High energy solar/stellar atmospheres

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Lecture outline

I) Observations, motivations

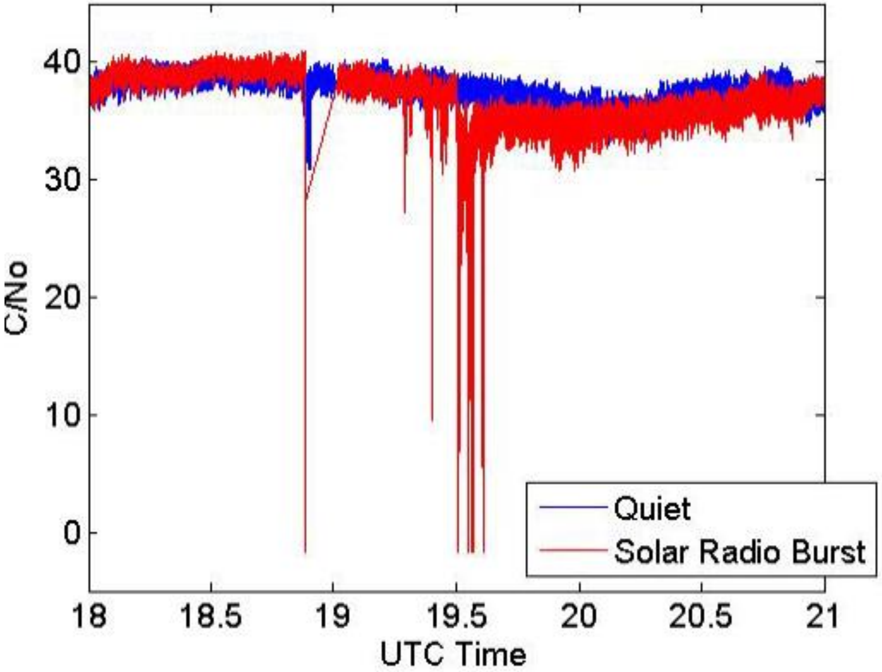
II) X-ray and emission mechanisms/properties

III) Energetic particles from the Sun to the Earth

IV) Particle acceleration mechanisms

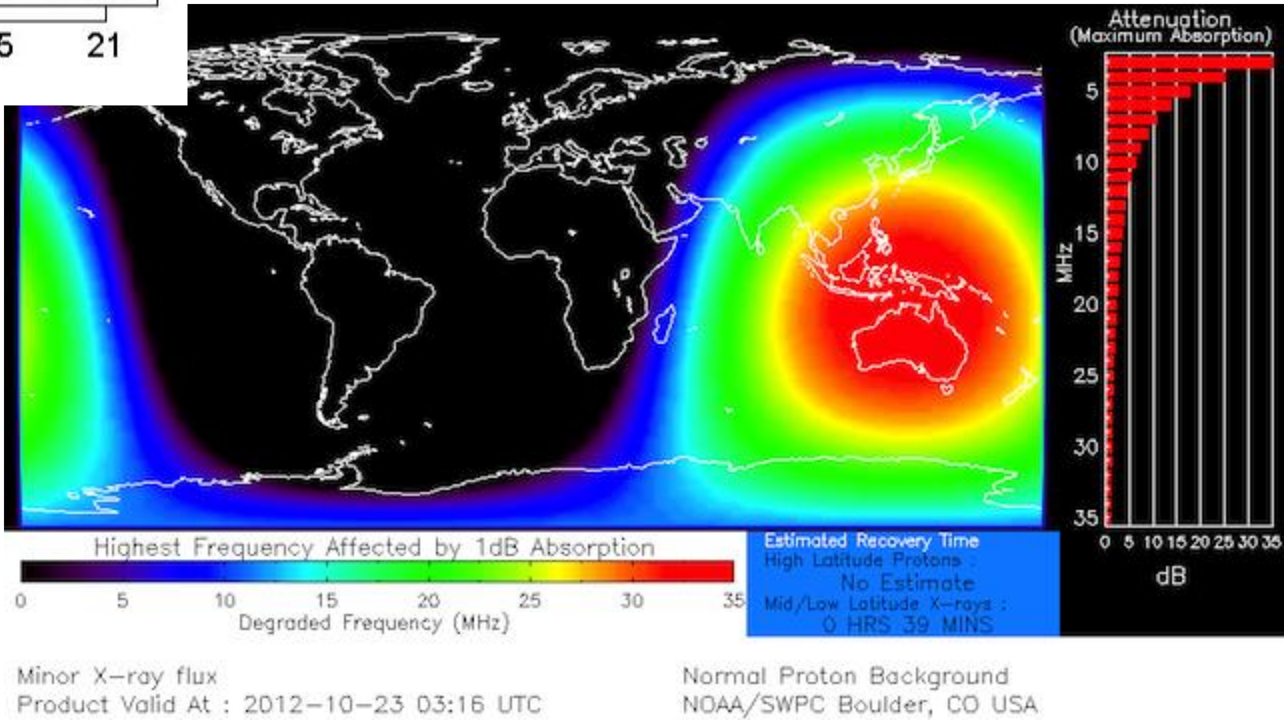
Solar flares and accelerated particles

X-ray and radio impact



Most GPS receivers in the sunlit hemisphere failed for ~10 minutes. (P. Kintner) at Dec 6th, 2006
(tracking less than 4 s/c)
See Gary et al, 2008

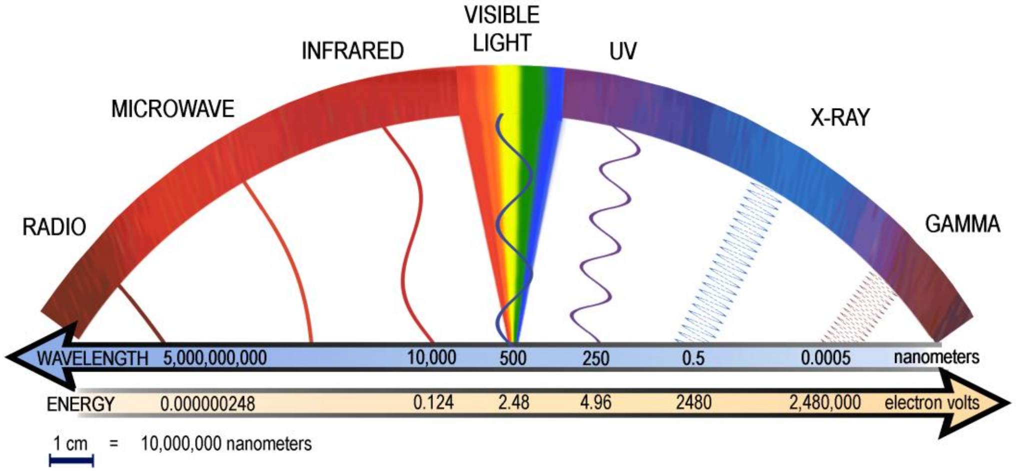
Ionising radiation and impact on ionosphere



Solar flares: basics

Solar flares are rapid localised brightening in the lower atmosphere.

More prominent in X-rays, UV/EUV and radio…. but can be seen from radio to 100 MeV



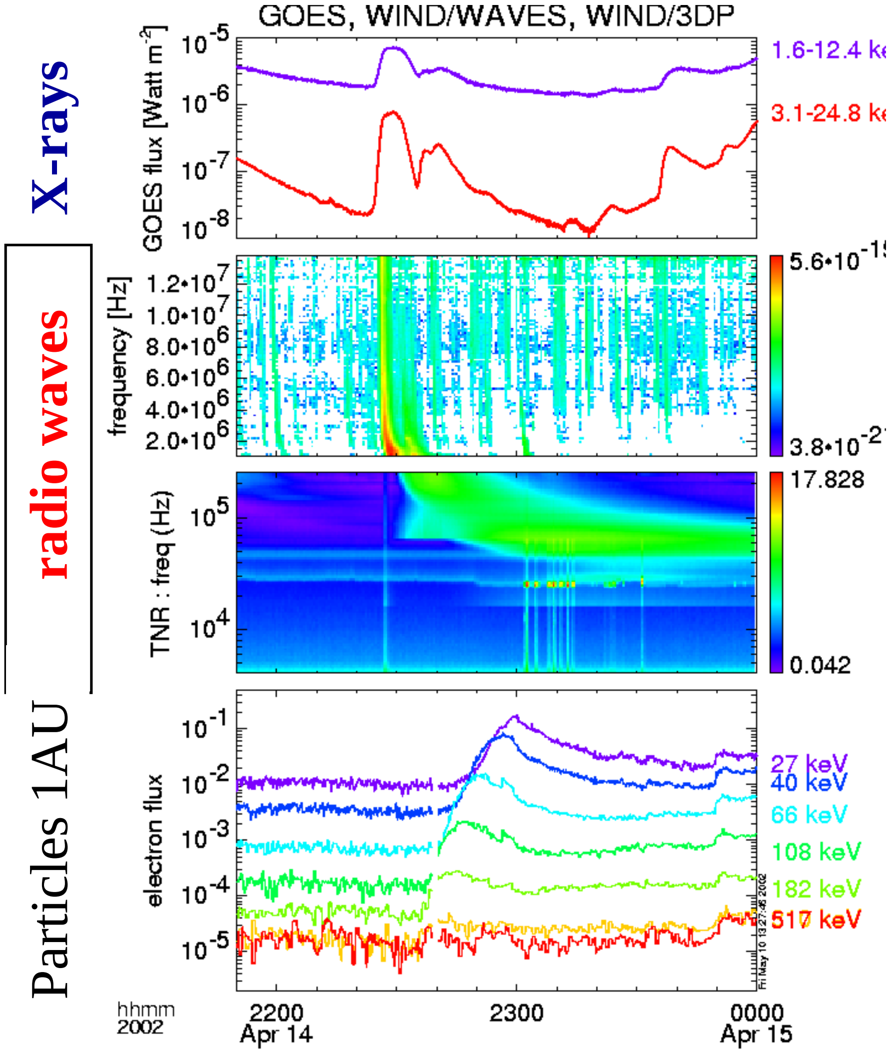


Figure from Krucker et al, 2007

Solar Flares: Basics

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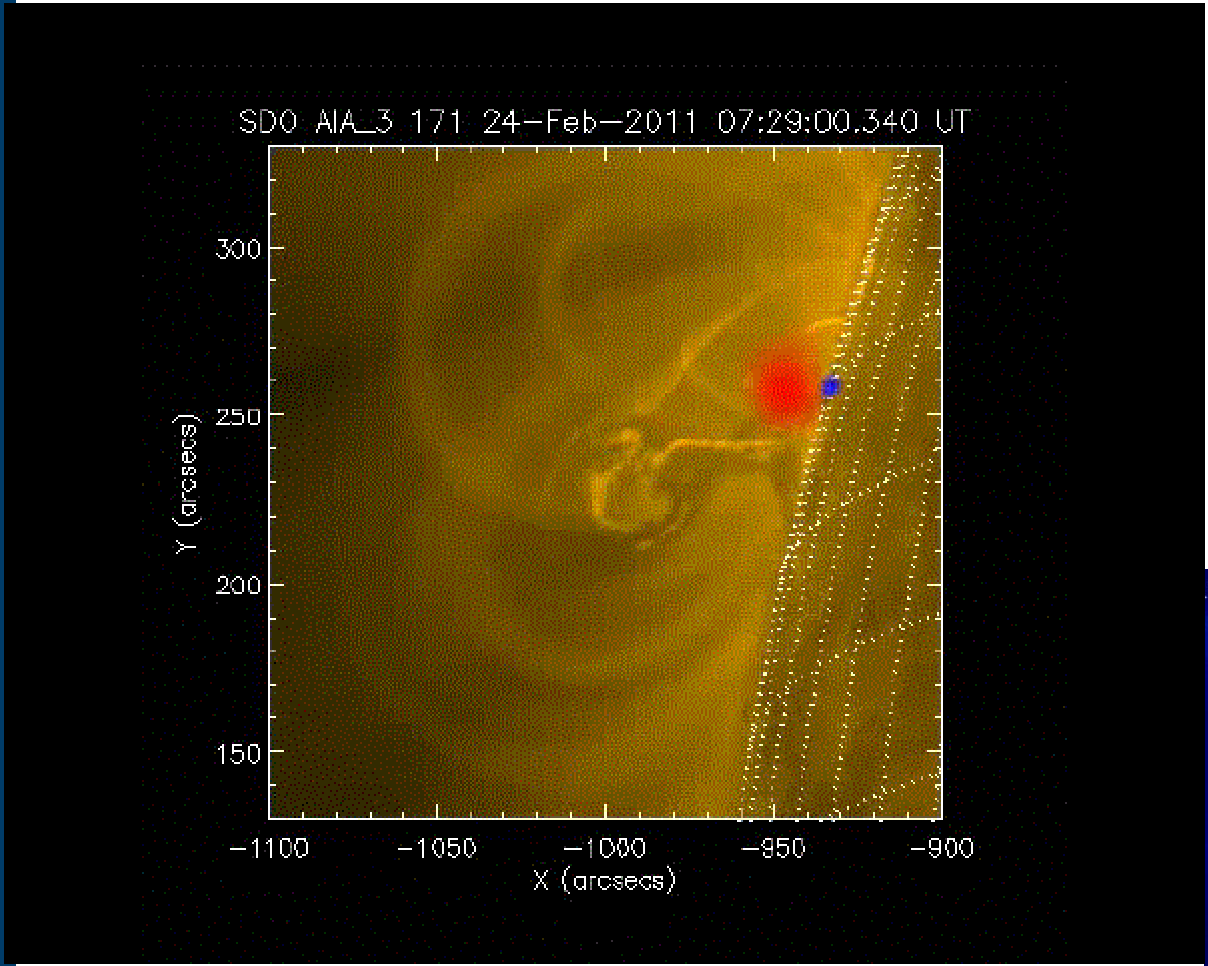
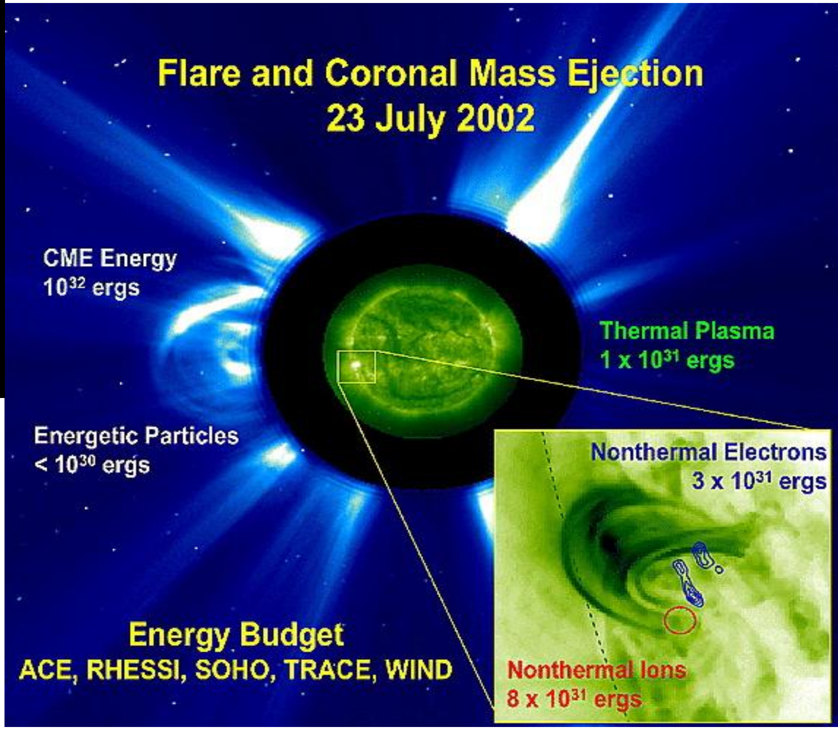


