WG-V: Theoretical Implications-Summary

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Main constraints on theoretical models

- C1: Energetics: Why flares are so efficient accelerators? Around 50% of the total magnetic energy released in a large flare goes to energetic particles. In most astrophysical objects the efficiency is less than 50%. Exceptions are GRB and a few other objects.

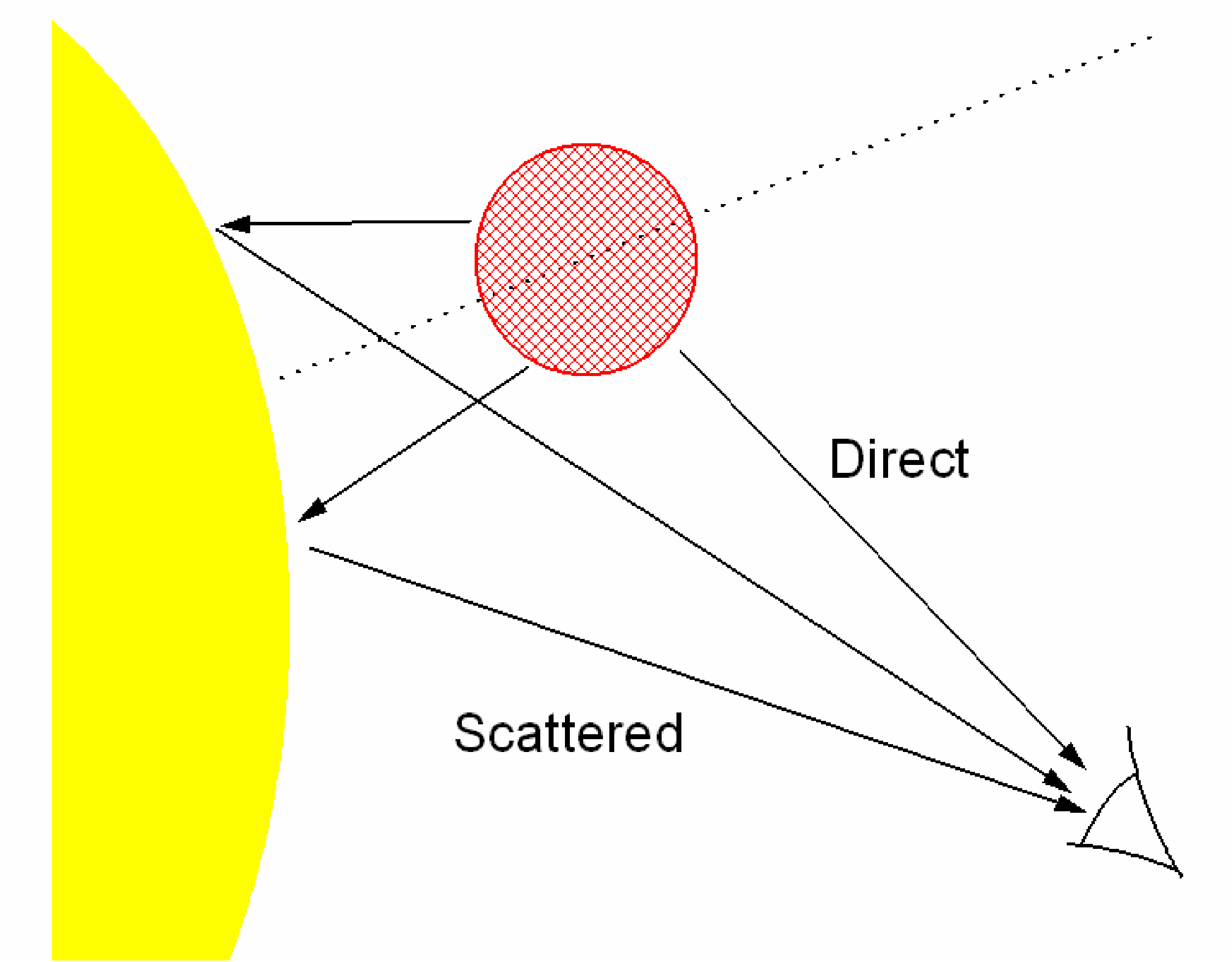
Main constraints on theoretical models

- C2 The number problem: We usually quote that 10^37 electron/sec. Assuming that the flares duration is 100 secs this number may get up to 10^39 particles. Which means that a volume of 10^30 cm^3 with 10^9 particles/cm^(-3) was evacuated!

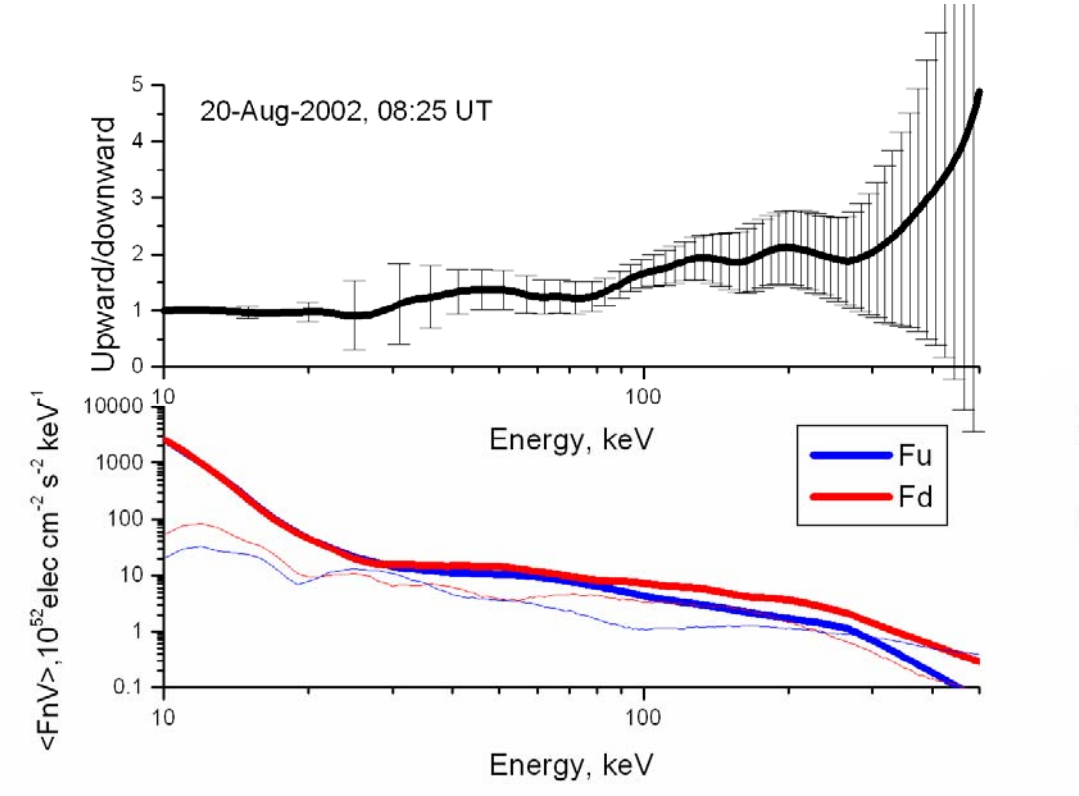
Main constraints on theoretical models

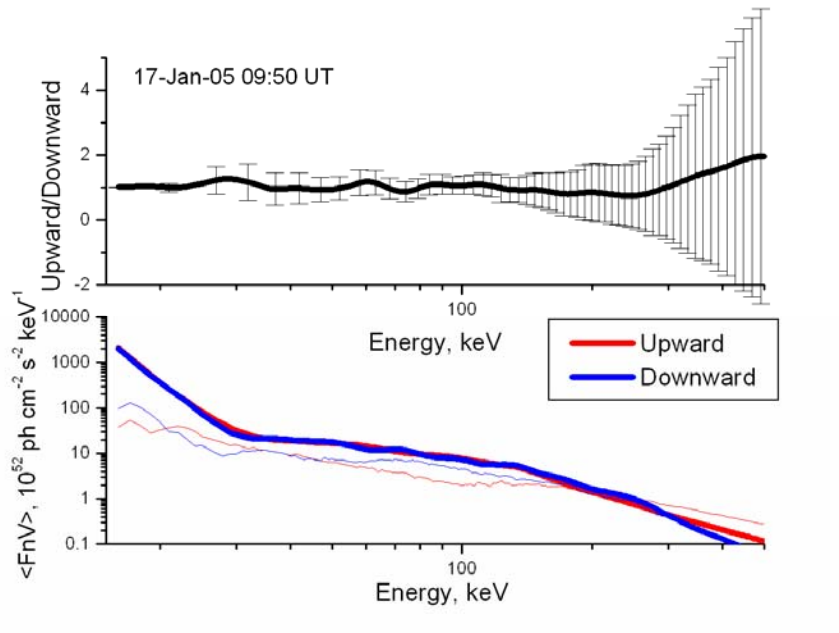
- Are these numbers model dependent?
  - The basic assumption is the thick target model which assumes that the accelerator is in the corona, were collisions are irrelevant, and the X-ray source in the chromoshere were collisions are dominant.

