Almost every interplanetary type III burst, whose spiral field line is connected to the visible disk or limb of the Sun, Is found to be associated with a group of solar metric type III bursts.

This is the finding of a study With Ulysses/URAP and Artemis/Nancay (Pocquerusse et al. 1996).

Clue 5:

Flare particles can escape into interplanetary space (1) either via pre-existing open field lines in active region plages, (2) or by dynamic opening during the reconnection process (e.g., during the "magnetic breakout model").

CONCLUSIONS :

1) *Magnetic topology of acceleration region show dipolar, tripolar and quadrupolar configurations. Only dipolar and tripolar cases involve open field lines, and thus allow particles to escape into interplanetary space.*

2) *The altitude of acceleration regions in flare sites is confined to h_acc=5000-35,000 km (<0.05 solar radii). Acceleration sites at larger distances to the Sun are likely to associated with CME shocks.*

3) *The vertical symmetry of acceleration sites warrants simultaneous acceleration in upward and downward direction (e.g., electric DC fields, wave turbulence regions, fast shocks in Petschek-type reconnection sites).*

CONCLUSIONS (cont.):

4) *Outgoing magnetic field lines in upward direction of magnetic reconnection regions can be open (type III bursts) or closed (type U bursts), and thus do not always warrant a getaway for accelerated particles into interplanetary space.*

5) *Accelerated flare particles can escape into interplanetary space (a) either via pre-existing open field lines in active region plages, or (b) by dynamic opening during the reconnection process (e.g., during the "magnetic breakout model").*

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