From Battaglia & Kontar, 2011



Energy ~2 10^{32} ergs

From Emslie et al, 2004, 2005

“Standard” model of a solar flare/CME

Energy release/acceleration

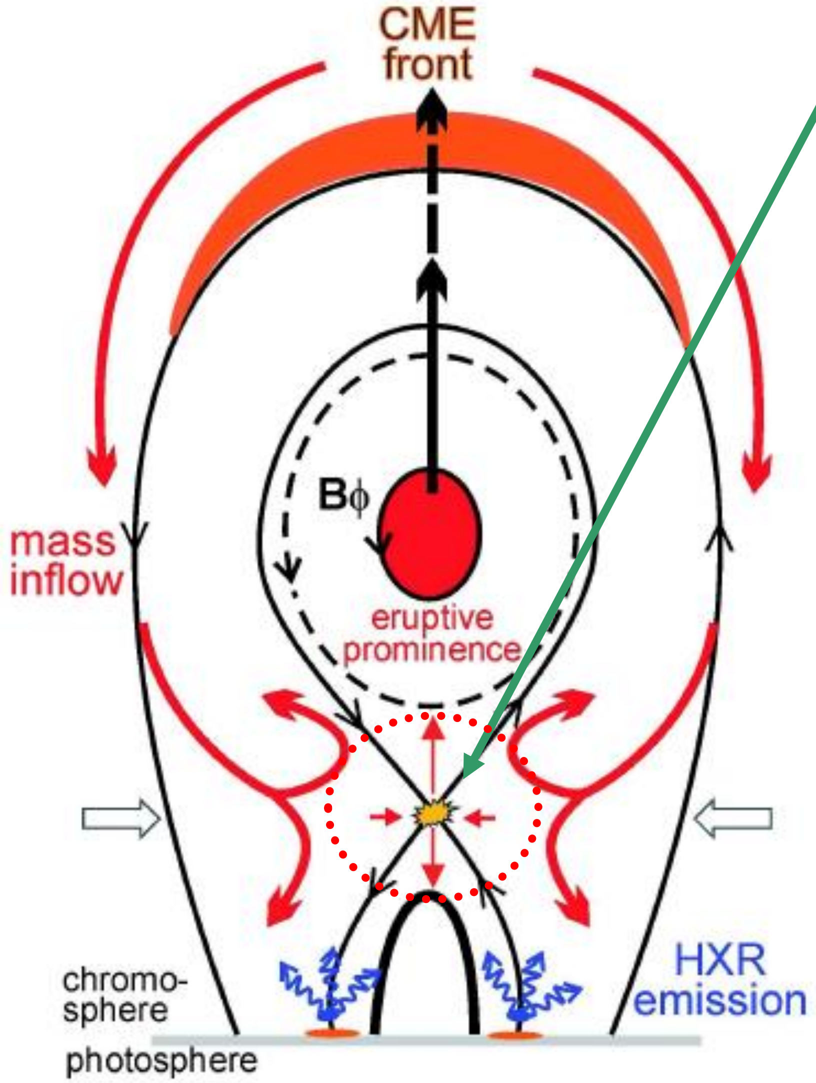


Figure from Temmer et al, 2009

Solar corona T ~ 10^6 K => 0.1 keV per particle

Flaring region T ~ 4×10^7 K => 3 keV per particle

Flare volume 10^{27} cm^3 => $(10^4 \text{ km})^3$

Plasma density 10^{10} cm^{-3}

Photons up to > 100 MeV

Number of energetic electrons 10^{36} per second

Electron energies >10 MeV

Proton energies >100 MeV

Large solar flare releases about 10^{32} ergs (about half energy in energetic electrons)

1 megaton of TNT is equal to about 4 x 10^{22} ergs.

X-ray and gamma-ray emissions

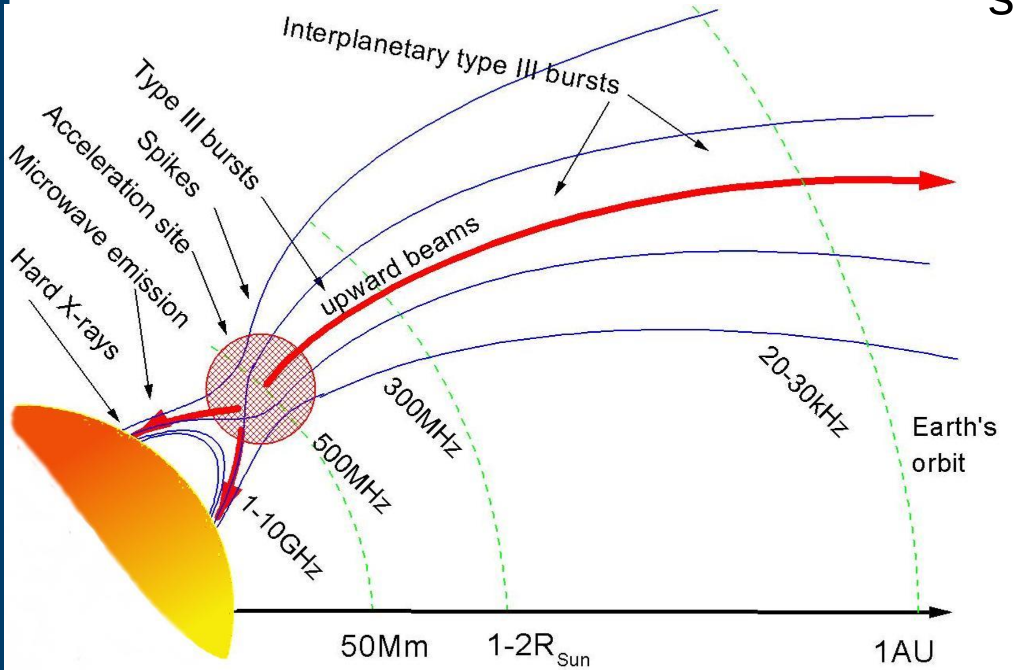
X-rays and flare accelerated electrons

Observed X-rays

Unknown electron distribution

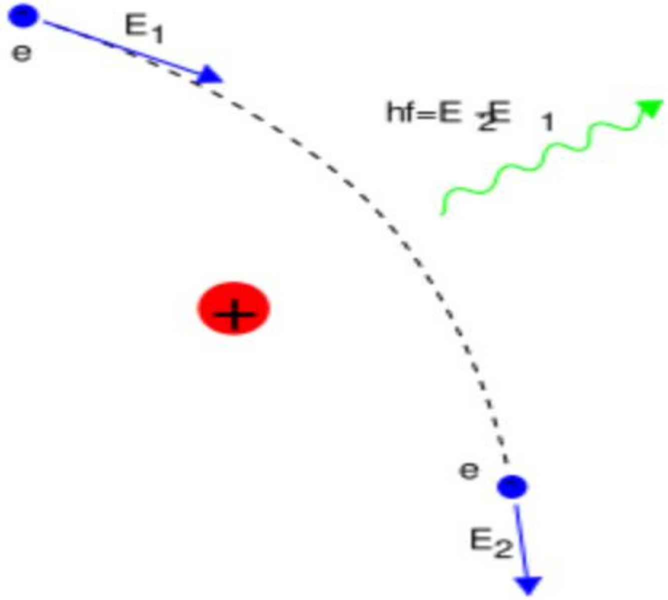
Emission cross-sections

$$I(\epsilon,\Omega,t) = \int_{\ell} \int_{\Omega'} \int_{\epsilon}^{\infty} n(\mathbf{r})\bar{F}(E,\Omega',\mathbf{r},t)Q(\Omega,\Omega',\epsilon,E)\,\mathrm{d}E\,\mathrm{d}\Omega'\,\mathrm{d}\ell,$$



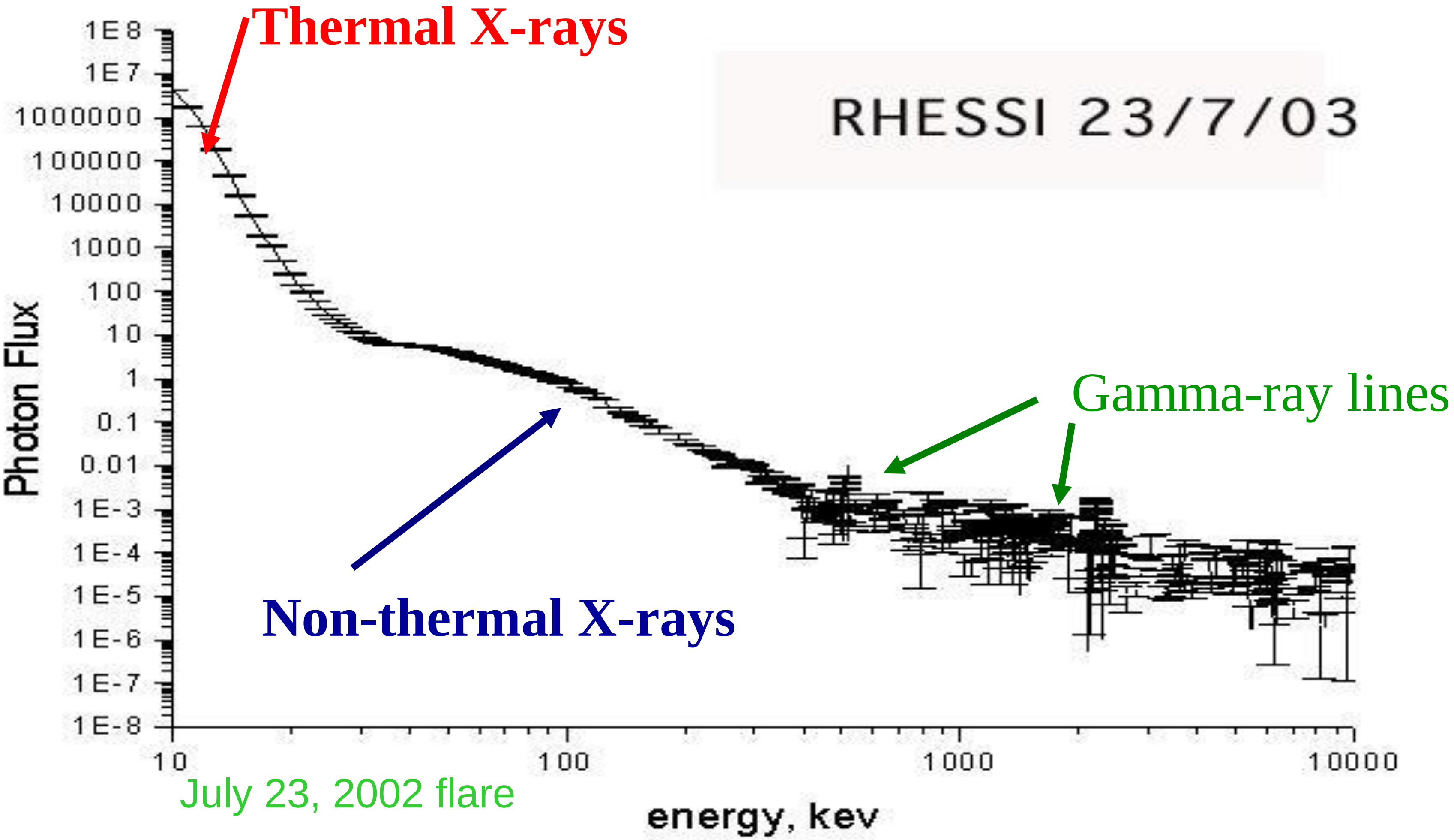
Thin-target case: For the electron spectrum **$F(E) \sim E^{-\delta}$** ,

Electron-ion bremsstrahlung (free-free emission)



Dominant process for energies ~10 – 400 keV the photon spectrum is **$I(\varepsilon) \sim \varepsilon^{-\delta-1}$**

X-ray spectrum of solar flares



July 23, 2002 flare

Ramaty **H**igh **E**nergy **S**olar **S**pectroscopic **I**mager (**RHESSI**) spectrum

X-ray emission processes

For spatially integrated spectrum:
$$I(\epsilon) = \frac{1}{4\pi R^2}\,\overline{n}V \int_{\epsilon}^{\infty} \overline{F}(E)\,Q(\epsilon, E)\,dE,$$

Thin-target case: For the electron spectrum **$F(E) \sim E^{-\delta}$** ,

a) Electron-ion bremsstrahlung (free-free emission)

Dominant process for energies ~10 – 400 keV

the photon spectrum is **$I(\varepsilon) \sim \varepsilon^{-\delta-1}$**

In the simplest form Kramers’ approximation:
$$Q(\epsilon, E) = Z^2 \frac{\sigma_o}{\epsilon E},$$

b) Electron-electron bremsstrahlung (free-free emission)