Directivity of the Hard X-ray emitting radiation



20-Aug-2002 and 17-Jan-2005



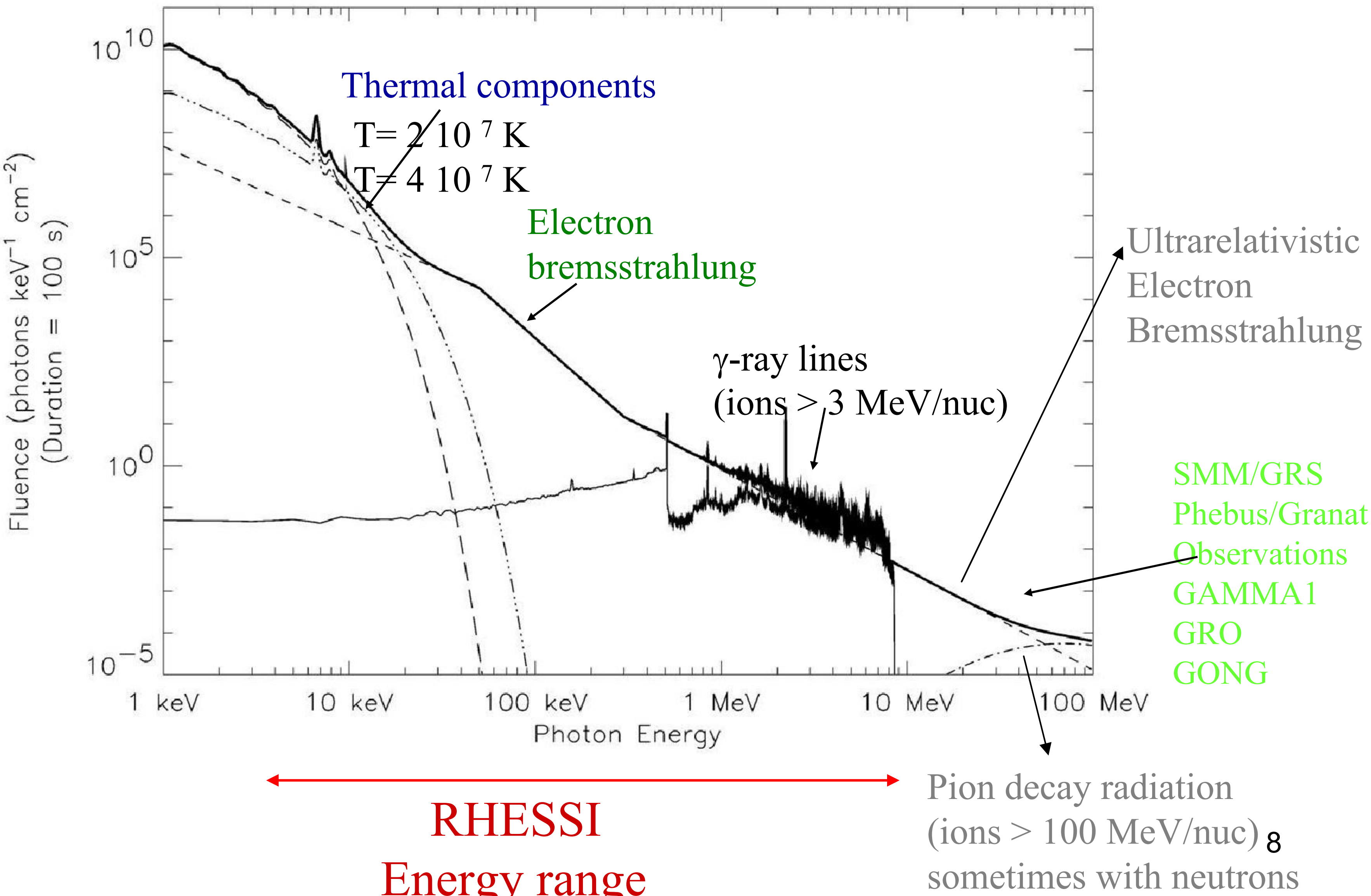


Distribution is close to isotropic

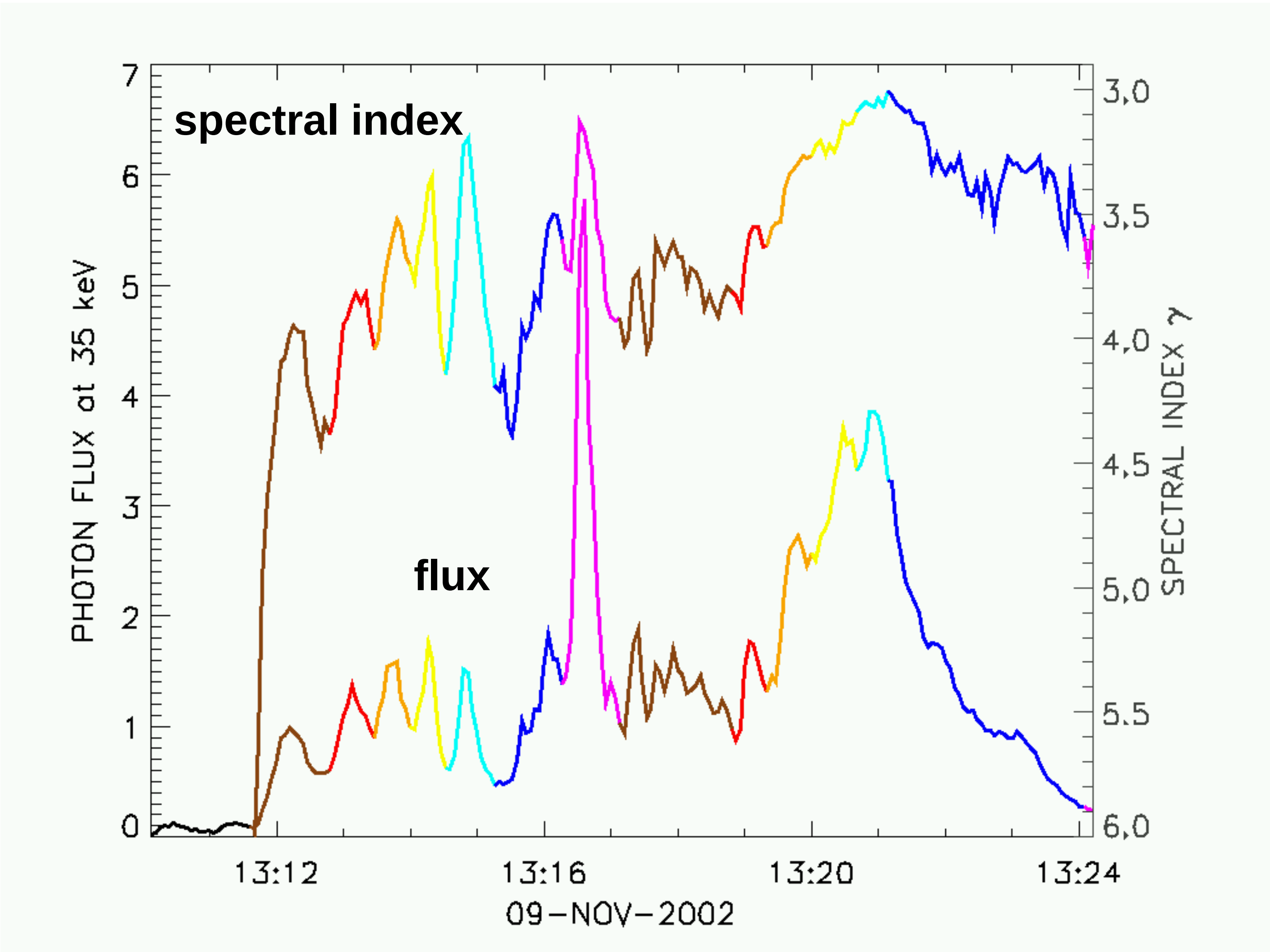
Data are not consistent with downward directed beam

Main constraints on theoretical models

- C3. The shape of the electron energy distribution
  - We have now define this with some confidence

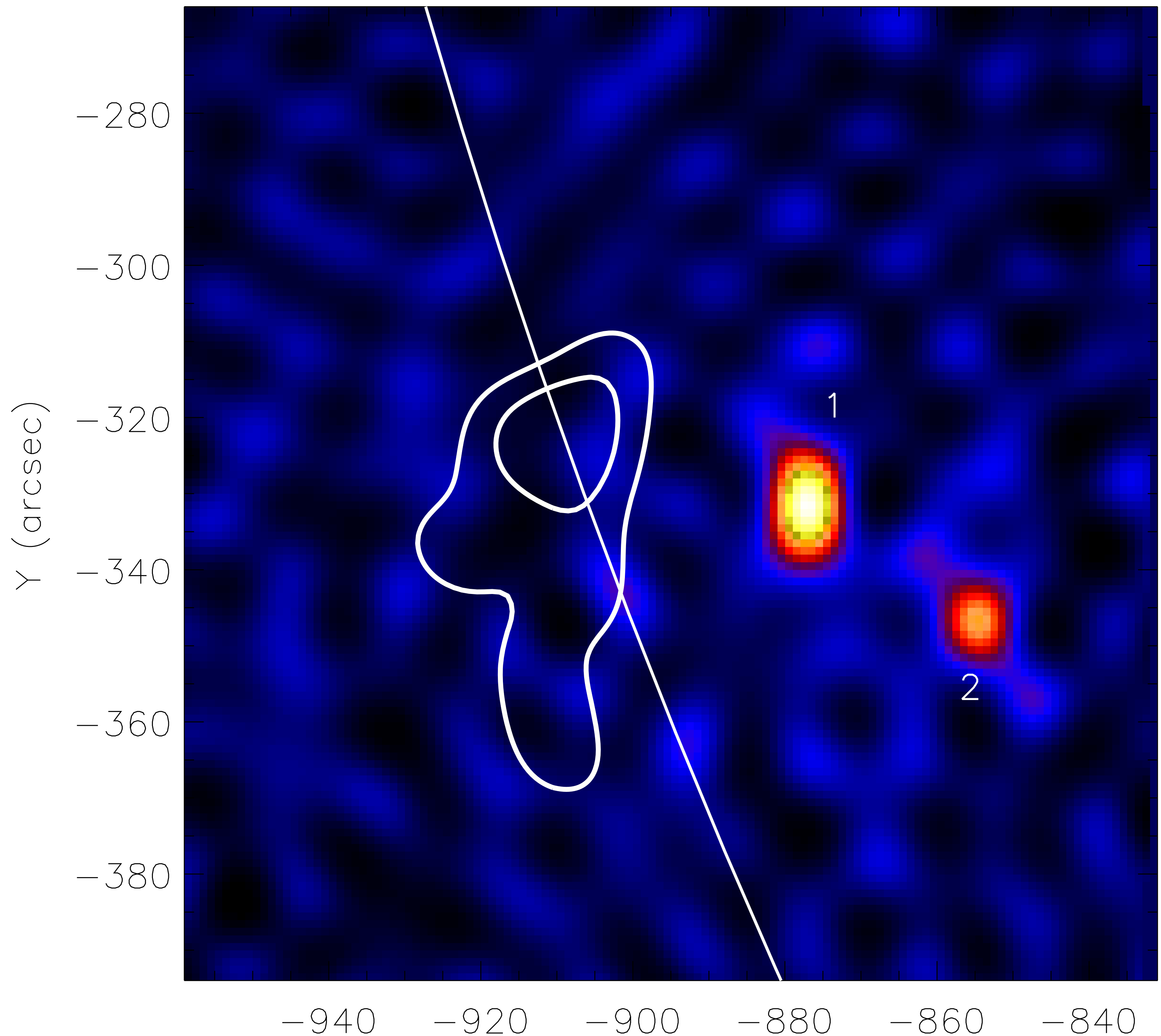

Thermal components
T= 2 10 7 K
T= 4 10 7 K
Electron
bremsstrahlung
γ-ray lines
(ions > 3 MeV/nuc)
Ultrarelativistic
Electron
Bremsstrahlung
SMM/GRS
Phebus/Granat
Observations
GAMMA1
GRO
GONG
Fluence (photons keV^{-1} cm^{-2})
(Duration = 100 s)
10^{10}
10^{5}
10^{0}
10^{-5}
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
Photon Energy
RHESSI
Energy range
Pion decay radiation
(ions > 100 MeV/nuc)
sometimes with neutrons

C4. The hard-soft-hard evolution



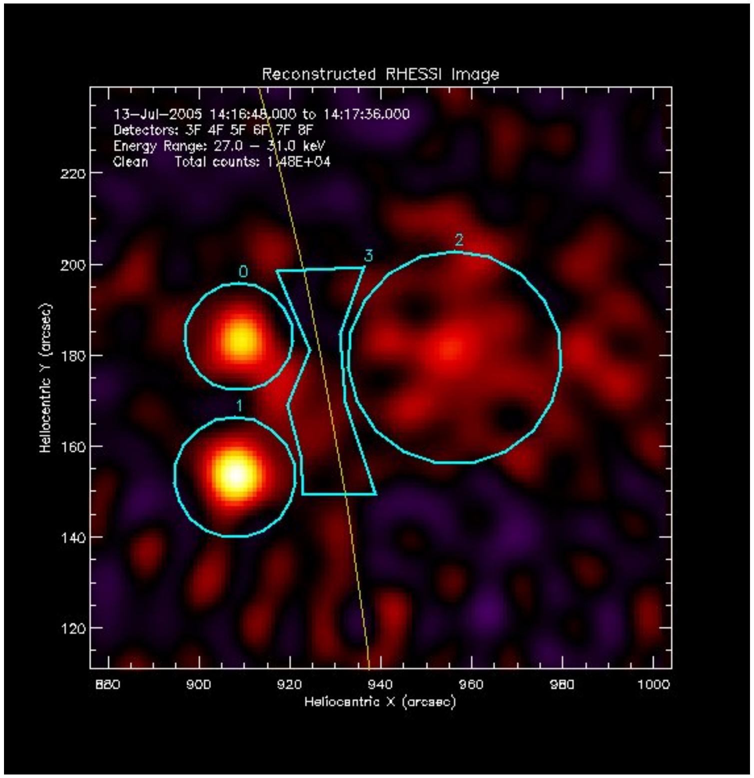
Grigis & B.

1. C5 Multiple (choromosheric and coronal) sources and their correlation


Y (arcsec)
−280
−300
−320
−340
−360
−380
−940
−920
−900
−880
−860
−840
1
2

What relation between sources?

- Use imaging spectroscopy
- Define regions of interest



Main constraints on theoretical models

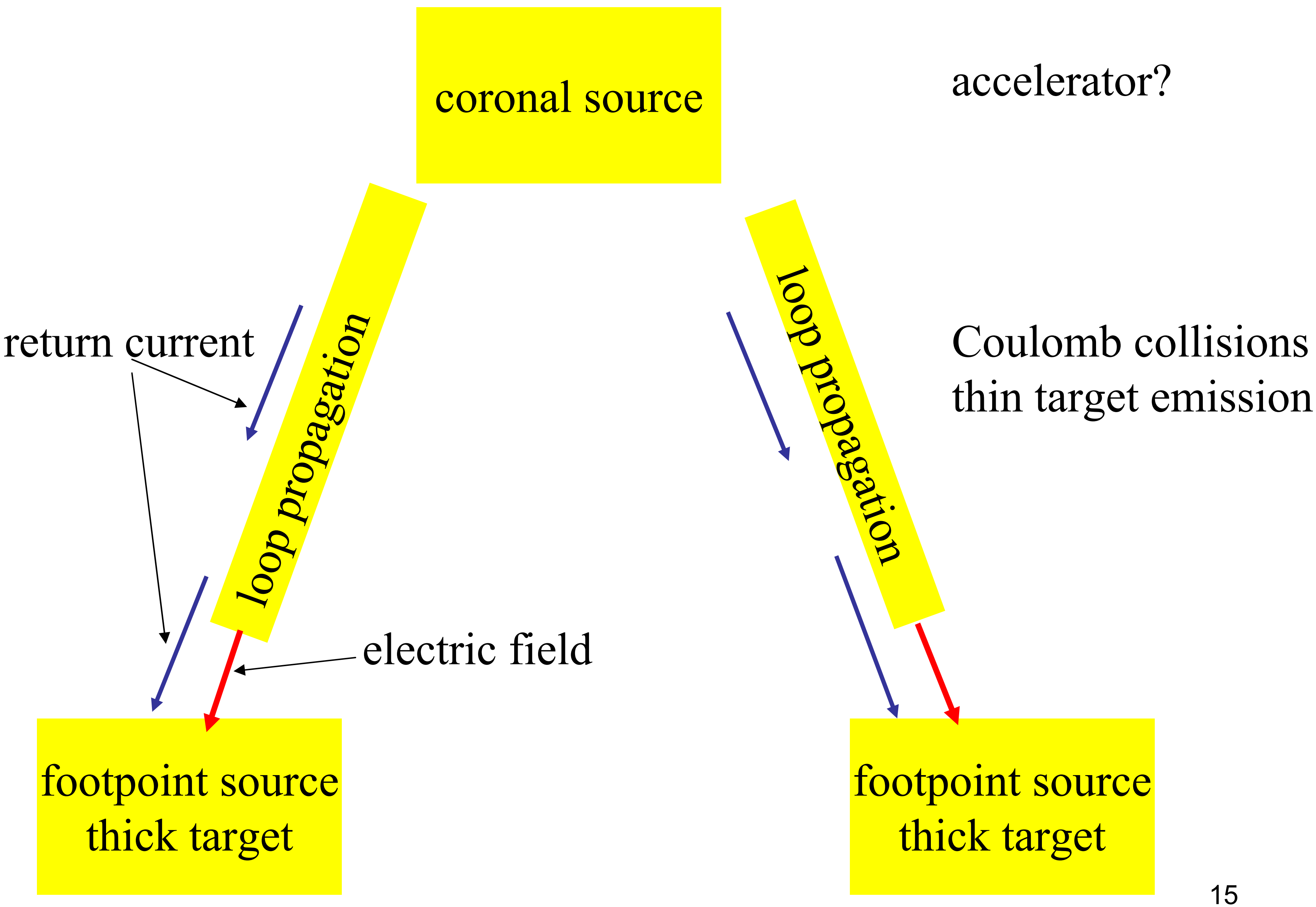
Coronal source

- dominant thermal component
- weak and soft non-thermal component
- soft-hard-soft behavior
- evolves nearly simultaneously to footpoints

Footpoint sources

- γ between 0 and 4 harder than in coronal source

- same spectral index in footpoints in 4 of 5 flares


coronal source
accelerator?
return current
loop propagation
loop propagation
Coulomb collisions
thin target emission
electric field
footpoint source
thick target
footpoint source
thick target

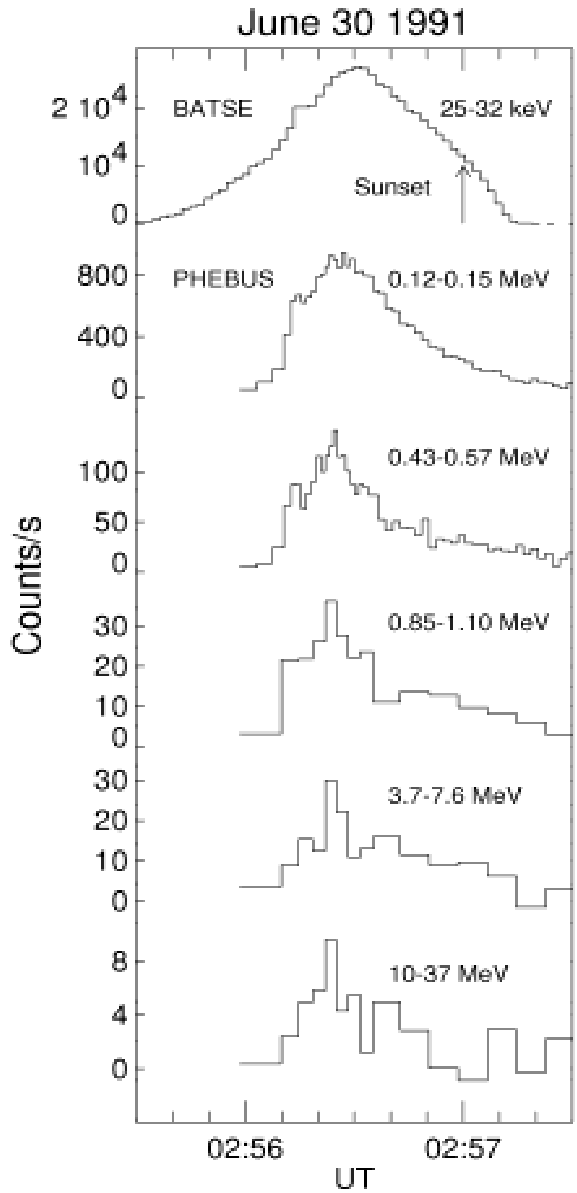
Relativistic electrons and Ions

- C6. ENHANCEMENT OF A/P AND HEAVIES—ACCELERATION PROCESSES THAT DO THIS AT THE SUN.
- C7. SHIFT IN LOCATIONS OF ION AND ELECTRON FOOTPOINTS.
- C8. WHAT CAUSES THE HIGH-ENERGY LONG DURATION TAILS (ASSOCIATED WITH RADIO)?

Relativistic electrons and Ions

- C9. HOW DOES THE SUN ACCELERATE ELECTRONS TO SEVERAL HUNDRED MEV?

ne 30 1991 electron dominated event



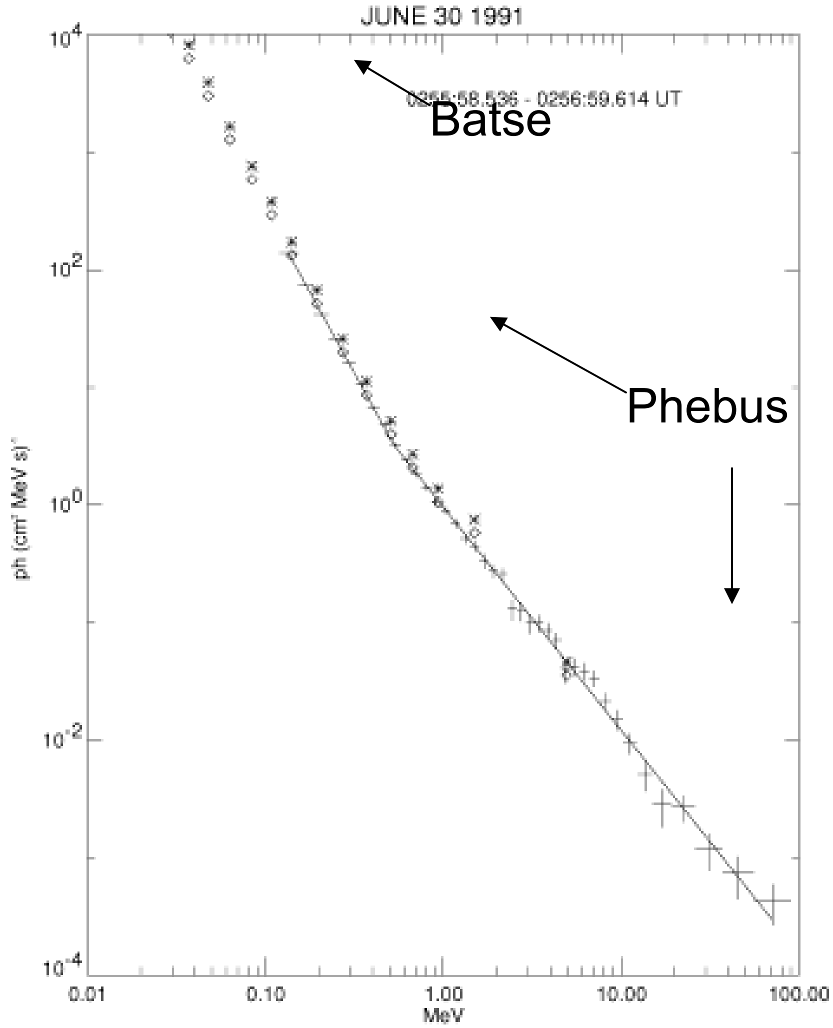
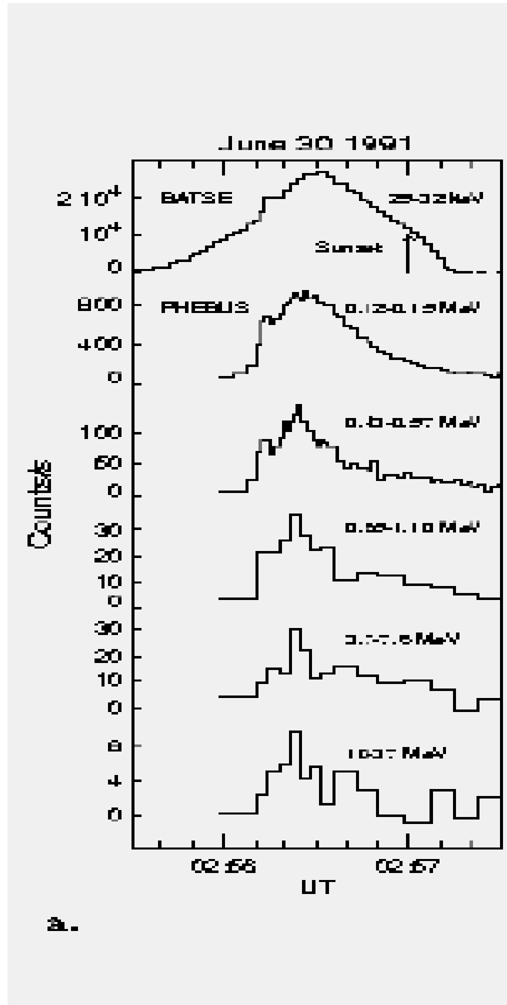


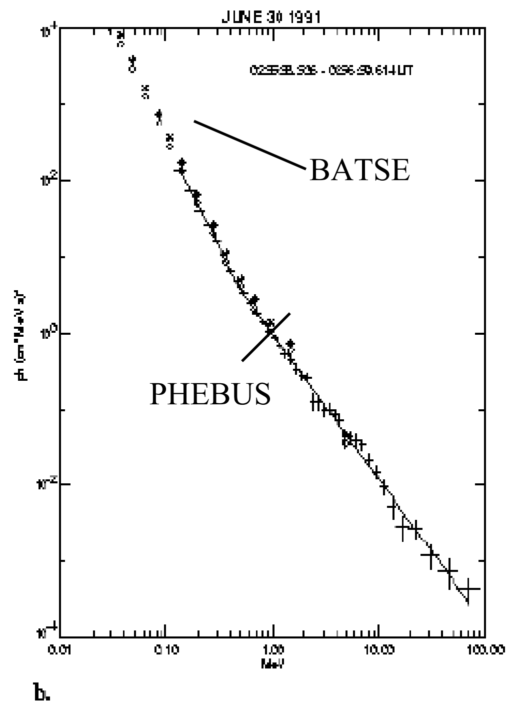
Fig. 2. HXR/GR Photon spectrum observed by PHEBUS between 0255:58.536 and 0256:59.614 UT (error bars). The solid curve represents the best fit double power law photon spectrum. The stars represent the photon spectrum deduced from the spectral analysis of BATSE count-rates in the same time interval. The diamonds represent the same quantities divided by 1.3

Electron-Dominated Events

- First observed with SMM (Rieger et al, 1993)
- Short duration (s to 10 s)
  high energy (> 10 MeV) bremsstrahlung emission
- No detectable GRL flux
- Photon spectrum > 1 MeV ($\delta_X \approx$-1.5—2.0)
- For 2 PHEBUS events
  - o if $W_{i>1MeV/nuc} \sim W_{e>20 keV}$
  - o No detectable GRL above continuum
  - o Weak GRL flares?



Vilmer et al (1999)



- C10. HOW DOES THE SUN ACCELERATE IONS TO GEV ENERGIES IN 10'S OF SECONDS AND YET LAST FOR HOURS?
- C11. WHY DO WE ONLY SEE GAMMA-RAY LINES WHEN ELECTRONS > 300 KEV ARE PRESENT?
- C12. WHY ARE THE ELECRON AND ION FLUENCES SO CLOSELY ASSOCIATED (ON AVERAGE)?

Main constraints on theoretical models

- C13 The type III radio sources, microwave coplexity
- C14 The SEP and their relation to X ray sources

New theoretical results

- Comparing Electron stochastic acceleration models with RHESSI hard X-ray observations of solar flares
- Paolo Grigis
- Magnetic reconnection and particle acceleration. Marco Onofri
- Linking energy release and particle accelertation Cyril Dauphin