Dominant process for energies above 400 keV

the photon spectrum is **$I(\varepsilon) \sim \varepsilon^{-\delta}$**

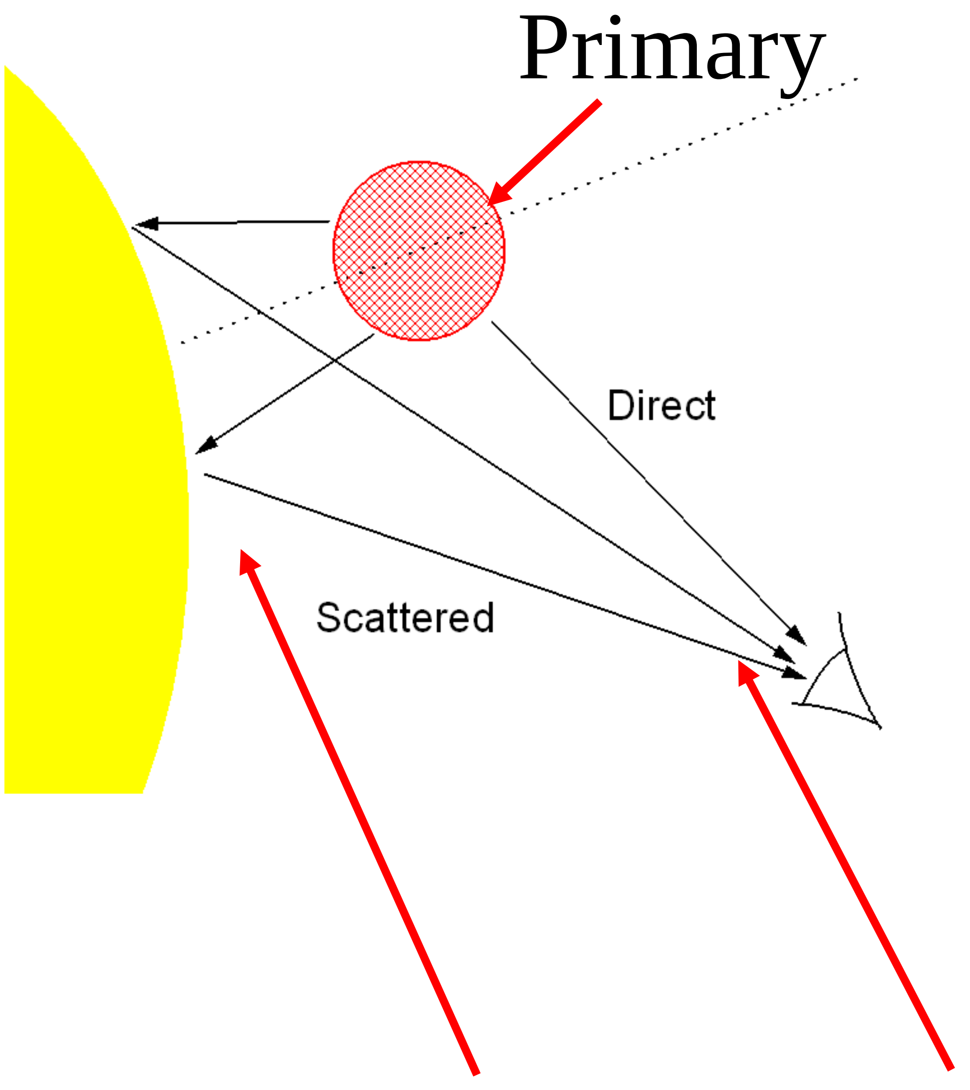
c) Recombination emission (free-bound emission)

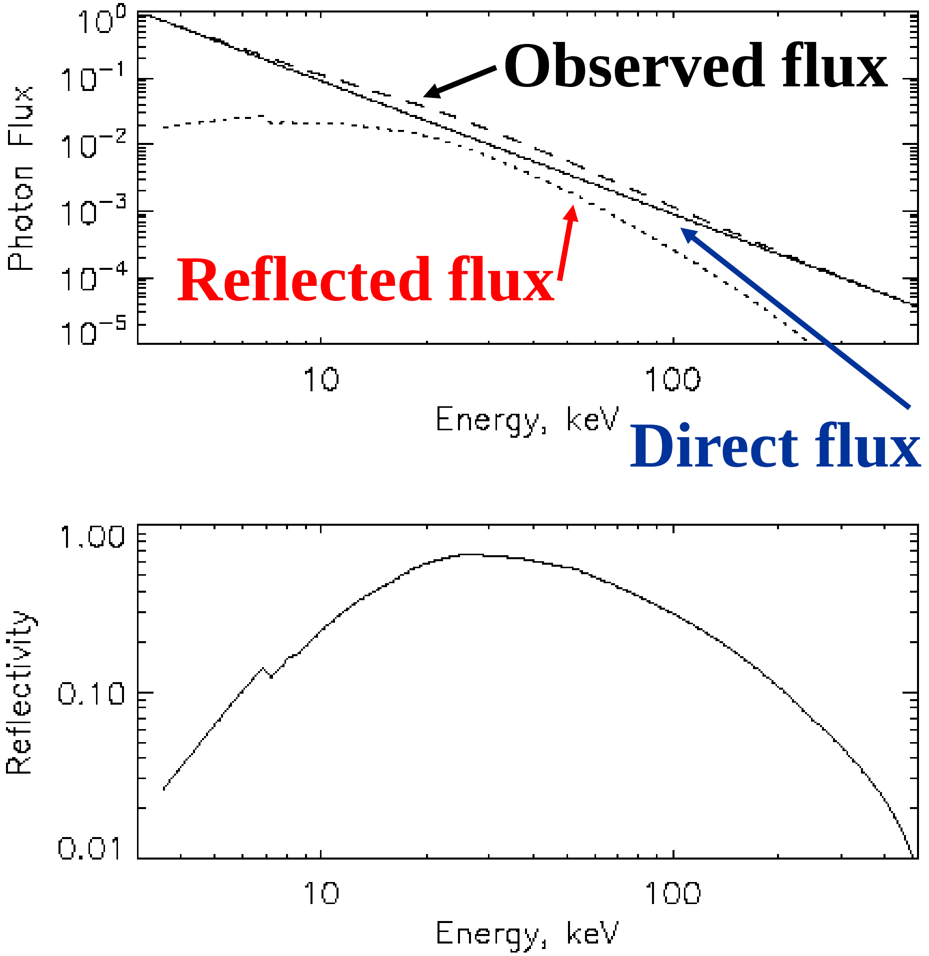
Could be dominant process for energies up to 20 keV

the photon spectrum is **shifted by ionisation potential** and **$I(\varepsilon) \sim \varepsilon^{-\delta-2}$**

(The process requires high temperatures and detailed ionisation calculations)

Compton scattering and X-rays

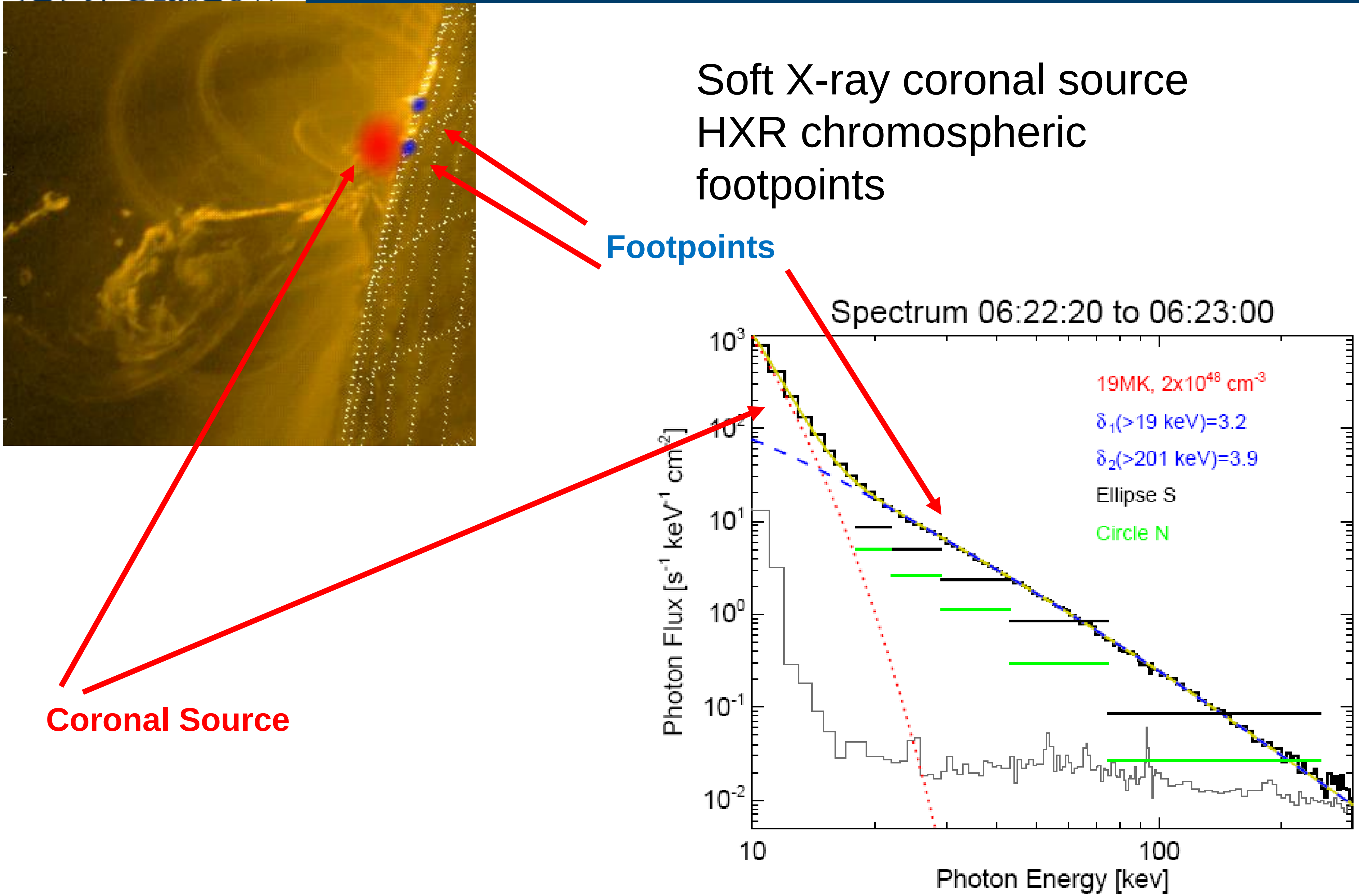




See Bai & Ramaty, 1978
Kontar et al, 2006

X-ray emission from typical flares

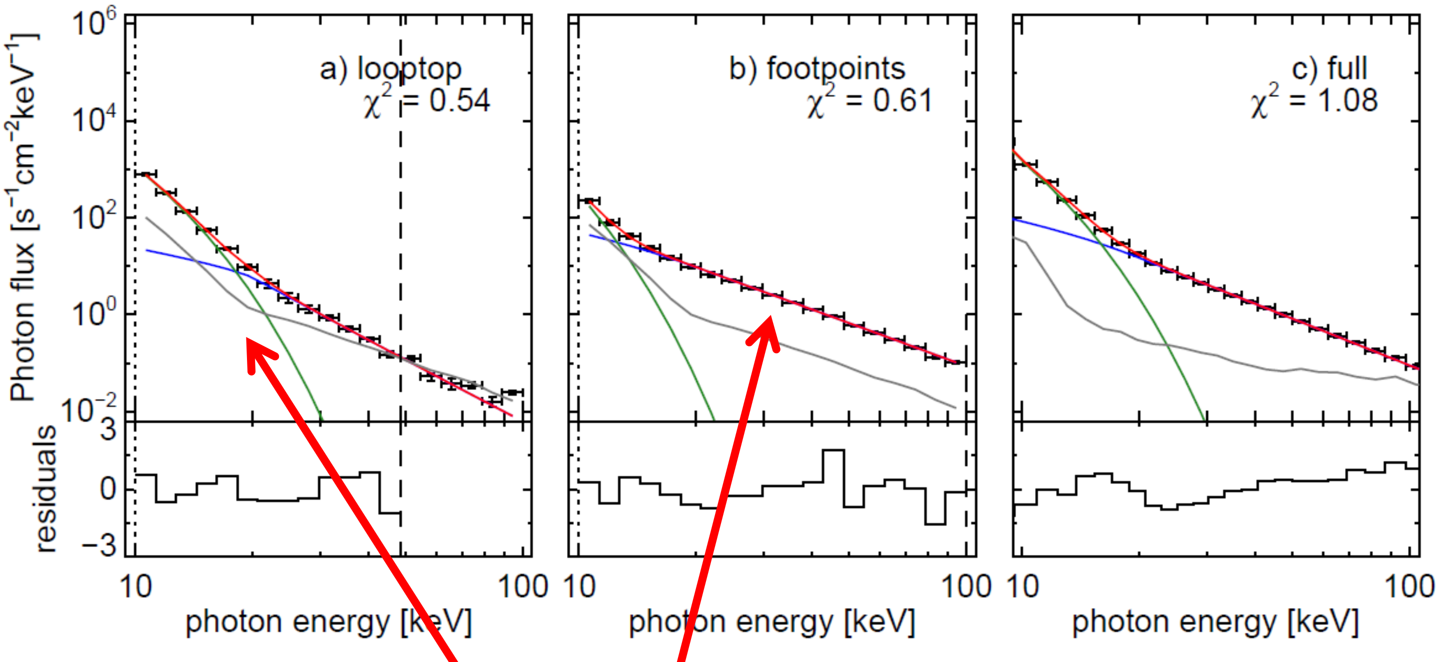
Soft X-ray coronal source
HXR chromospheric
footpoints