Escape/Trapping

- We add a sink and source term to the FP equation

$$\frac{\partial N}{\partial t} = \frac{1}{2}\frac{\partial^2}{\partial E^2}\Big[(D_C + D_T)N\Big] - \frac{\partial}{\partial E}\Big[(A_C + A_T)N\Big] - S\,N + Q$$

with

$$S(E) = \frac{T_H \beta}{\tau(E)}$$

β → Electron speed

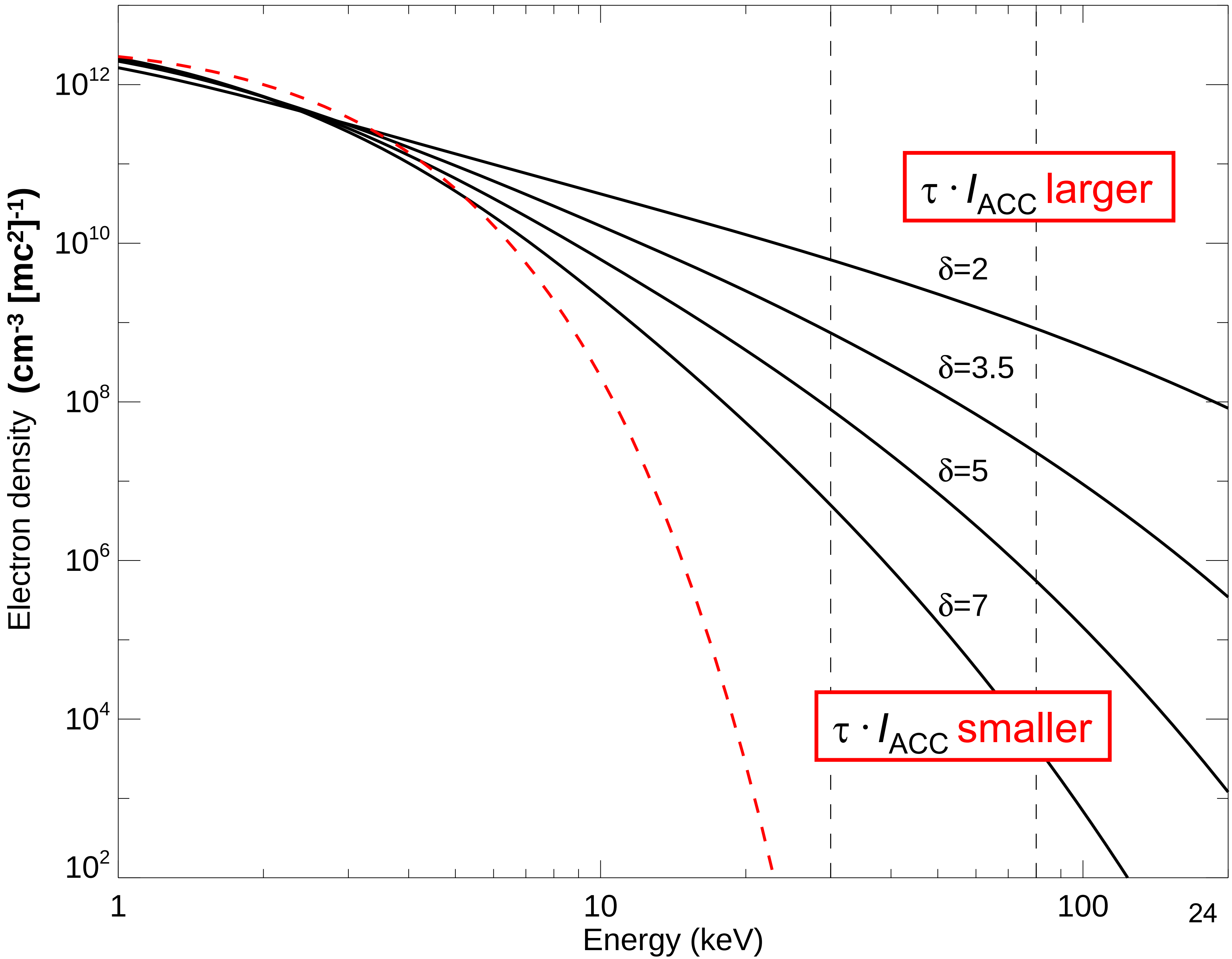
$\tau(E)$ → Escape Time

and

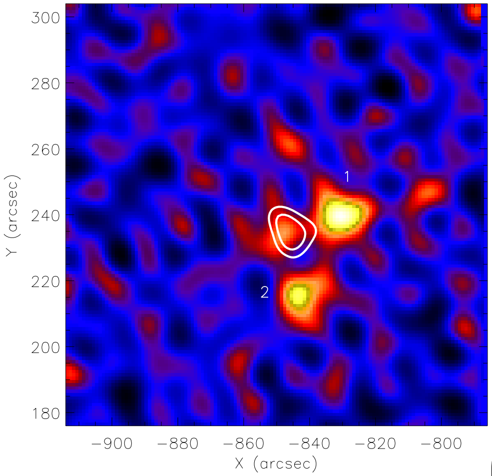
$$Q = n_0 \cdot N_{MB}(E)$$

$N_{MB}(E)$ → Maxwell-Boltzmann distribution with temperature *T*

n_0 → Number of lost particles $n_0 = \int S\,N\,dE$

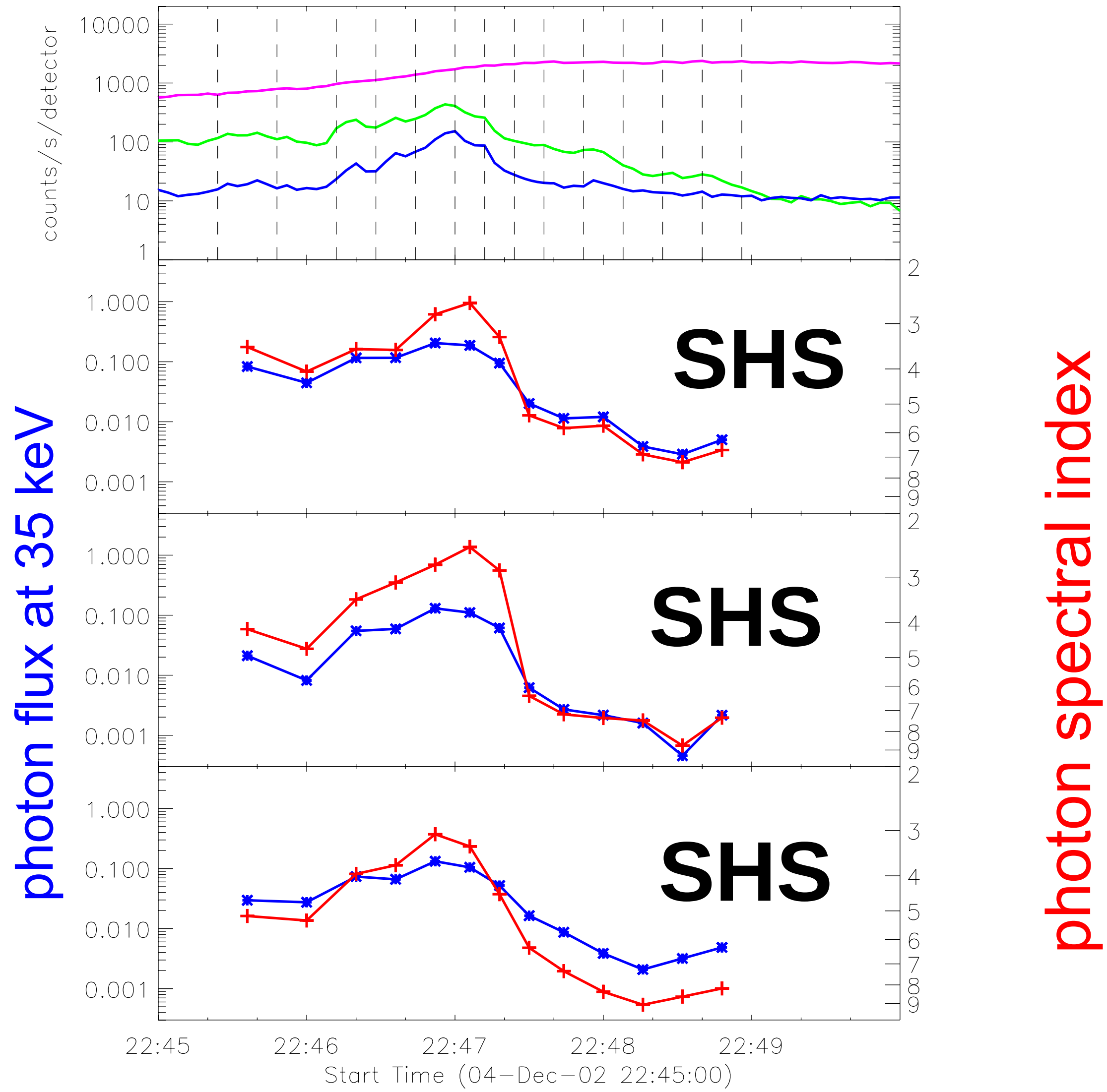


τ · I_ACC larger
δ=2
δ=3.5
δ=5
δ=7
τ · I_ACC smaller
10^12
10^10
10^8
10^6
10^4
10^2
1
10
100
Energy (keV)
Electron density (cm^-3 [mc^2]^-1)



Footpoints:

Looptop source:



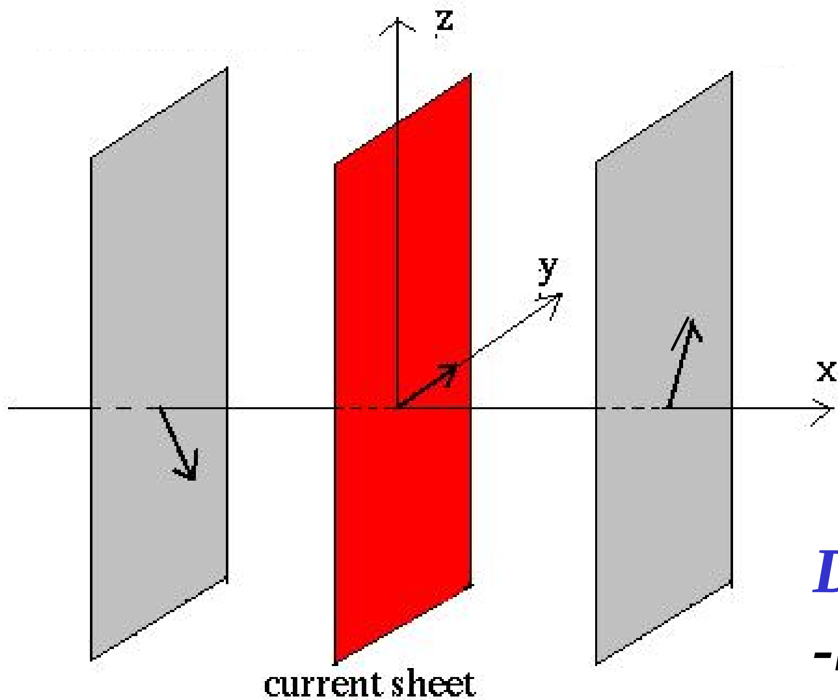
from Battaglia & Benz (2006)

Conclusions

- The introduction of a simple escape term does soften the electron spectra in the accelerator produced by the TTD model.
  - hard spectra results from strong acceleration and strong trapping
  - soft spectra results from weak acceleration and weak trapping
- The Soft-Hard-Soft spectral evolution is approximately compatible with the presence of a pivot point at energies around 10 keV.
- Observations suggest a value near 20 keV: this can be accomplished by increasing the trapping efficiency below electron energy of ~30 keV, but this results in too hard spectra in the range 10-20 keV.

Geometry

The MHD incompressible equations are solved to study magnetic reconnection in a current layer in slab geometry:



Periodic boundary conditions along y and z directions

Dimensions of the domain:

$-l_x < x < l_x, \; 0 < y < 2\pi l_y, \; 0 < z < 2\pi l_z$

Description of the simulations

Incompressible, viscous, dimensionless MHD equations:

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V} \cdot \nabla)\mathbf{V} - \nabla P + (\nabla \times \mathbf{B}) \times \mathbf{B} + \frac{1}{R_v} \nabla^2 \mathbf{V}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{1}{R_M} \nabla^2 \mathbf{B}$$

$$\nabla \cdot \mathbf{B} = 0$$

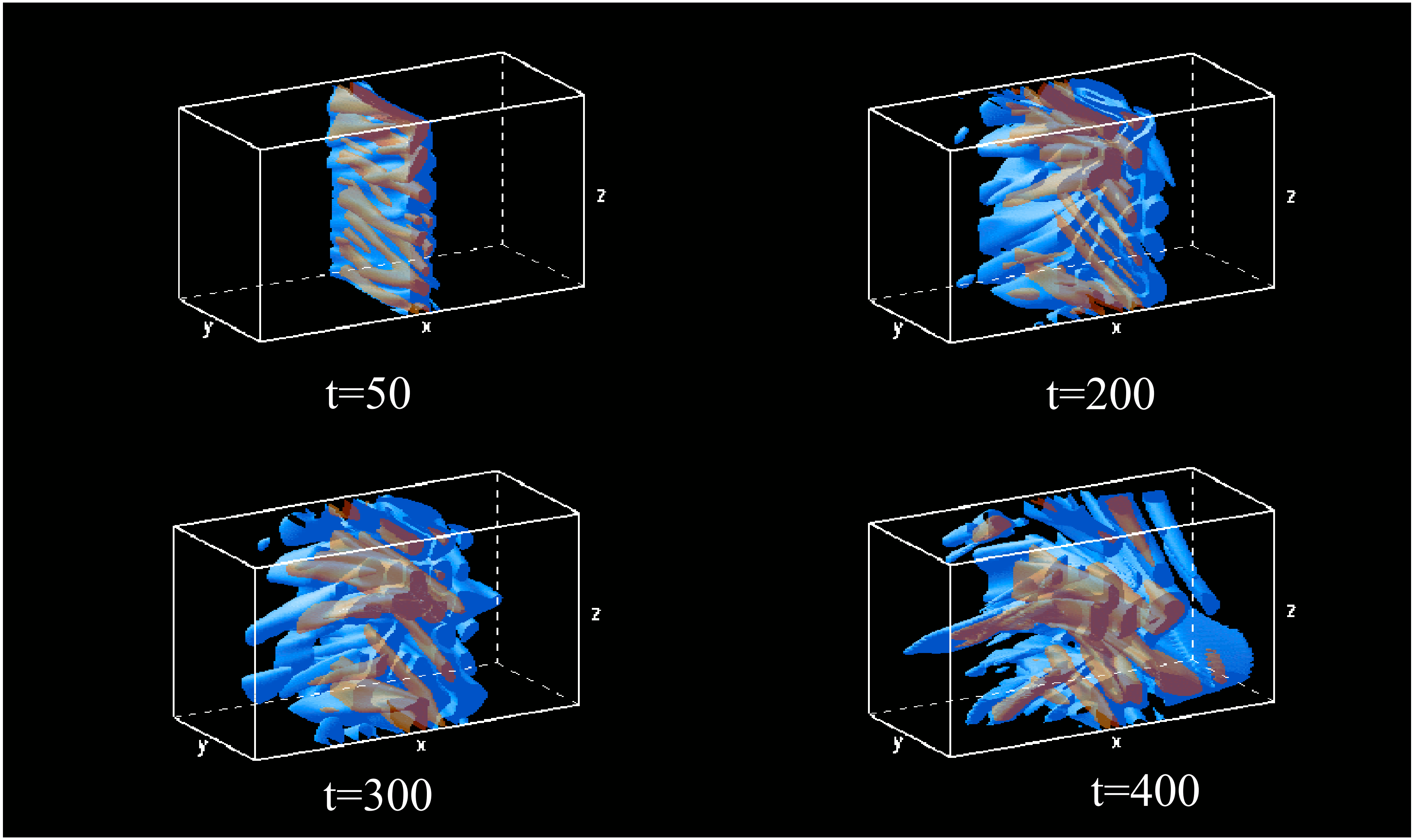
$$\nabla \cdot \mathbf{V} = 0$$

B *is the magnetic field,* **V** *the plasma velocity and* **P** *the kinetic pressure*