Footpoints

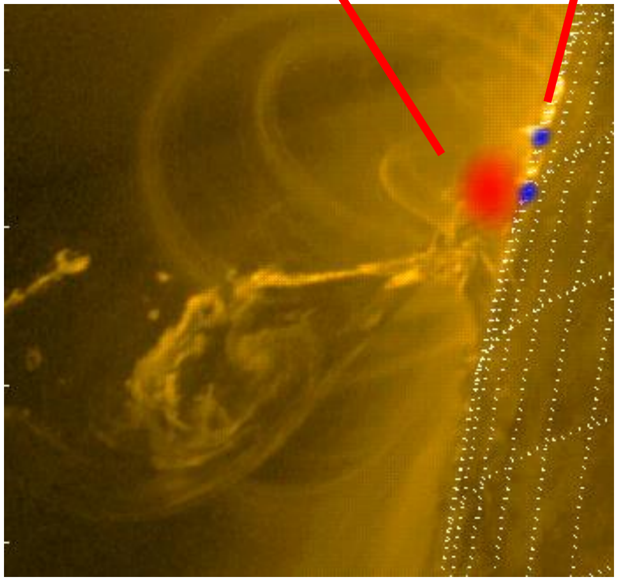
Coronal Source

Typical solar flare: X-ray prospective



Loop-top: Soft X-ray plus non-thermal component

Footpoints: Hard X-ray non-thermal power-law

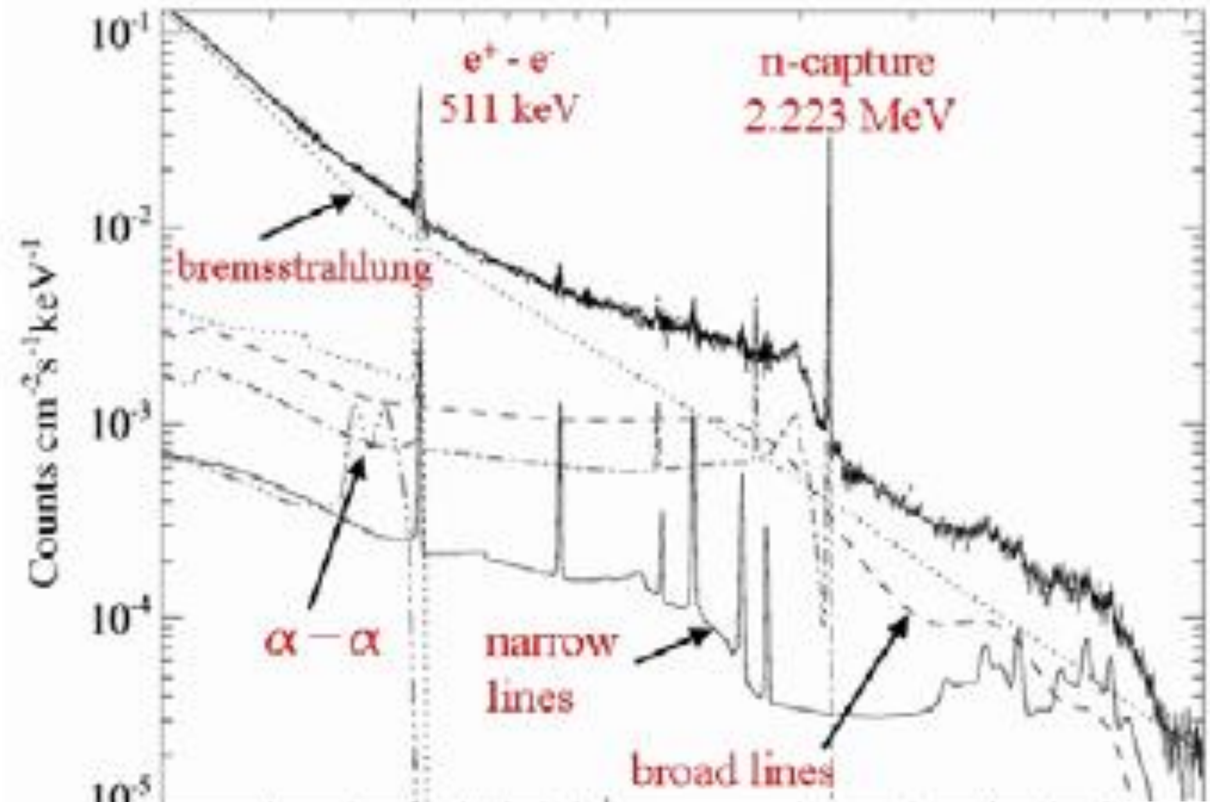


Using imaging spectroscopy, we can infer spectra and numbers of energetic electrons both in coronal and foot-points sources.

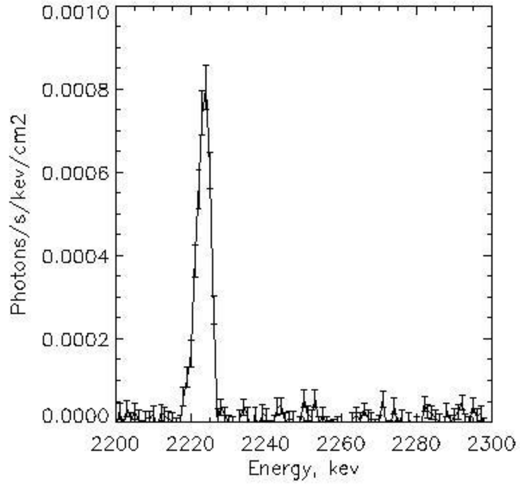
Above 30 keV, we have normally a few times electrons more in the LT than in FP source. *Possible trapping by waves or mirror?*

e.g. Simoes & Kontar, A&A, 2013 Battaglia & Benz, 2006 Emslie et 2003

Gamma-lines and accelerated ions



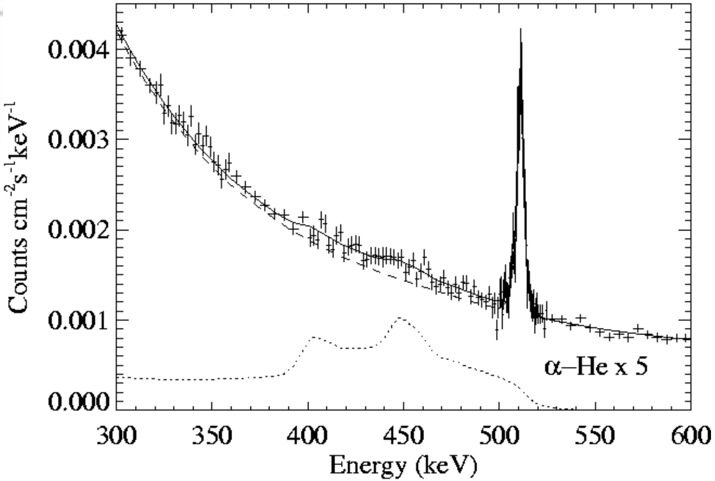
October 28, 2003 X-class flare
(Share et al, 2004)
spectrum



Alpha-alpha lines favours forward **isotropic distribution**

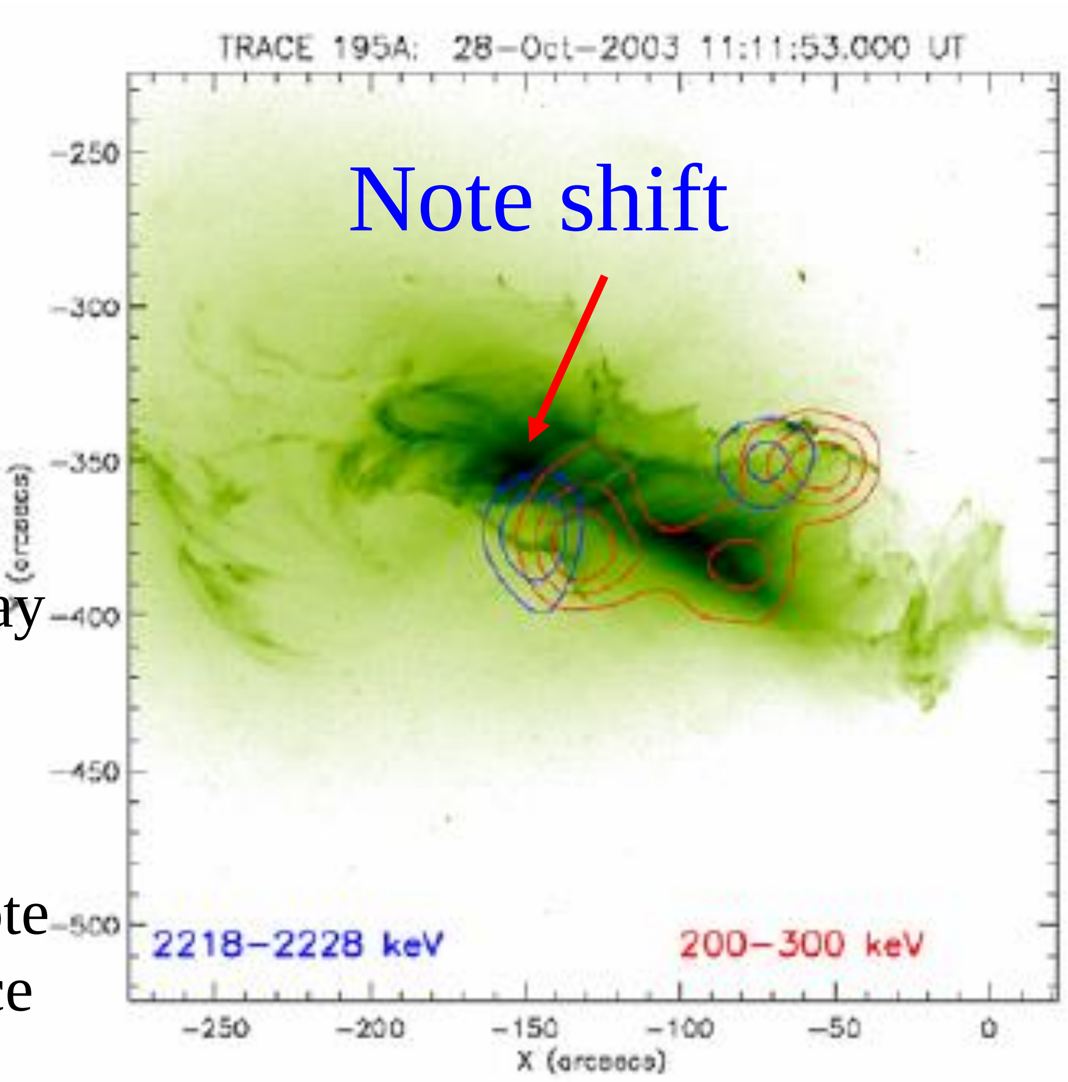
Proton & Alpha power law index is 3.75

2.2MeV line shows ~100 s delay

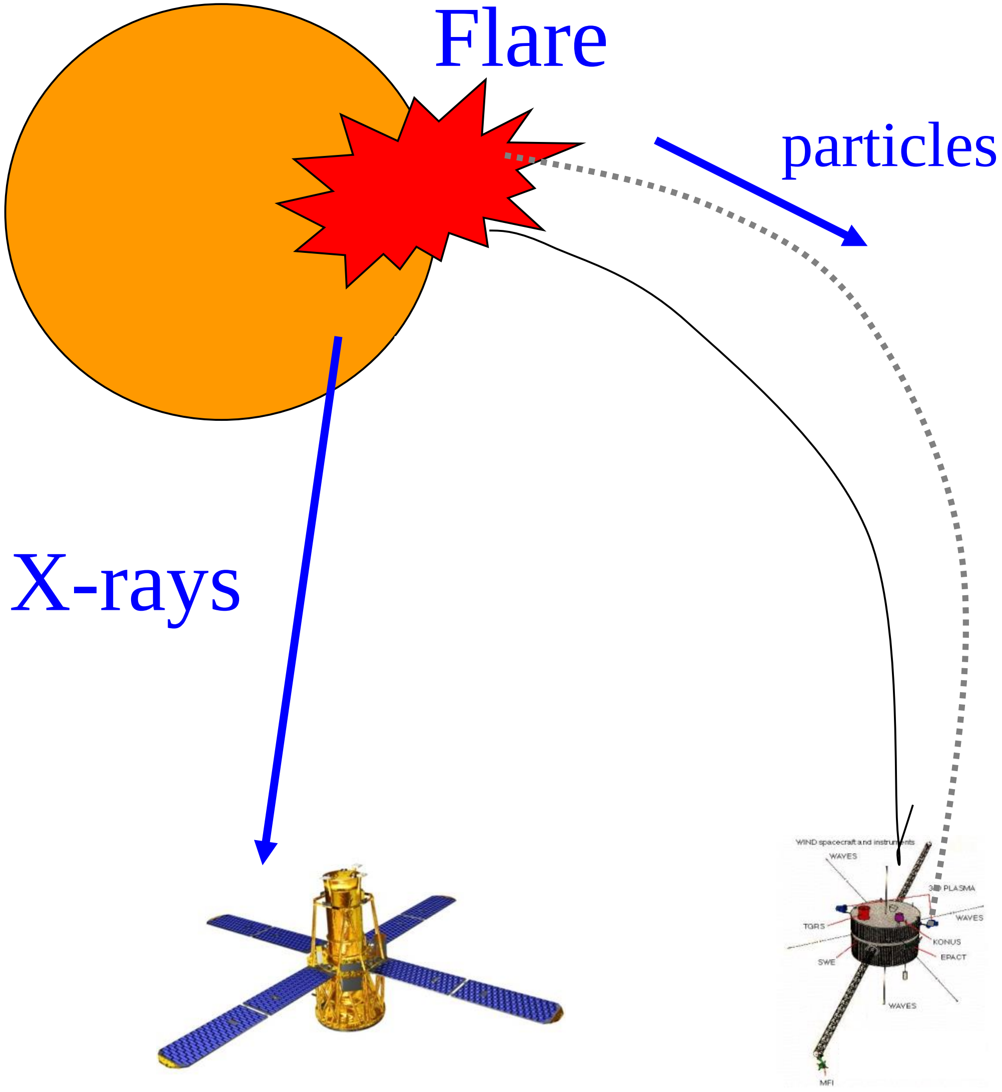


Gamma ray emission

Imaging of the 2.223 MeV neutroncapture line (blue contours) and the HXR electron bremsstrahlung (red contours) of the flare on October 28, 2003. The underlying image is from TRACE at 195 Å. The X-ray and γ-ray imaging shown here used exactly the same selection of detector arrays and imaging procedure. Note the apparent loop-top source in the hard X-ray contours Hurford et al 2006.



Energetic particles at 1AU

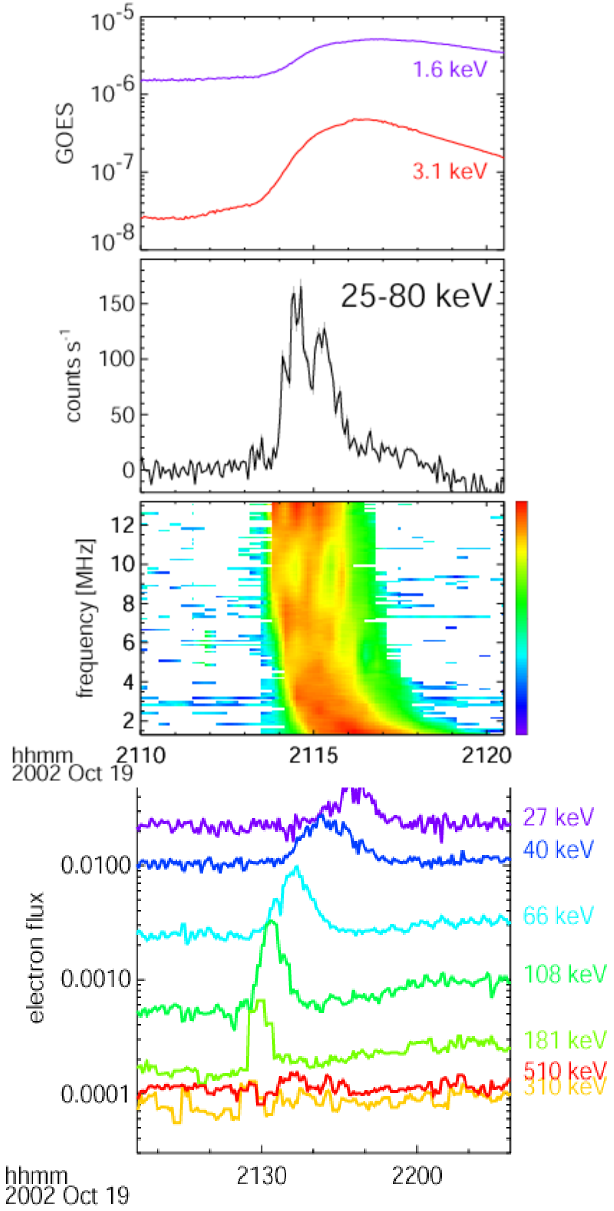


Flare

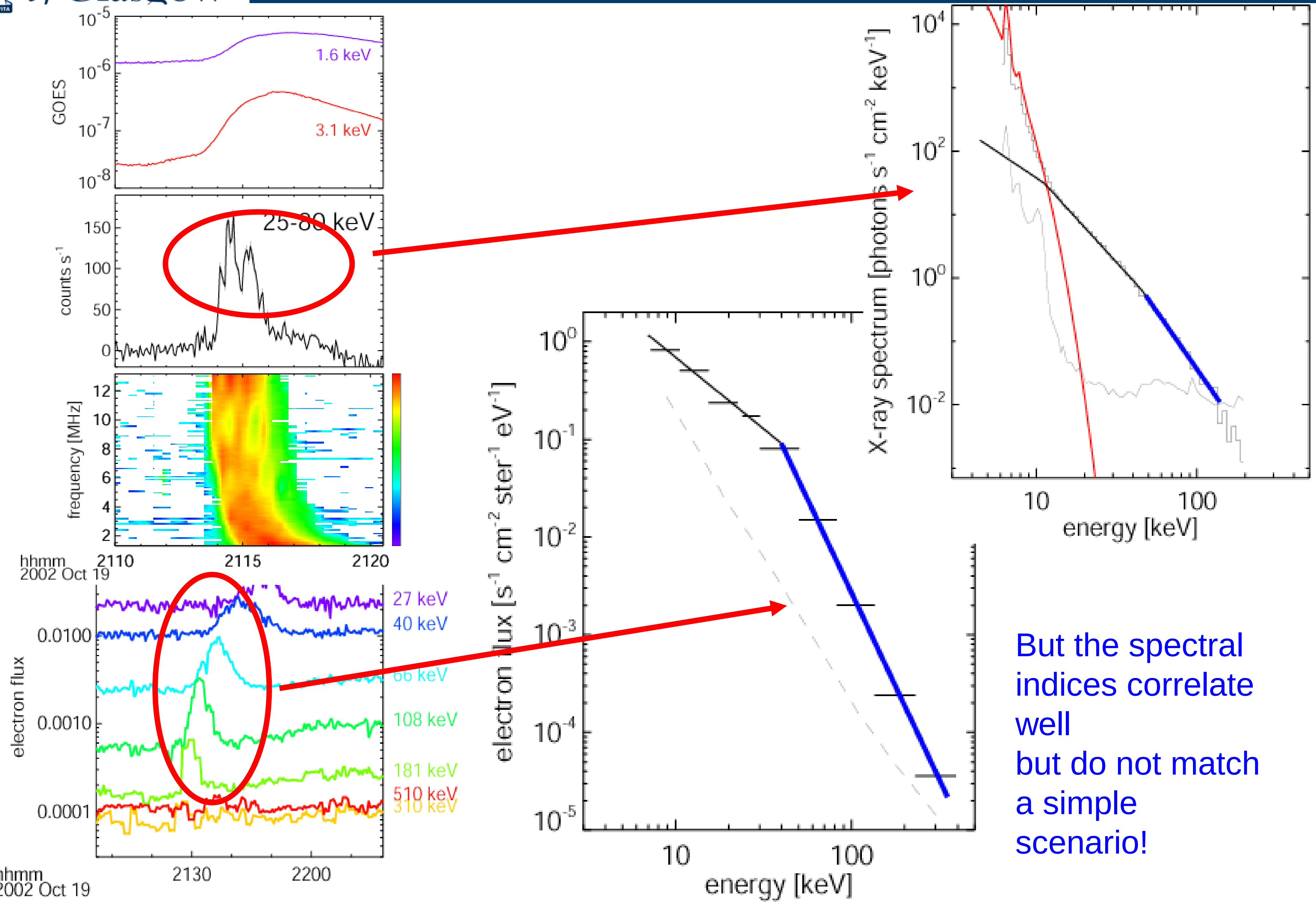
particles

X-rays

RHESSI

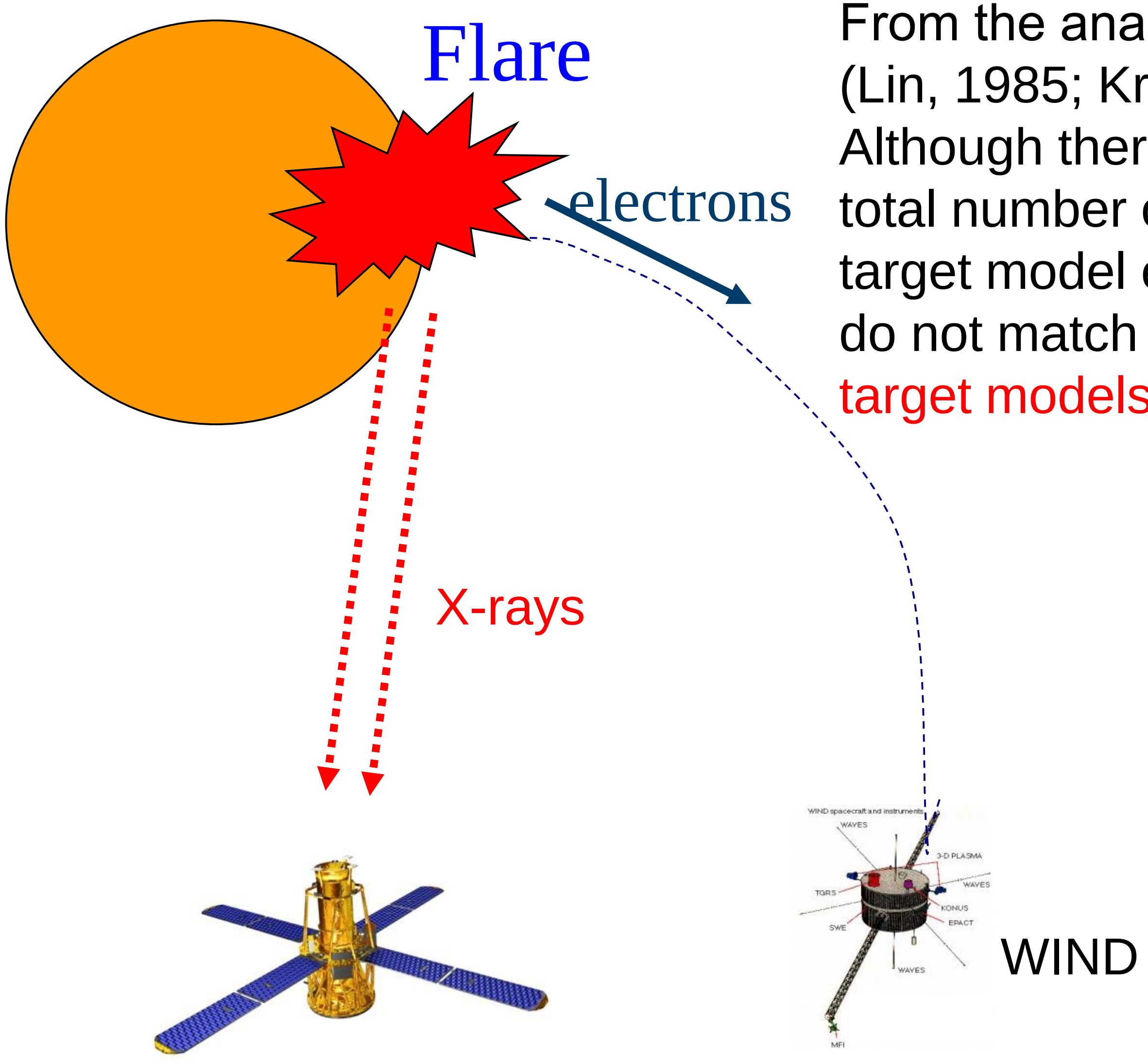


Energetic particles at 1AU



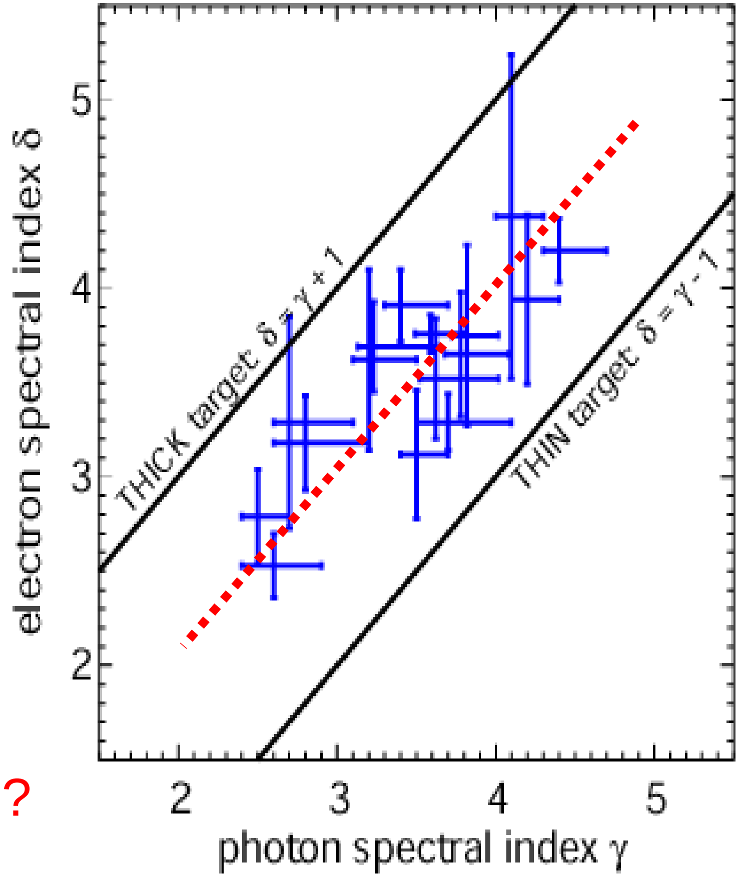
But the spectral indices correlate well
but do not match a simple scenario!

From X-rays to electrons



RHESSI

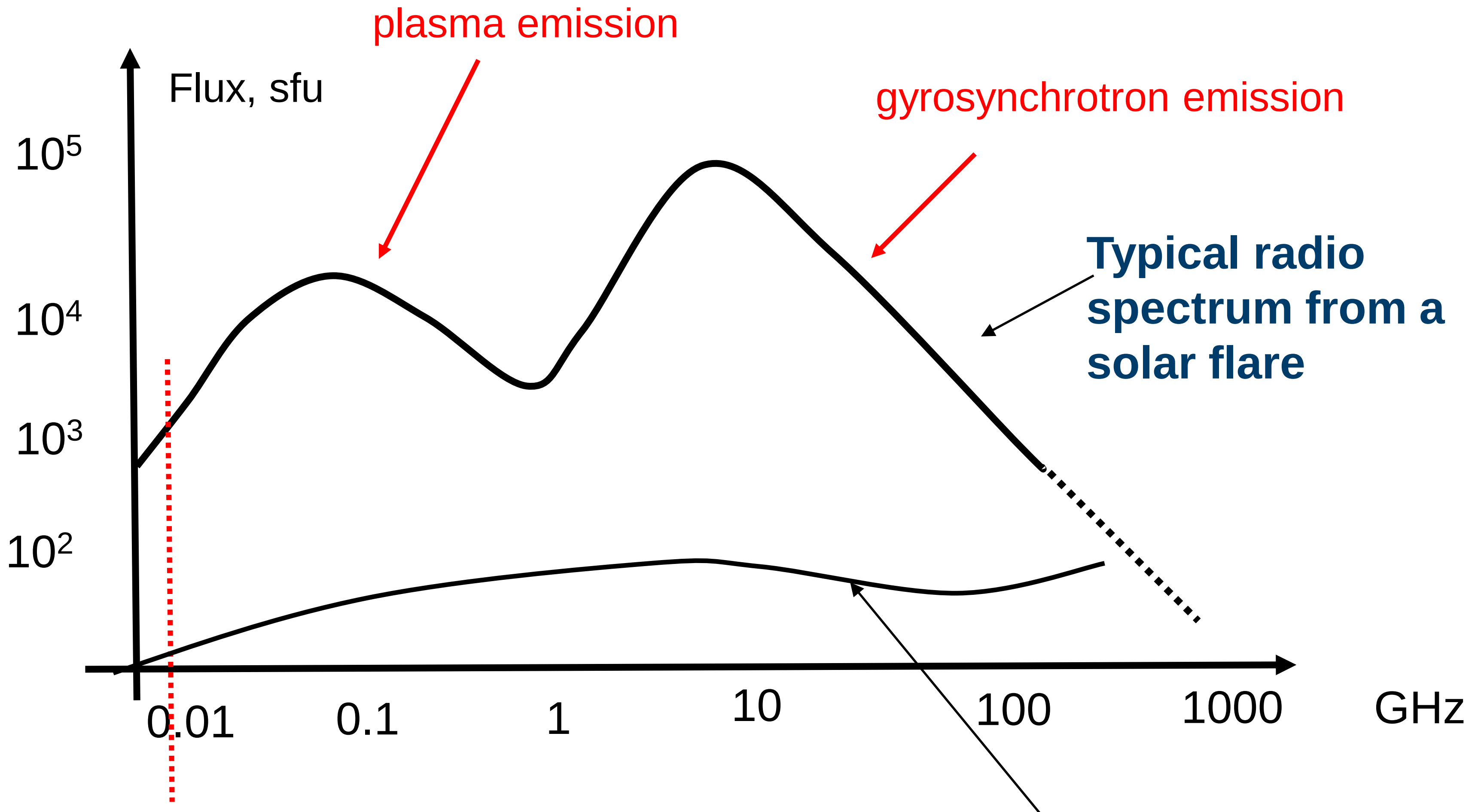
From the analysis of 16 “scatter-free” events (Lin, 1985; Krucker et al, 2007) :
Although there is correlation between the total number of electrons at the Sun (thick-target model estimate) the spectral indices do not match either thick-target or thin-target models.