R_M ***and*** R_v ***Are the kinetic and magnetic Reynolds numbers.***

Three-dimensional structure of the electric field

Isosurfaces of the electric field at different times



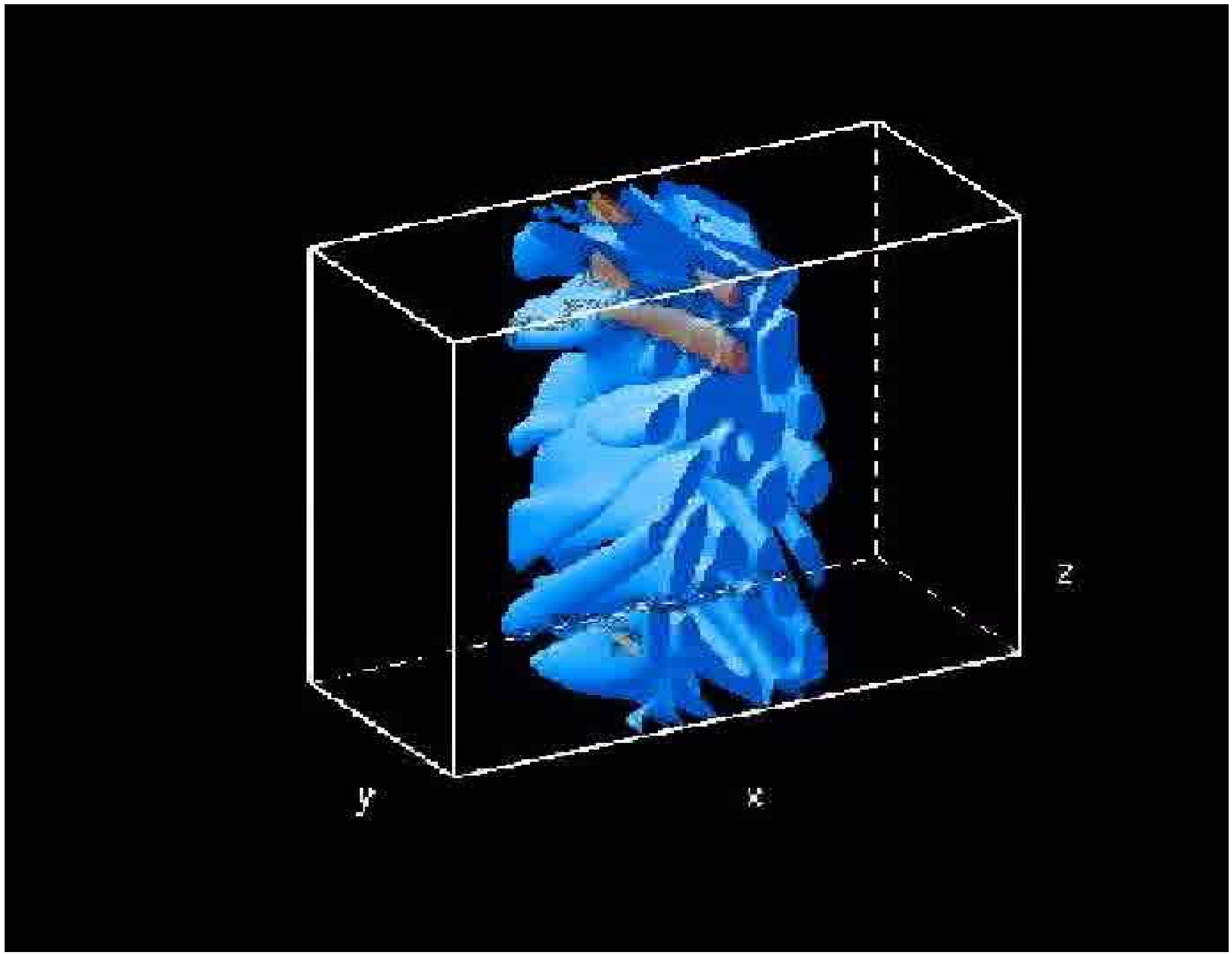
Time evolution of the electric field

Isosurfaces of the electric field from **t=200** *to* **t=400**

$E = 1.5 \times 10^{-3}$

$E = 7 \times 10^{-3}$

$E = 1.7 \times 10^{-2}$

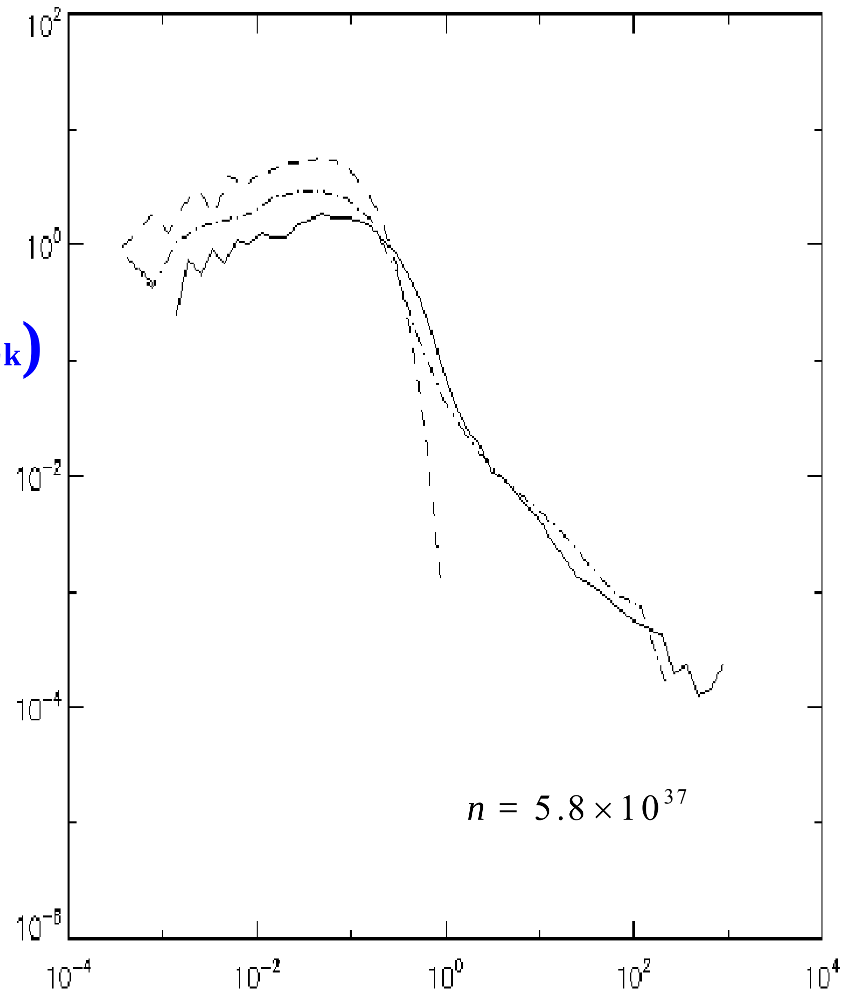


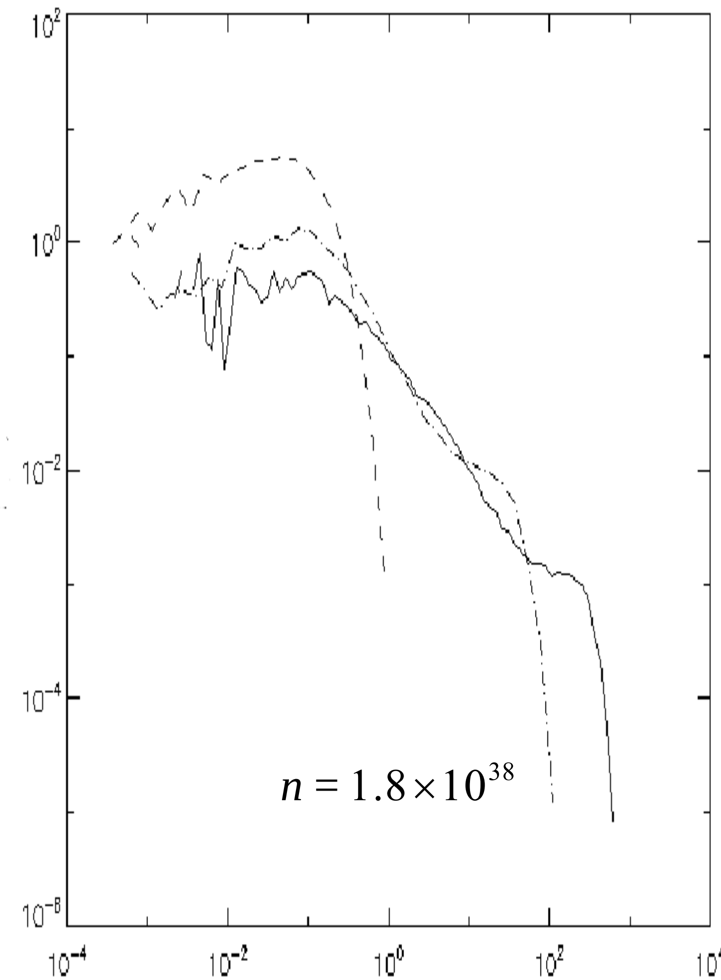
Kinetic energy distribution function of electrons

t=50 T_A

T=400 T_A

$P(E_k)$

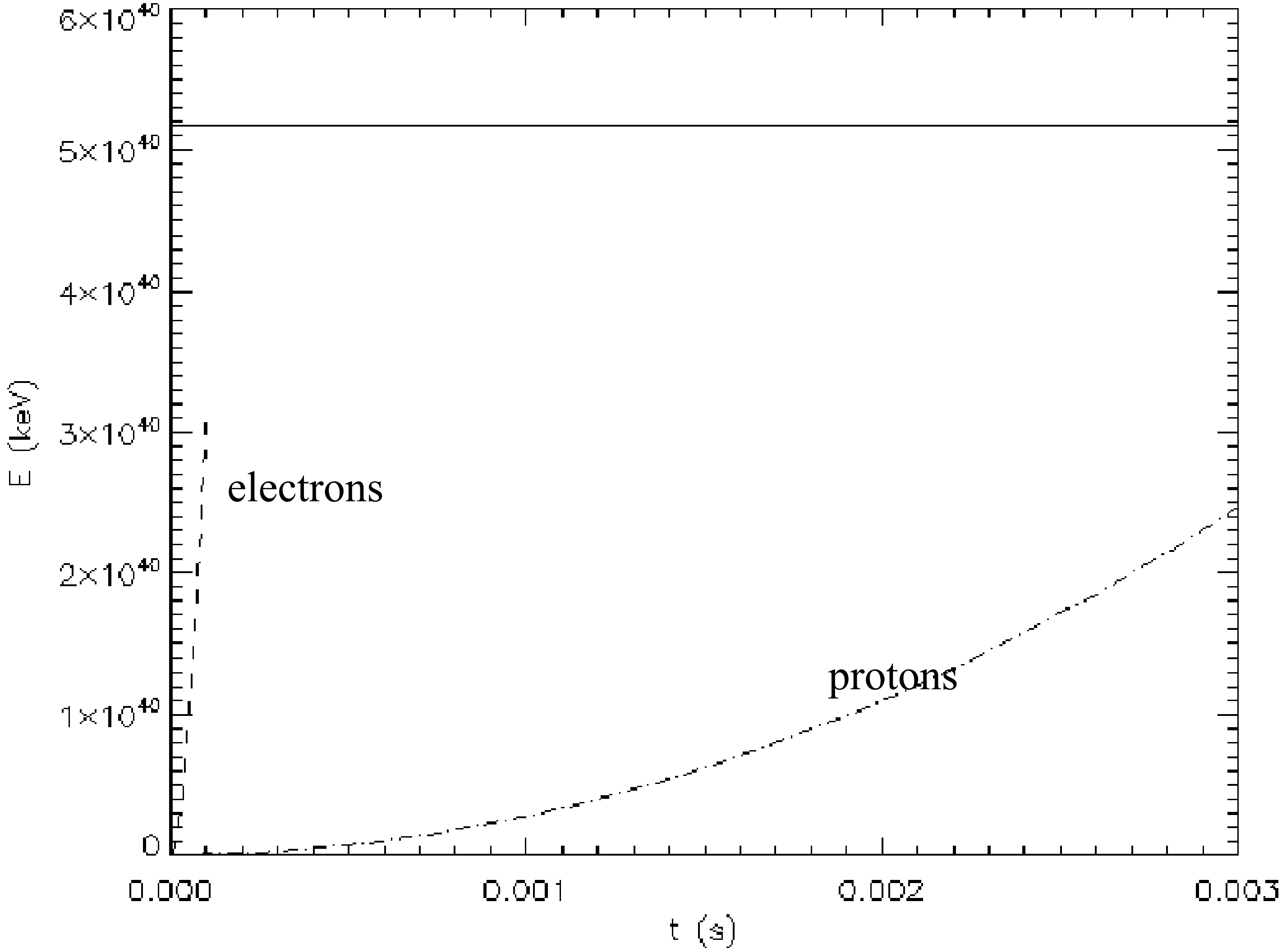




E_k (keV)