Acceleration or transport effects?

Radio emission – important basics

Solar radio emission



plasma emission

gyrosynchrotron emission

Typical radio spectrum from a solar flare

Ionospheric cut-off ~10 MHz

Radio spectrum quiet Sun

1 sfu = 10^4 Jansky

Brightness temperature

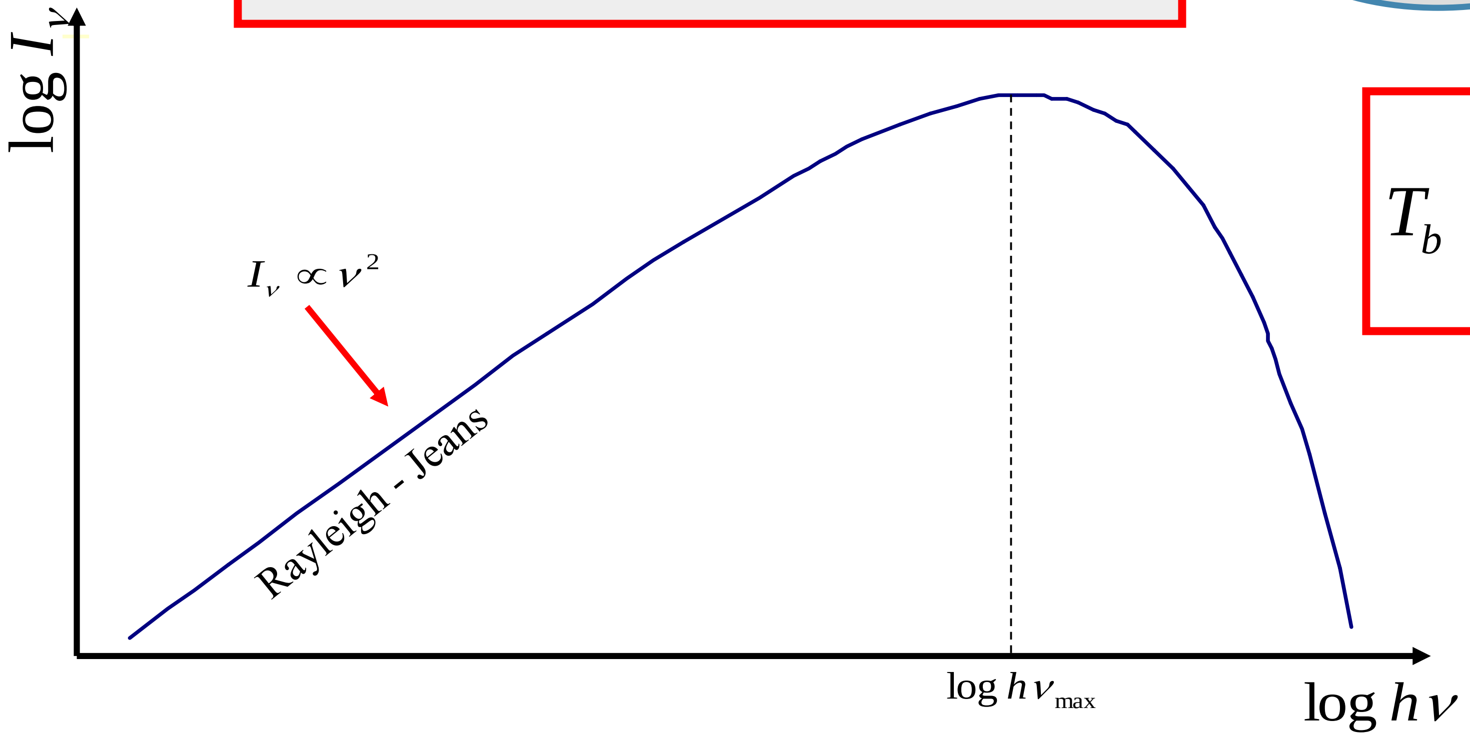
We can always make a definition, common in radio astronomy: Brightness temperature

At typical radio frequencies and temperatures $h\nu << kT \Rightarrow \exp\left(\frac{h\nu}{kT}\right)-1 \approx \frac{h\nu}{kT}$

Hence

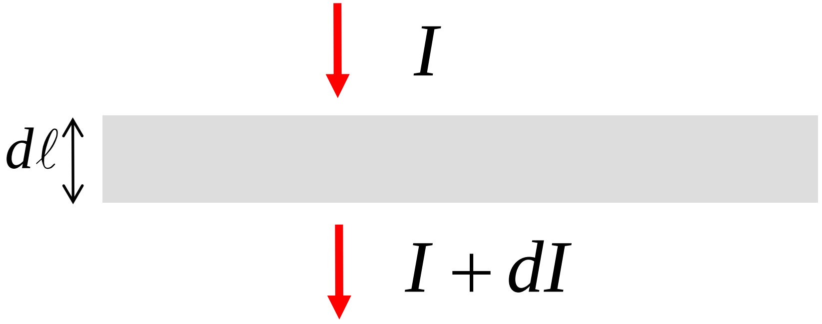
$$\boxed{I_\nu = \frac{2h\nu^3}{c^2\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]} \cong \frac{2\nu^2 kT}{c^2}}$$

Rayleigh – Jeans approximation



$$\boxed{T_b = \frac{c^2 I_\nu}{2\nu^2 k}}$$

Optically thick and optically thin emission



If we model the absorption in the slab as:

$$\boxed{dI = -I\,\kappa\,d\ell}$$

Absorption coefficient, which is not in general constant, but depends on depth and frequency in the atmosphere

The optical depth, denoted by τ , so that $$I_{\text{obs}} = I_0\,e^{-\tau}$$

- If $\tau = 0$ we describe the atmosphere as **"transparent"** and $I_{\text{obs}} = I_0$
- If $\tau << 1$ we describe the atmosphere as **"optically thin"** and $I_{\text{obs}} \approx I_0$
- If $\tau \geq 1$ we describe the atmosphere as **"optically thick"** and $I_{\text{obs}} << I_0$

For example, free-free absorption coefficient (Dulk, 1985):

$$\kappa(\nu) = 0.2 n_e^2 T^{-\frac{3}{2}} \nu^{-2} (\text{cm}^{-1})$$

Radio emission mechanisms

Solar radio emission mechanisms

Free-free emission (collisions of electrons with protons and other particles)

Gyromagnetic emission *(cyclotron and gyrosynchrotron)*

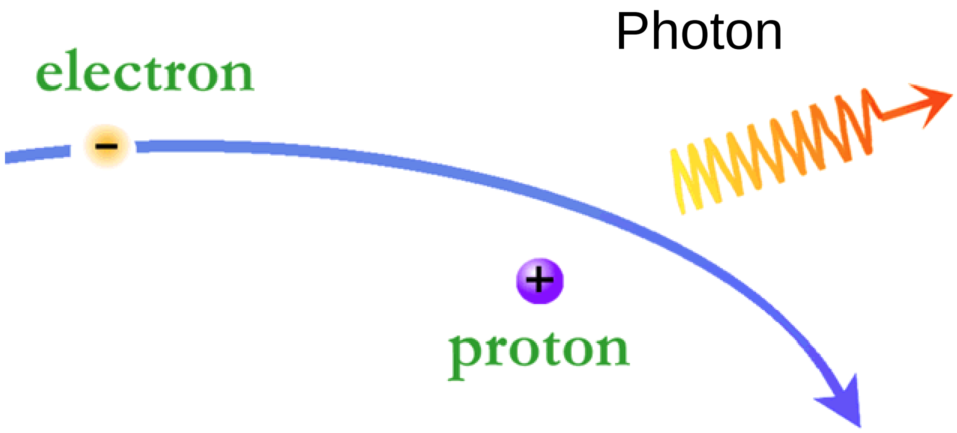
Coherent emission *due to wave-wave and wave-particle interaction*

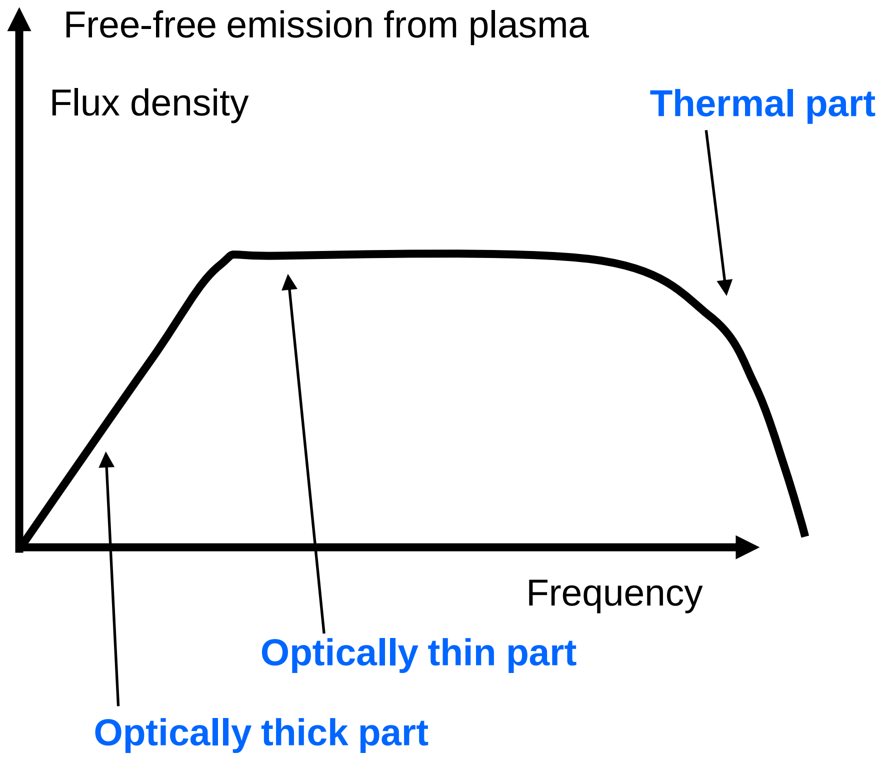
$$\nu_B = \frac{eB}{2\pi m_e c},$$ <= gyrofrequency

$$\nu_p = \sqrt{\frac{n_e e^2}{\pi m_e}},$$ <= plasma frequency

Free-free emission

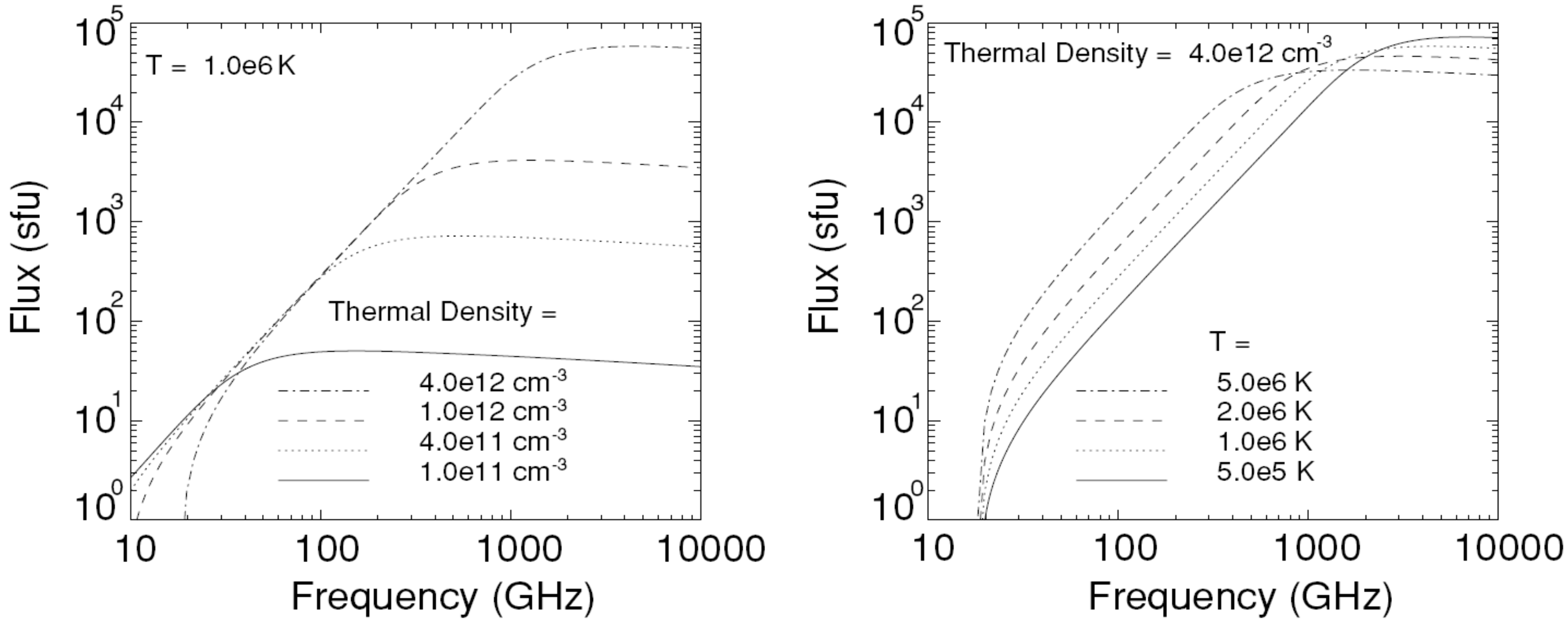
Photons are produced by **free-free transitions** of electrons – also known as **Bremsstrahlung** ('braking radiation')





Free-free emission

A rising spectrum from a compact (20”) source requires that the source is relatively **dense** (n_e~10^{11} cm^{-3}) and **hot** (T_e ~10 MK).