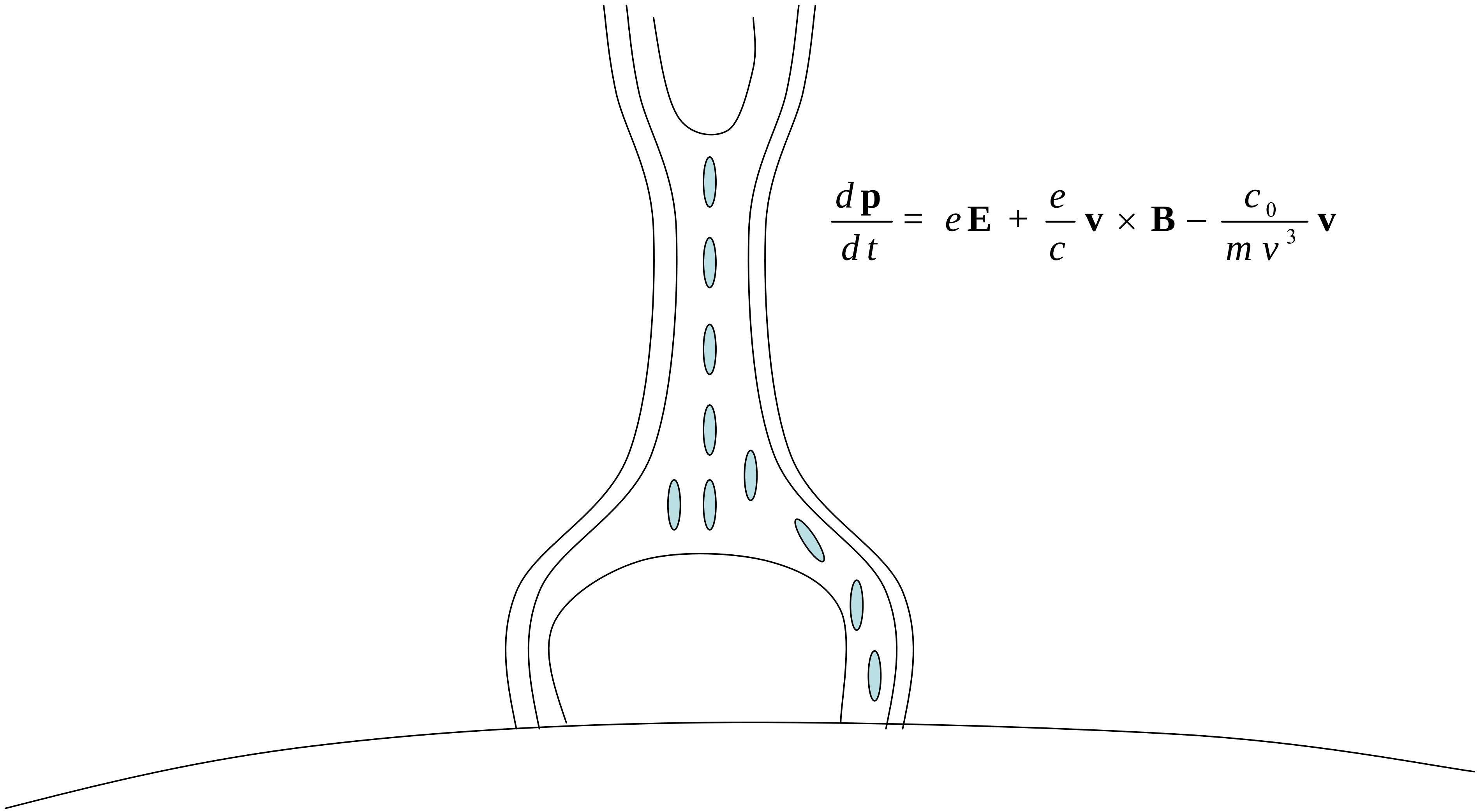
E_k (keV)

Energetics



6×10^{40}
5×10^{40}
4×10^{40}
3×10^{40}
2×10^{40}
1×10^{40}
0
E (keV)
electrons
protons
0.000
0.001
0.002
0.003
t (s)

A big current sheet is fragmented in small current sheets in different locations, with different conditions of temperature and density



$$\frac{d\mathbf{p}}{dt} = e\mathbf{E} + \frac{e}{c}\mathbf{v} \times \mathbf{B} - \frac{c_0}{m v^3}\mathbf{v}$$

Discussion and conclusions

- ***A decayed and fragmented current sheet can be a very efficient accelerator***

- ***The electrons absorb*** **50%** ***of the energy of the magnetic field in*** $10^{-4}s$ ***and reach an energy of*** **1 MeV**

- ***Protons cannot be accelerated to the observed energy by a single current sheet***

- ***After the formation of a current sheet the acceleration of electrons becomes important and kinetic effects start to dominate***

• ***The lifetime of a current sheet in the solar corona is comparable with the aceleration time only for current sheets smaller than*** $10^6 cm$

•***The number of accelerated particles increases with the fragmentation of the current sheet***

• ***Electrons must be accelerated in different regions of the corona to explain the observations***

• ***The HXR spectrum has a double power law tail with slopes*** **1.6** ***and*** **4.5**

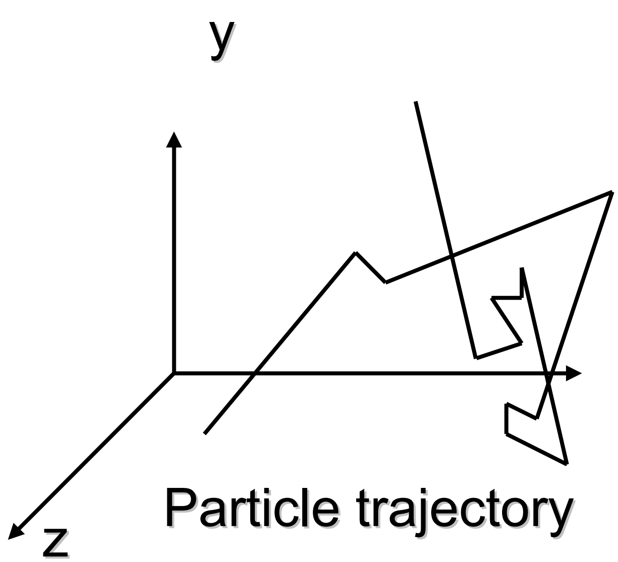
- Linking the magnetic energy release and acceleration process

- Current models: Particle acceleration from

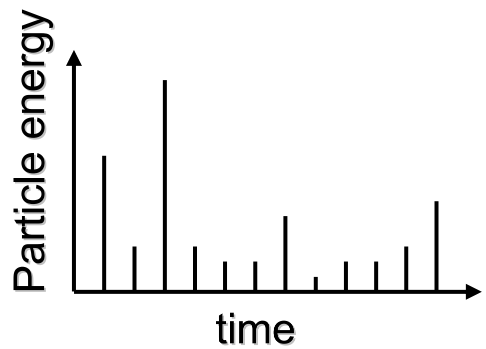
  1) One acceleration site

     - each particle have a different energy gain

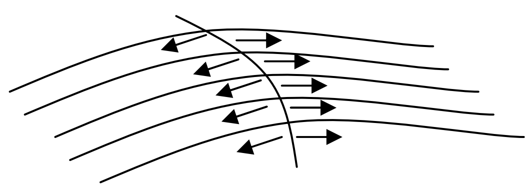
  2) Multiple interactions of one particle with multiple acceleration sites



Particle trajectory



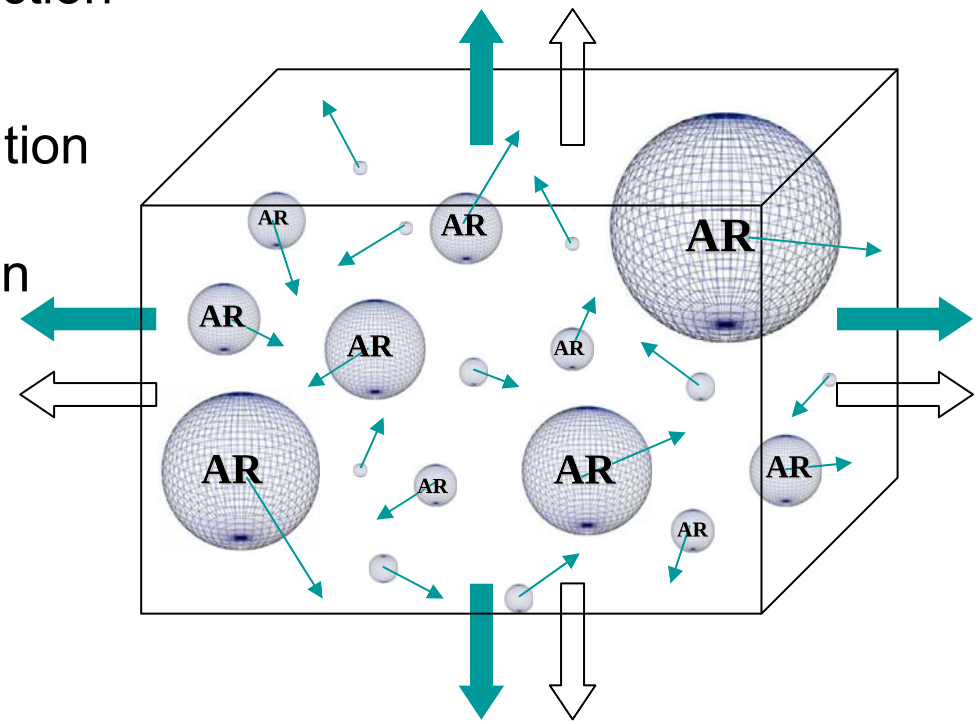
- We try a new assumption: Multiple acceleration sites but most of the particles are accelerated one time in different accelerators



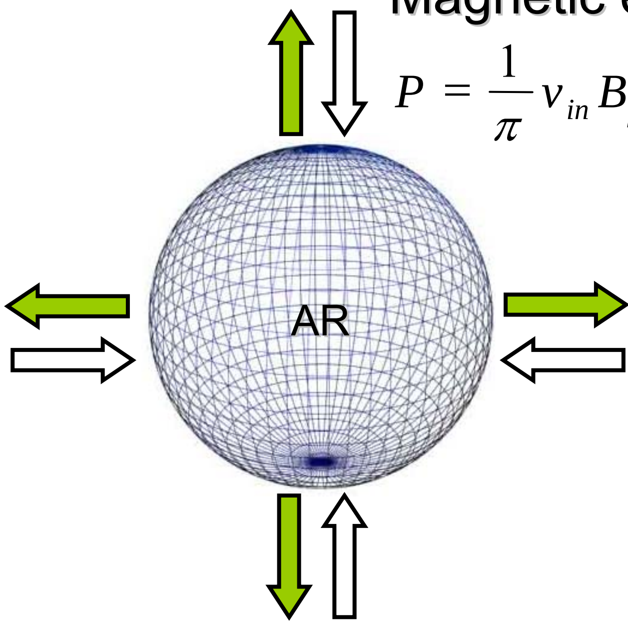
- Multiple acceleration regions but not “well connected”

Particles accelerated in each acceleration region leave the global acceleration region without interaction

The total particles energy distribution is the sum of the particles energy distribution from each acceleration site



- In each acceleration region, we equate the magnetic energy flux to the particle energy flux in order to determine the electric field



Magnetic energy flux

$$P = \frac{1}{\pi} v_{in} B_{free}^2 S_{AR}$$

Particle energy flux

$$P = \dot{N}_e e E_{AR} < \Delta l_e >_{n_e} + \dot{N}_p e E_{AR} < \Delta l_p >_{n_p}$$

with $\dot{N} = 4 l b v_{in} n$

$$\Rightarrow E_{AR} = \alpha \frac{B_{free}^2}{4\pi e(\langle \Delta l_e \rangle_{n_e} n_e + \langle \Delta l_p \rangle_{n_p} n_p)}$$

- The particle energy gain of one particle is:

$$\varepsilon_{e,p} = eE_{AR}\Delta l_{e,p}$$

- We express the acceleration length of one particle as a function of the average acceleration length

$$\varepsilon_{e,p} = eE_{AR} < \Delta l_{e,p} > P(\Delta l)$$

↑ Density probability

Determine the particle acceleration length process

- The electron energy gain is:

$$\varepsilon_e = \alpha \frac{B_{free}^2}{2\pi n(1+\beta)} P(\Delta l)$$

With: $\beta = \frac{< \Delta l_p >_{n_p}}{< \Delta l_e >_{n_e}}$ here we choose β=1

- We have to make an assumption on P(Λl)

1) $P(\Delta l) = k_1(\Delta l)^{-\delta}$

2) $P(\Delta l) = exp(-\sqrt{\frac{\Delta l}{\Delta l_0}})(\Delta l)^{-1/2}$

- The electron energy distribution from one acceleration region is

$$N(\varepsilon) = nP(\Delta l)\frac{d(\Delta l)}{d\varepsilon}$$

1) $N(\varepsilon) = k_1 n(eE_{AR})^{\delta-1}\varepsilon^{-\delta}$

2) $N(\varepsilon) = \frac{n}{(eE_{AR})^{1/2}}exp\left(-\sqrt{\frac{\varepsilon}{\varepsilon_0}}\right)(\varepsilon)^{-1/2}$

- The total particles energy distribution is given by

$$N(\varepsilon)_{total} = \sum_{i=1}^{n_{AR}} N(\varepsilon)_{AR,i}$$

With the particle energy gain of each particle given by

$$\varepsilon_e = \alpha \frac{B^2_{free}}{2\pi n(1+\beta)} P(\Delta l)$$

- the free magnetic energy is different in each acceleration region.

We assume a power law distribution of the magnetic energy release

$$P(B^2_{free}) = k_2 (B^2_{free})^{-\zeta}$$

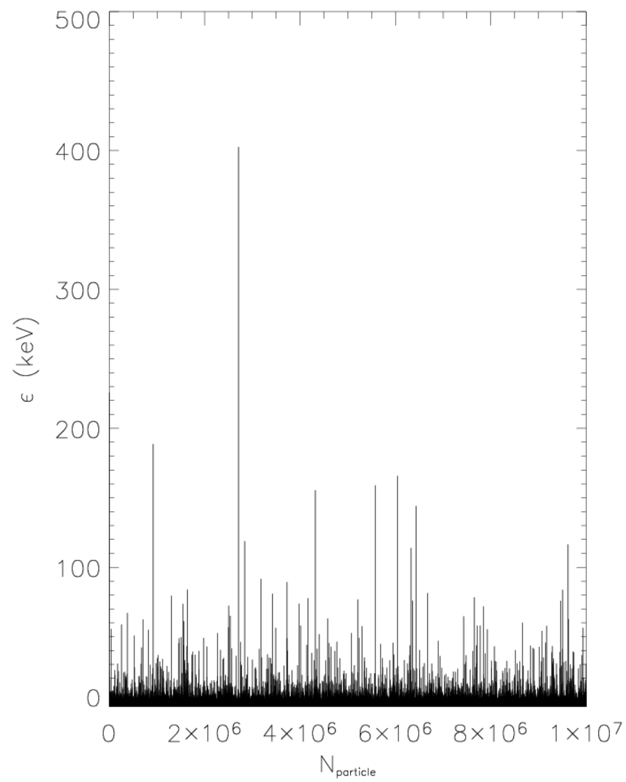
$$P(E_{AR}) = k_3 (E_{AR})^{-\zeta}$$

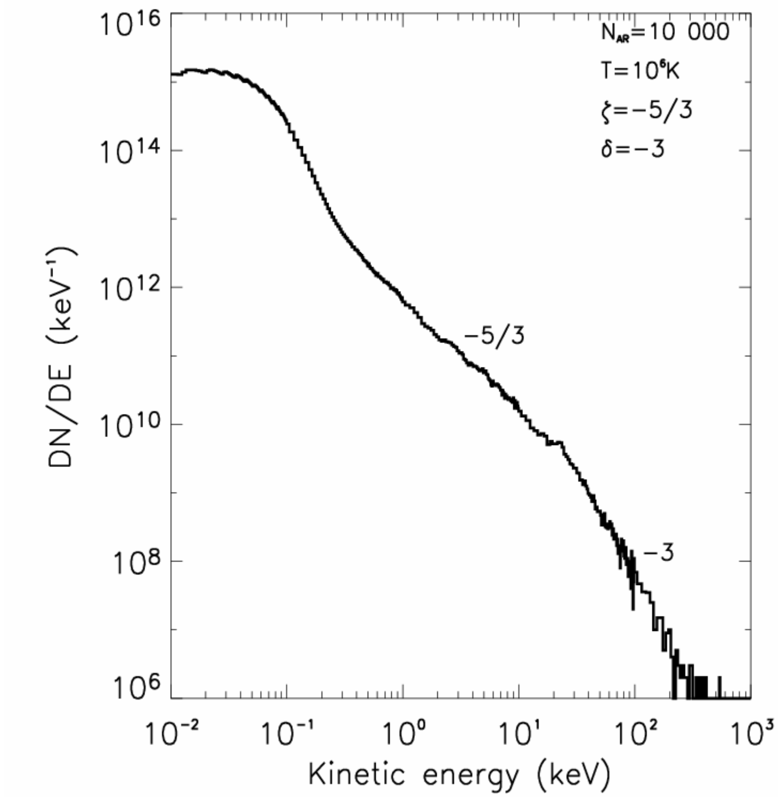
- We calculate the final particle energy distribution for a given number of acceleration region. We use different values of the spectral index of the particle acceleration process.

  We start with a maxwellian distribution of 10^6 K. The electric field is normalized to E_D ($n=10^{10}$ cm^{-3})

- Example with 10 000 AR, ζ=-5/3 and δ=-3

$$P(\Delta l) = k_1(\Delta l)^{-\delta}$$





- Our model leads naturally to the formation of double power law spectra

  -This is a direct consequence of the assumptions:

  1) Multiple acceleration sites

  2) Each particle is accelerated one time

- Spectral index of the particle energy distribution is a combination of the magnetic energy release and acceleration process

- Spectral index of the particle acceleration length process < -2.0

  ⇨ We observed at high energy a the slope of the particle acceleration length distribution

- Spectral index of the particle acceleration length process > -2.0

  ⇨ We observed at high energy a slope ~ -2.5; -2.0

A Strategy for a new generation of particle acceleration models

- Most acceleration processes known today succeed in a few aspect of the flare phenomenon and fail in others
- The stochastic acceleration have a number of good points which should be preserved
- The acceleration model should be closely related to the energy release processes
- The acceleration models should respect most if not all of the findings mentioned in the beginning)

Magnetic topologies:
where will reconnection occur ?

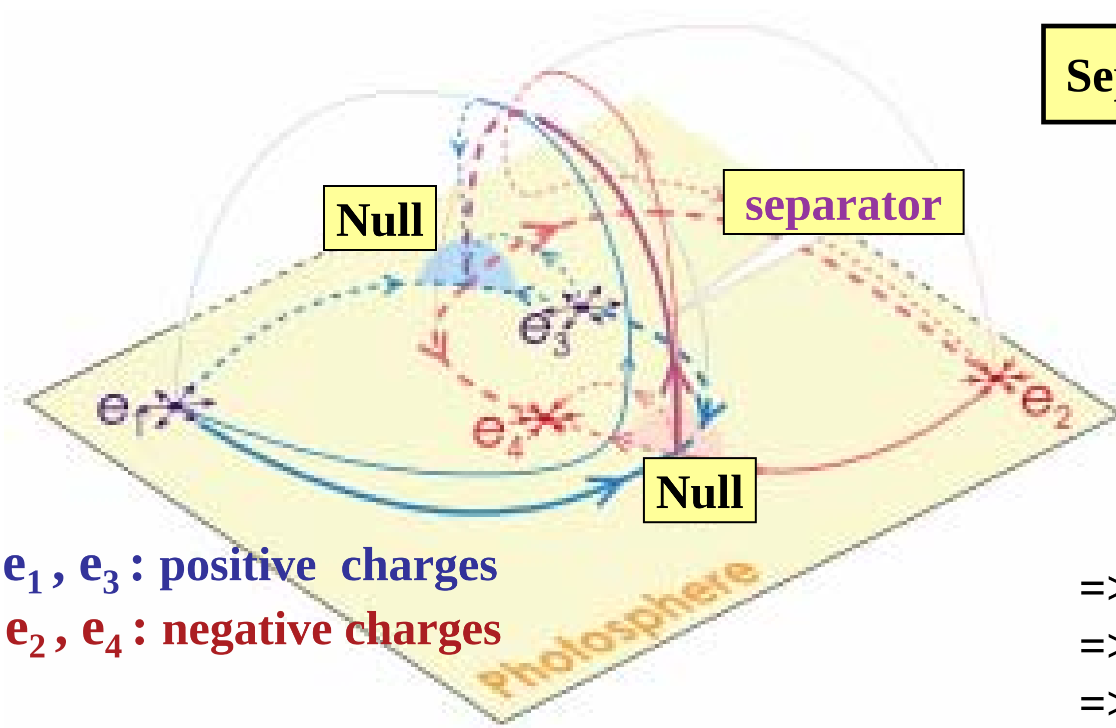
Magnetic reconnection :
an attractive mechanism for energy release in the corona
(heating, flares, CMEs …)

How to quantify this in 3D configurations ?

Pascal Démoulin

l'Observatoire de Paris | LESIA

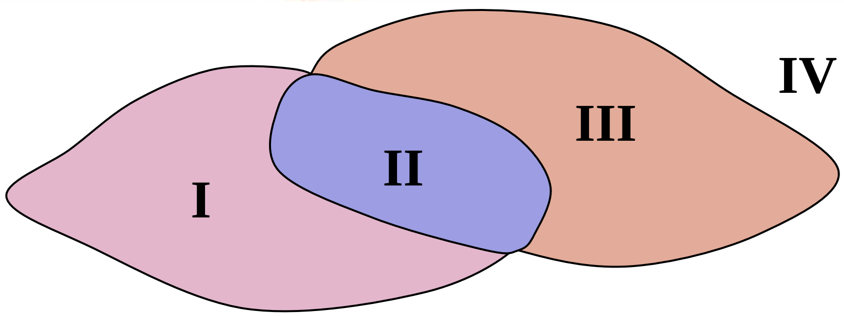
Configuration with 4 magnetic polarities



e_1 , e_3 : positive charges

e_2 , e_4 : negative charges

Separatrices: 2 intersecting cupola



4 connectivity domains

Motion of the charges

=> Current sheet at separator

=> Reconnection (with $E_{//}$)

=> Flux exchange between domains

(Sweet 1969, Baum & Brathenal 1980, Gorbachev & Somov 1988, Lau 1993)

Main properties

Skeleton :

Null points + spines + fans + separators
"summary of the magnetic topology"
(Molodenskii & Syrovatskii 1977, Priest et al. 1997, Welsch & Longcope 1999, Longcope & Klapper 2002)

Classification of possible skeletons (with 3 & 4 magnetic charges)

(Beveridge et al. 2002, Pontin et al. 2003, 1980, Gorbachev & Somov 1988, Lau 1993)

Global bifurcations :

They modify the number of domains

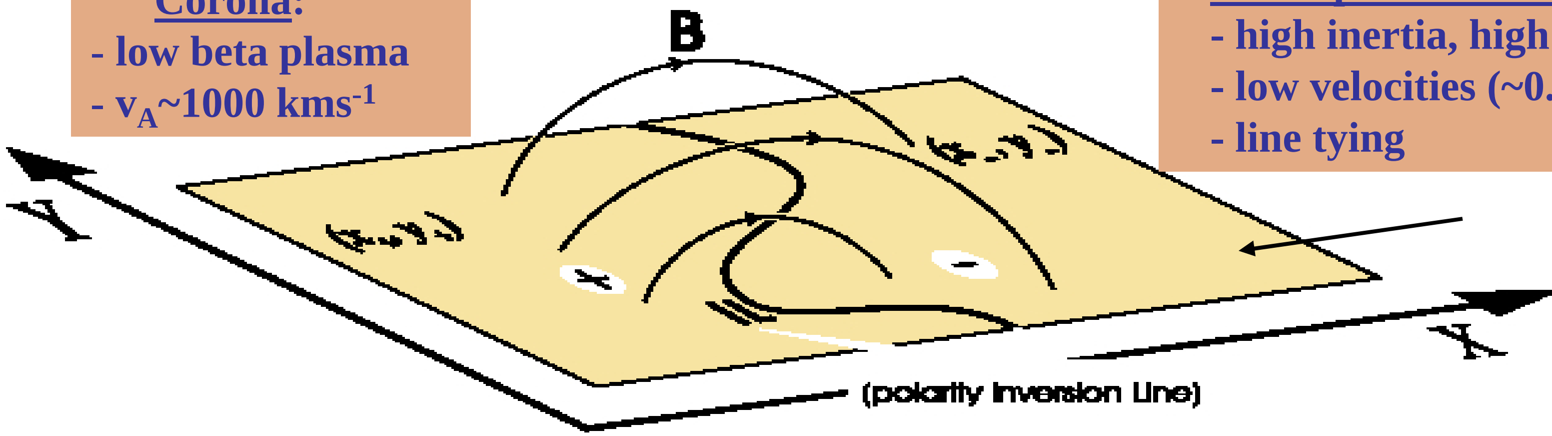
- **separator bifurcation (2 fans meet)**
- **spine-fan bifurcation (fan + spine meet)**