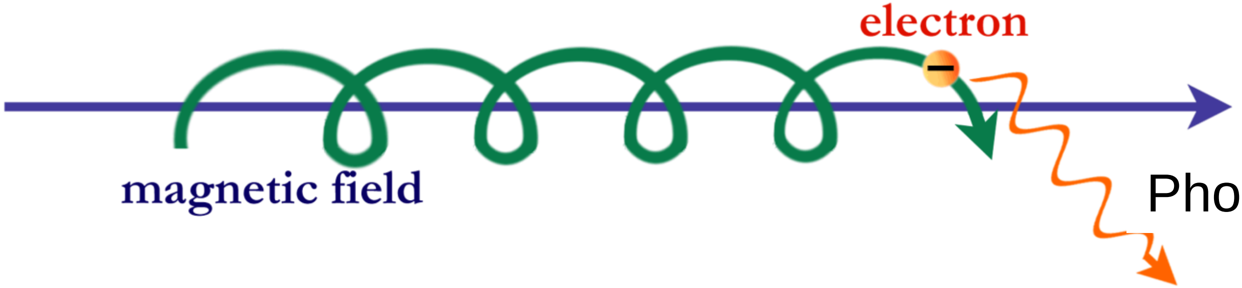


Thermal free-free radio spectra produced from a uniform cubic source with a linear size of 20’’ for $n_e = 10^{11}$ to 4×10^{12} cm^{-3} and T_e = 0.5–5 MK.

Gyro-magnetic emission

Cyclotron Radiation

Any constant velocity component parallel to the magnetic field line leaves the radiation unaffected (no change in *acceleration*), and electron spirals around the field line.



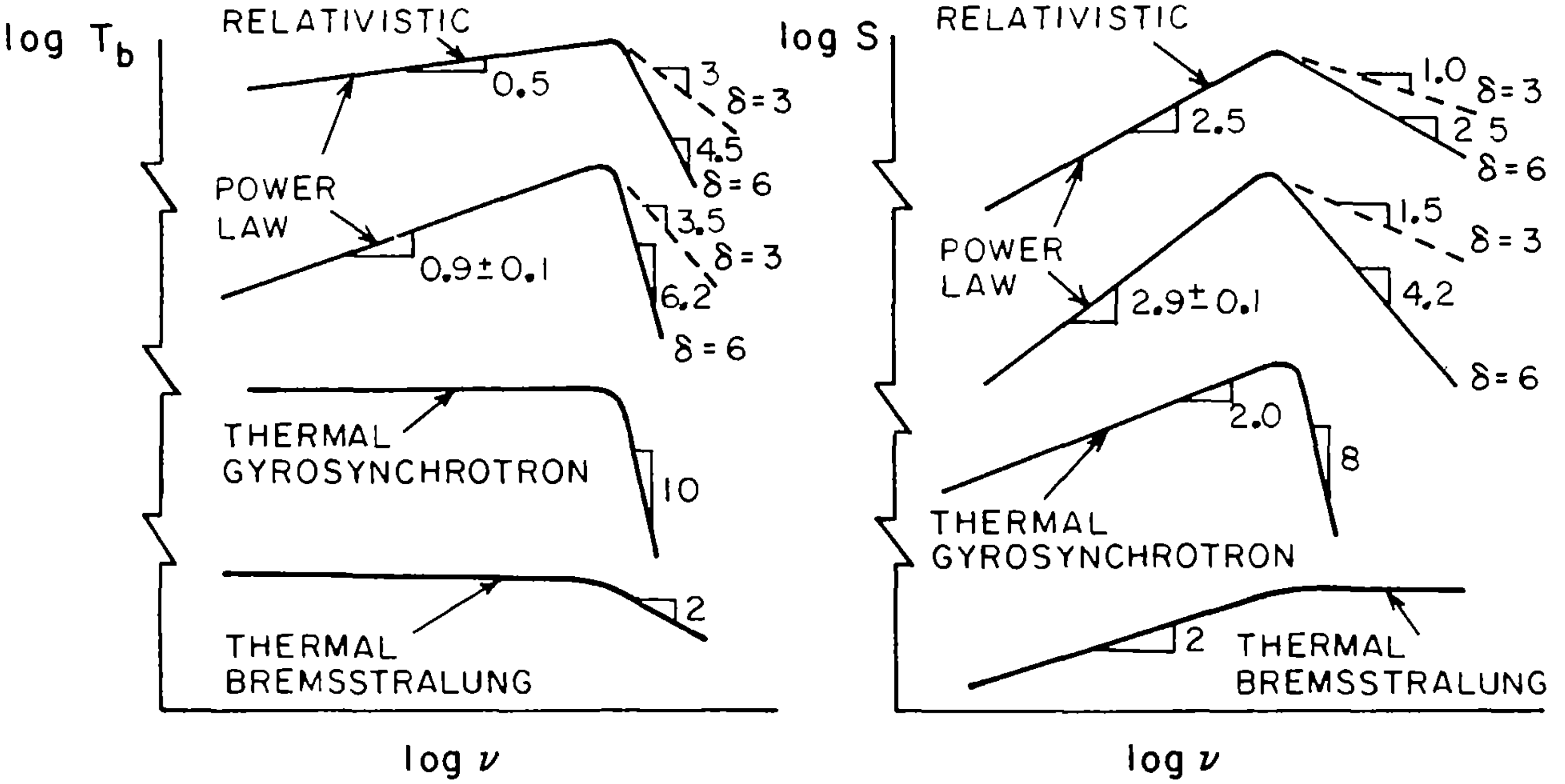
Electron cyclotron line has frequency

$$\nu_{\mathbf{B}} = \Omega_{\mathbf{e}}/2\pi = eB/2\pi m_{\mathbf{e}}c \approx 2.8 \times 10^6 B.$$

In ultra-relativistic limit, this radiation is known as **synchrotron** – it is strongly Doppler shifted and forward beamed due to relativistic aberration.

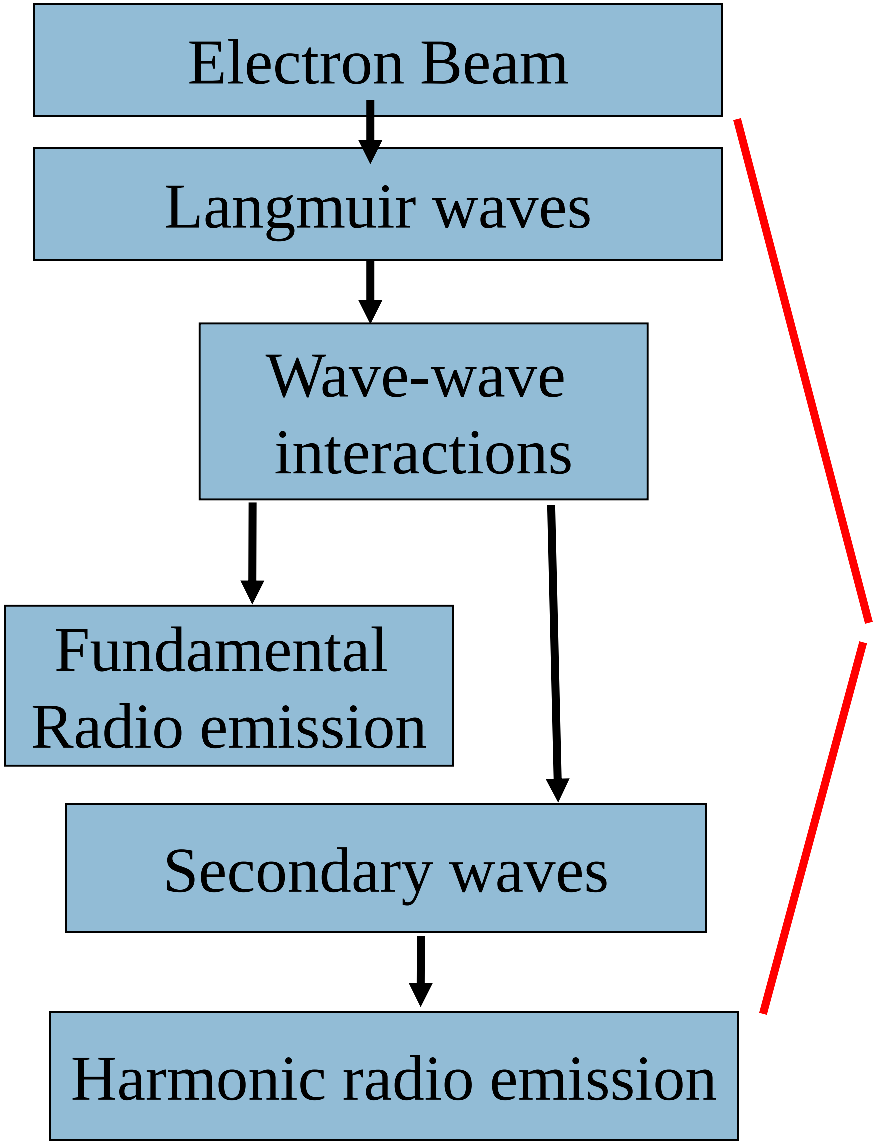
In mildly or sub relativistic limit, this radiation is known as **Gyrosynchrotron**

Gyro-magnetic emission



Brightness Temperature and Flux density as a function of frequency for various emission mechanisms (*Dulk, 1985*)

Plasma emission mechanisms



Electron Beam

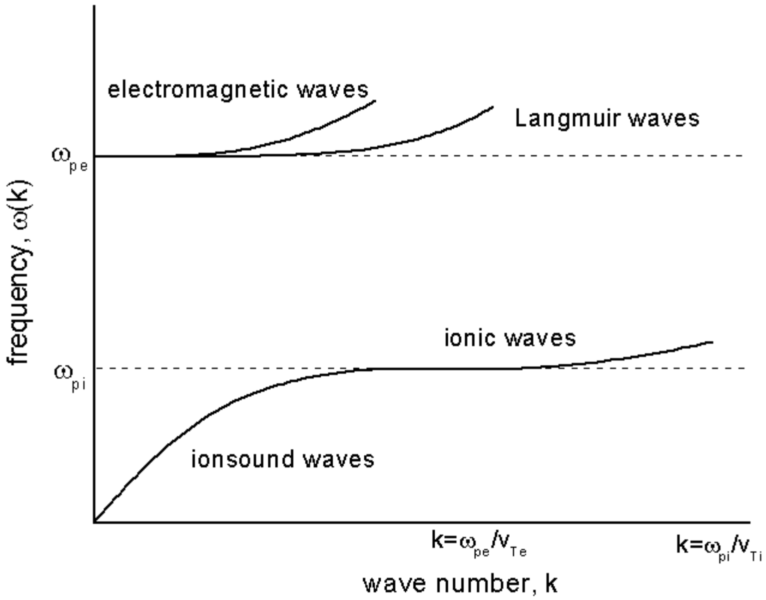
Langmuir waves

Wave-wave interactions

Fundamental Radio emission

Secondary waves

Harmonic radio emission



***Coherent emission** due to wave-wave and wave-particle interaction*

$$\nu_p = \omega_p/2\pi = [n_e e^2/\pi m_e]^{1/2} \approx 9000\, n_e^{1/2}$$

plasma frequency

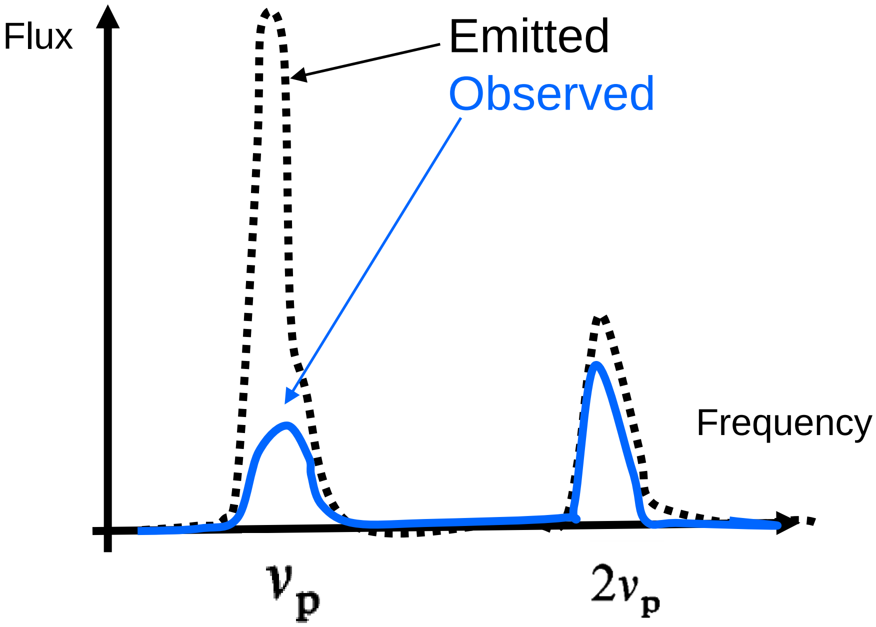
Plasma emission mechanisms

Fundamental radio emission (at local plasma frequency)

1) Ion-sound decay L=T+S
2) Scattering off ions L+i=T+i

Harmonic radio emission (double plasma frequency)

1) Decay and coalescence
   L =L'+S, L+L'=T
2) Scattering and coalescence
   L+i=L+i', L+L'=T