(Gorbachev et al. 1988, Brown & Priest 1999, Maclean et al. 2004)

Definition of Quasi-Separatrix Layers

Corona:
- low beta plasma
- $v_A \sim 1000\ \mathrm{kms}^{-1}$

Photosphere & below:
- high inertia, high beta
- low velocities (~0.1 kms^{-1})
- line tying



Field line mapping to the "boundary" :

$$x_+, y_+ \rightarrow x_-, y_- : \quad x_-(x_+, y_+), y_-(x_+, y_+)$$

Jacobi matrix :

$$F = \begin{pmatrix} \partial x_- / \partial x_+ & \partial x_- / \partial y_+ \\ \partial y_- / \partial x_+ & \partial y_- / \partial y_+ \end{pmatrix}$$

Initial QSL definition : regions where

$$N \equiv \| F \| >> 1$$

(Démoulin et al. 1996)

Better QSL definition : regions where

Squashing degree

$$Q \equiv \frac{\| F \|^2}{B_{n,+} / B_{n,-}} >> 1$$

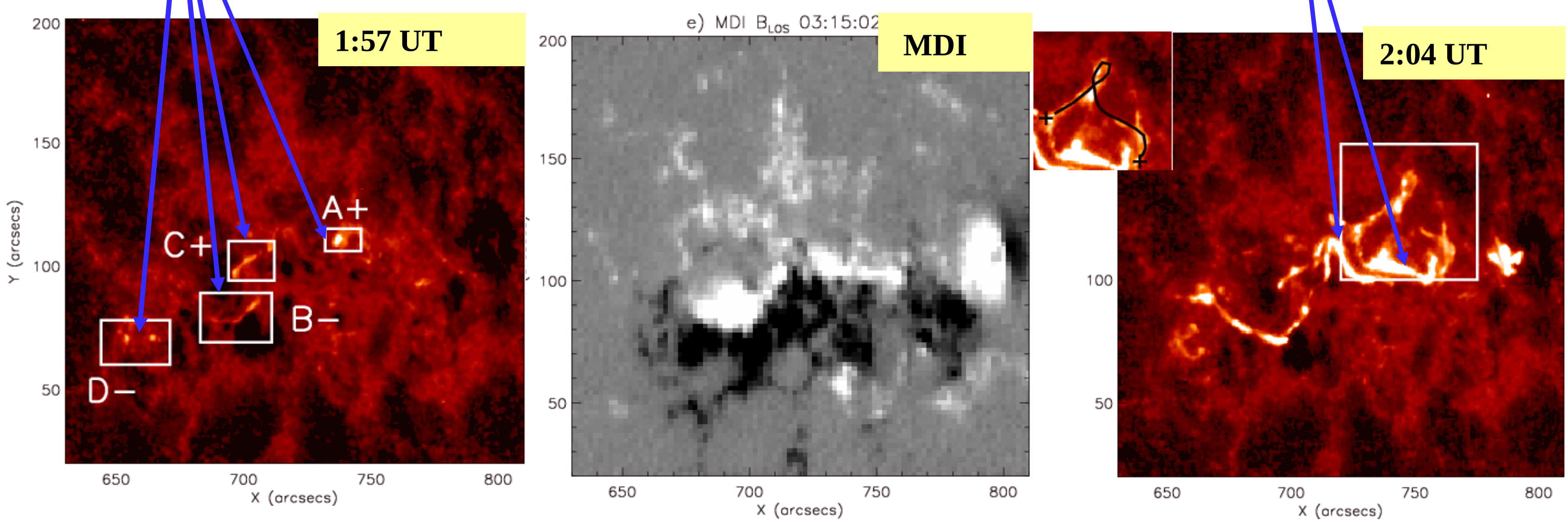
(Titov et al. 2002)

Same value of Q at both feet of a field line : $Q_+ = Q_-$

Example of an eruption

quadrupolar reconnection (breakout)
4 ribbons

reconnection behind the twisted flux rope
(with kink instability) 2 J-shaped ribbons



(Williams et al. 2005)

Brief summary

Discret photospheric field :
(Model with magnetic charges)

--> **Photospheric null points** --> **Skeleton**

Separatrices ↓ **Quasi-Separatrix Layers**

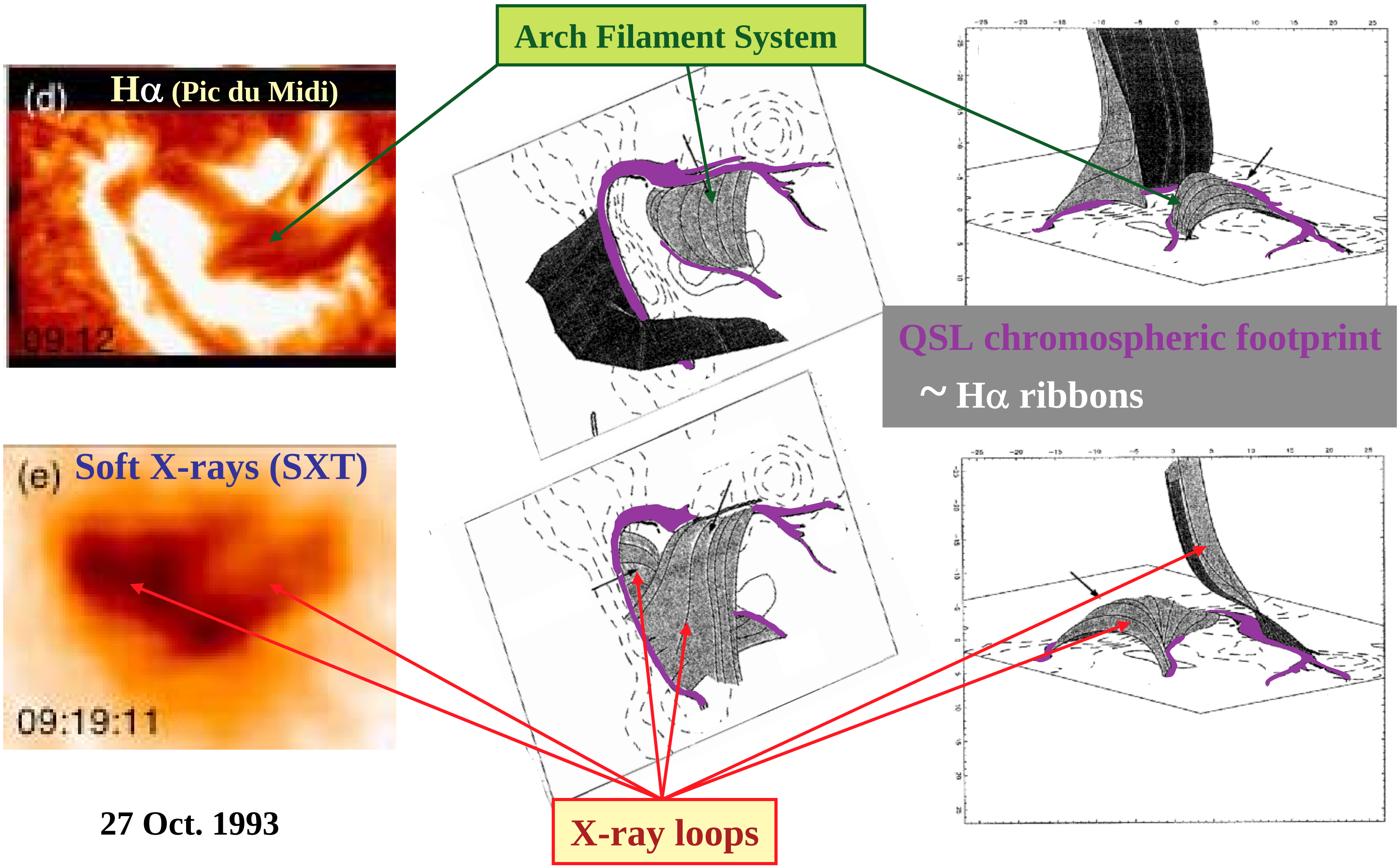
Separator ↓ **Hyperbolic Flux Tube**

Generalisation to continuous field distribution : **Quasi-Separatrix Layers** — **Hyperbolic Flux Tube**

Indeed, a little bit more complex…..

More still to come….

A different type of flaring configuration

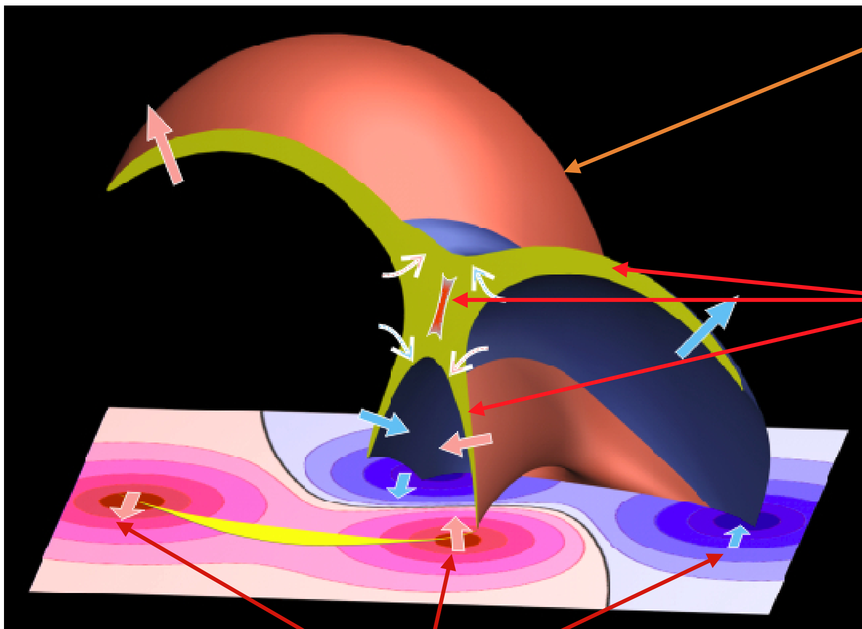


(Schmieder, Aulanier et al. 1997)

Formation of current layers at QSLs (1)

• **Expected theoretically** : - with almost any boundary motions
- with an internal instability

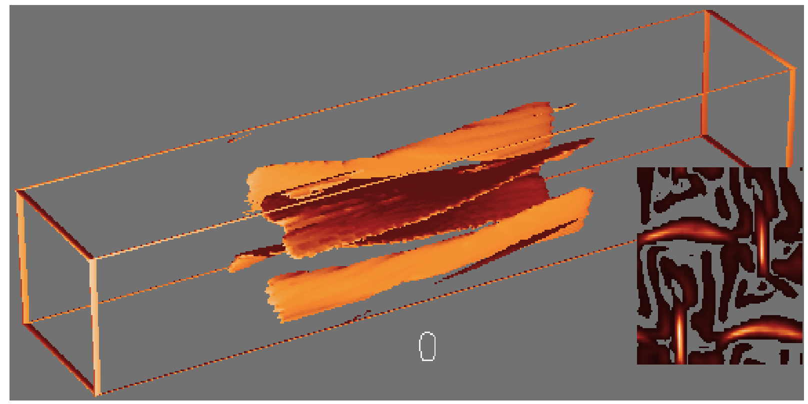
Using Euler potential representation: magnetic shear gradient across QSL **(Démoulin et al. 1997)**

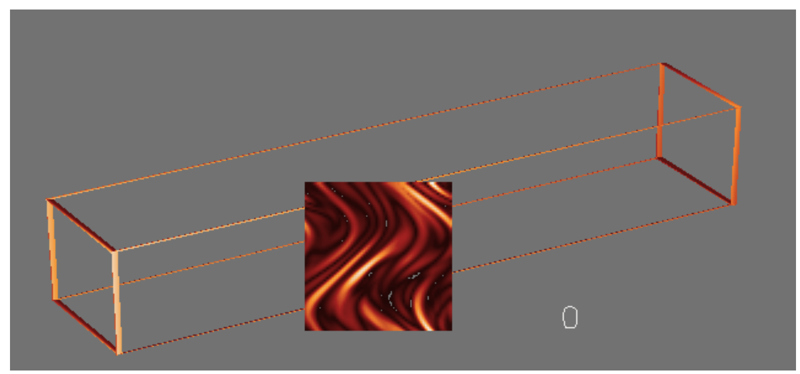


(Titov, Galsgaard & Neukirch. 2003)

The stochastic loop model
(Galsgaard)

- 3D MHD experiment of photospherically driven slender magnetic flux tubes
- Continued random driving of the foot points (incompressible sinusoidal large scale shear motions)
- Reconnection jets generate secondary perturbations in B
- Formation of stochastic current sheets





Conclusions

- We have to understand better a global active region driven by photospheric motions
- The skeleton is build by extrapolating magnetic fields and locating the places were the action will take place.
- The places were the action happens cannot be modeled by MHD. It is fully kinetic…
- The places were the current builds up are the locus of turbulent reconnection, heating and particle acceleration
- This new model allows the photosphere to confine our imagination. Moves us from the cartoons to real physical processes and the most important point the electric filed, the stochastic acceleration and the shocks are processes that are mix in a most general term called Turbulence…