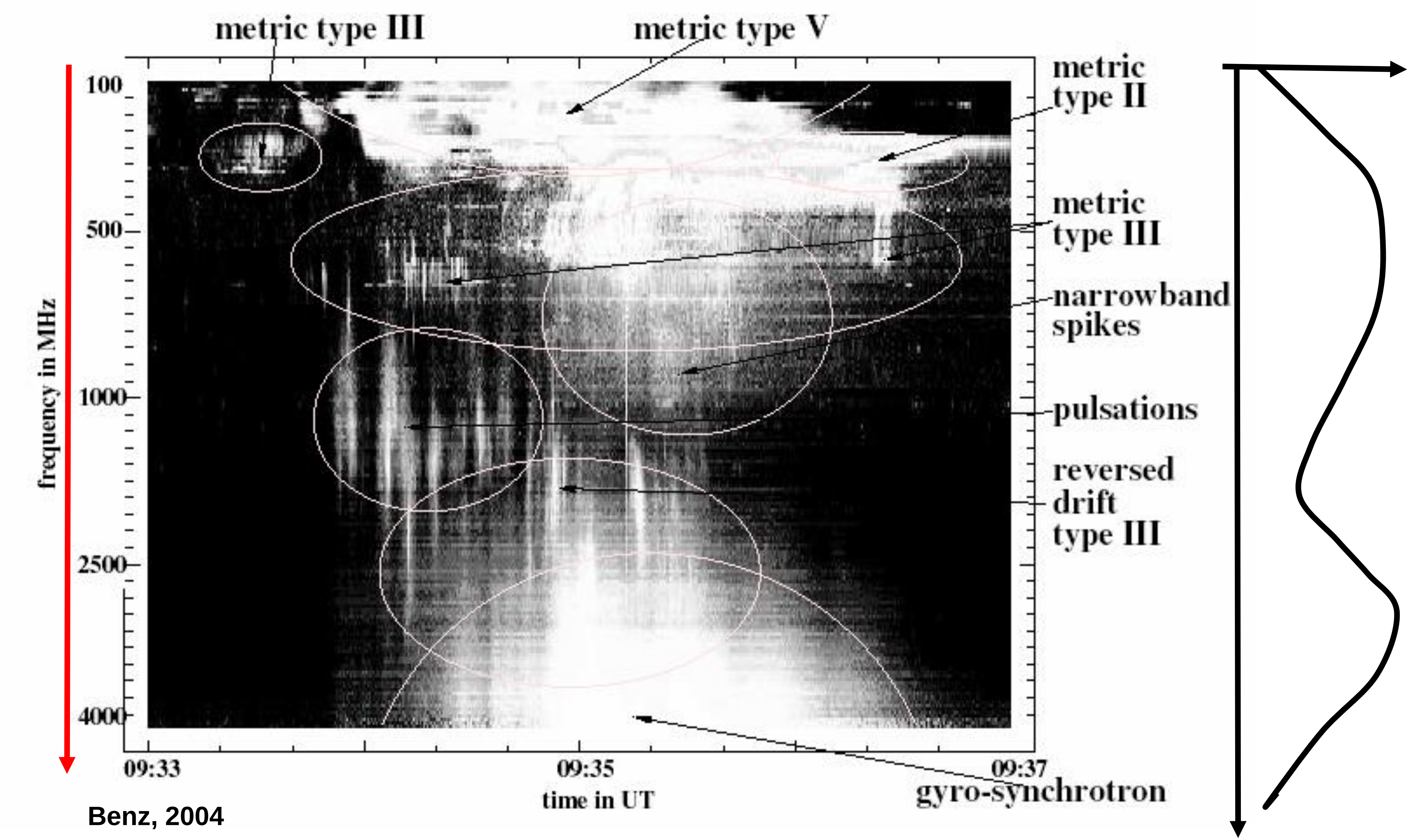
For each act of decay or coalescence we have the corresponding conservation laws for momentum and energy require:

$$\mathbf{k}' = \mathbf{k}'' + \mathbf{k}, \quad \omega(\mathbf{k})_{\sigma'} = \omega(\mathbf{k})_{\sigma''} + \omega(\mathbf{k})_{\sigma}$$

Radio emission from active Sun

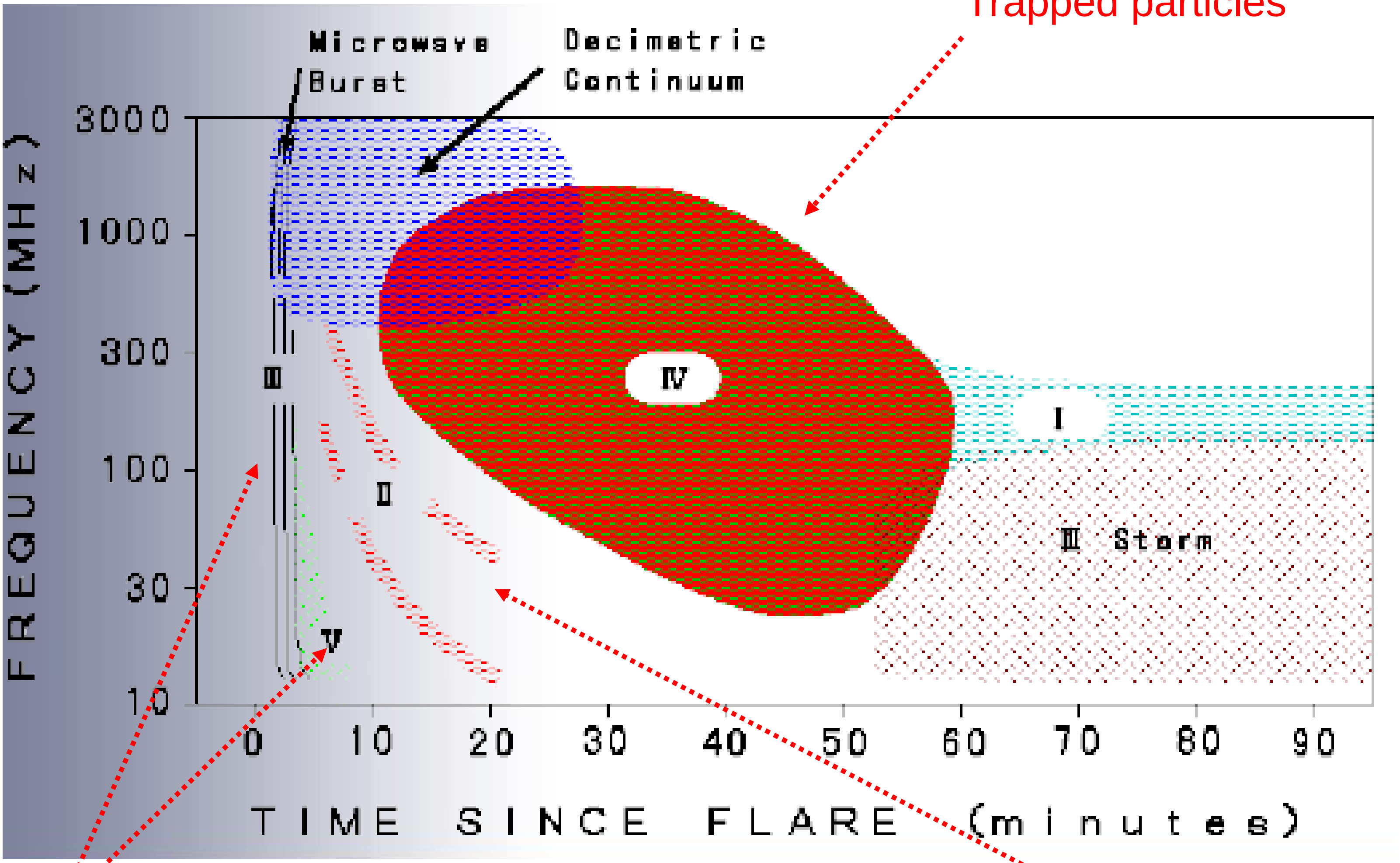
Solar radio emission is complex!

A typical dynamic spectrum of an active Sun



Benz, 2004

Source of information about various processes

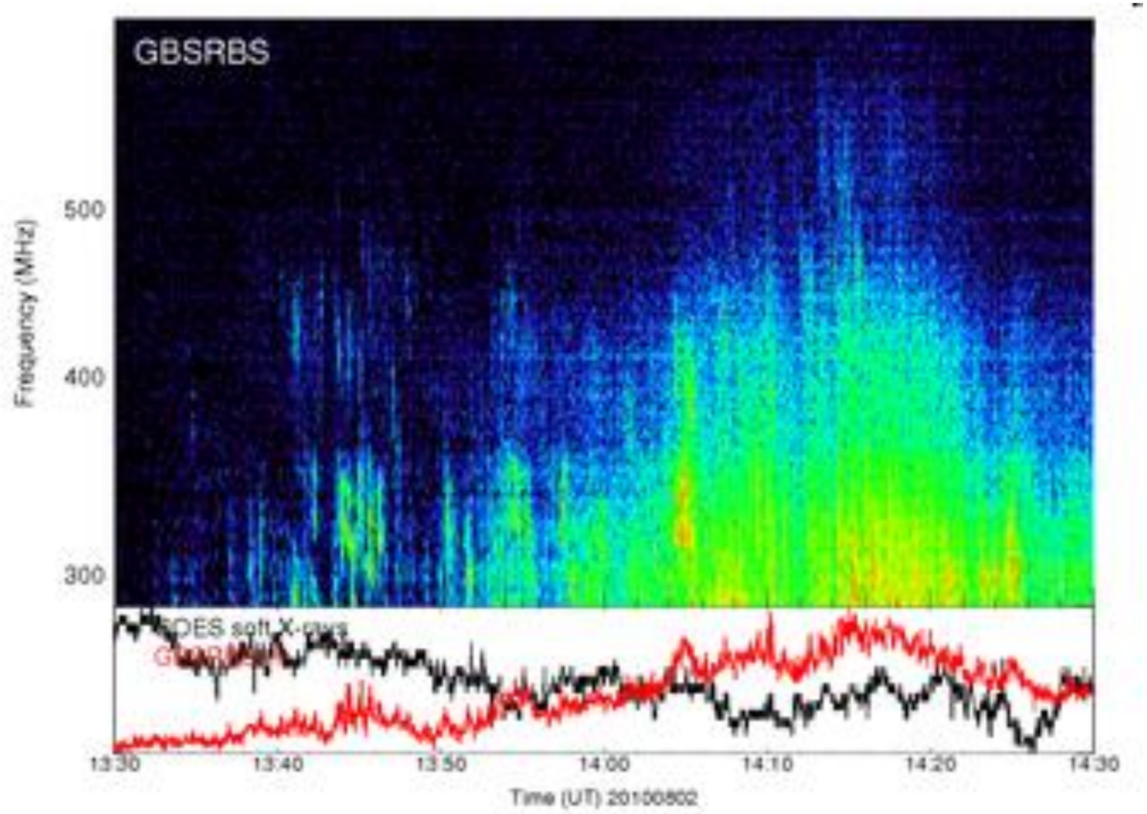


Trapped particles

Signatures of energetic electrons

Signatures of shocks

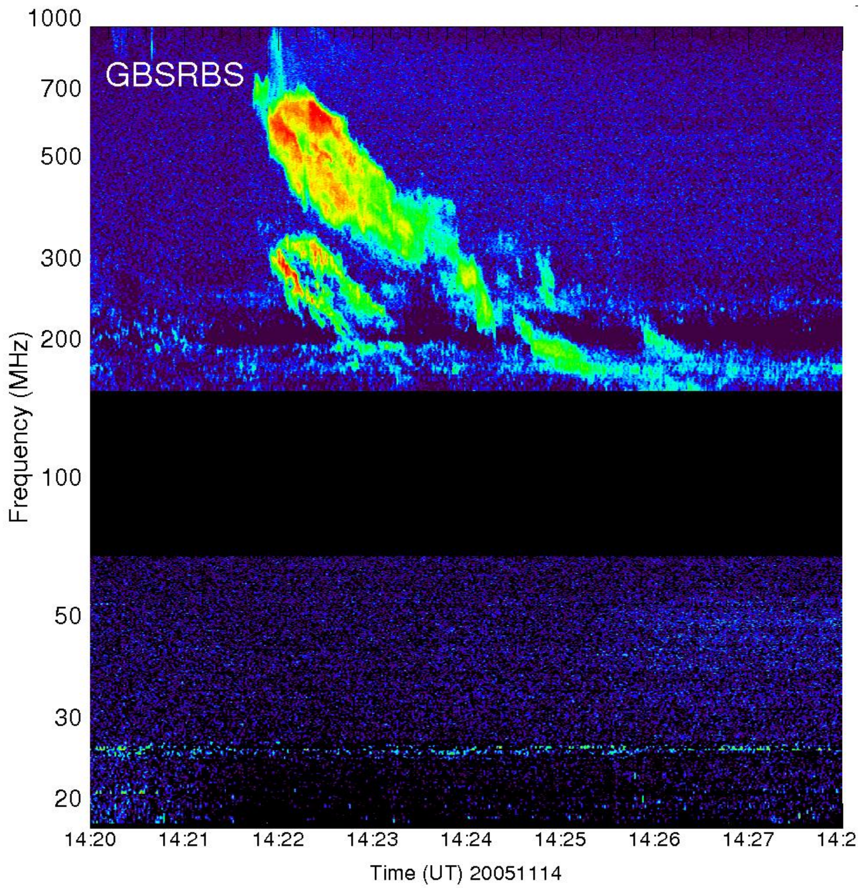
Type I



Emission mechanism: plasma emission

Exciter: hot plasma with non-thermal tail?

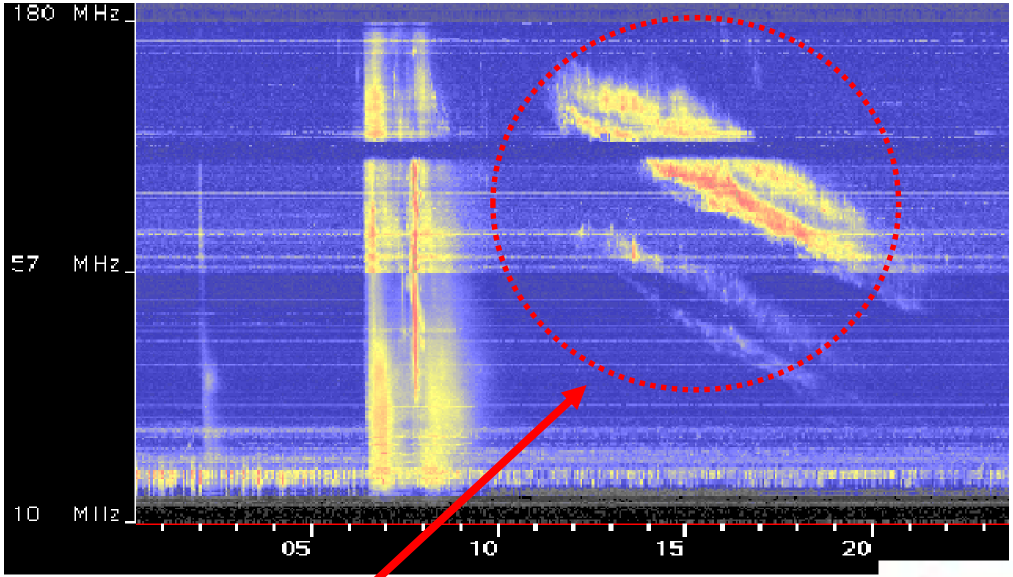
Type II



Emission mechanism: plasma emission

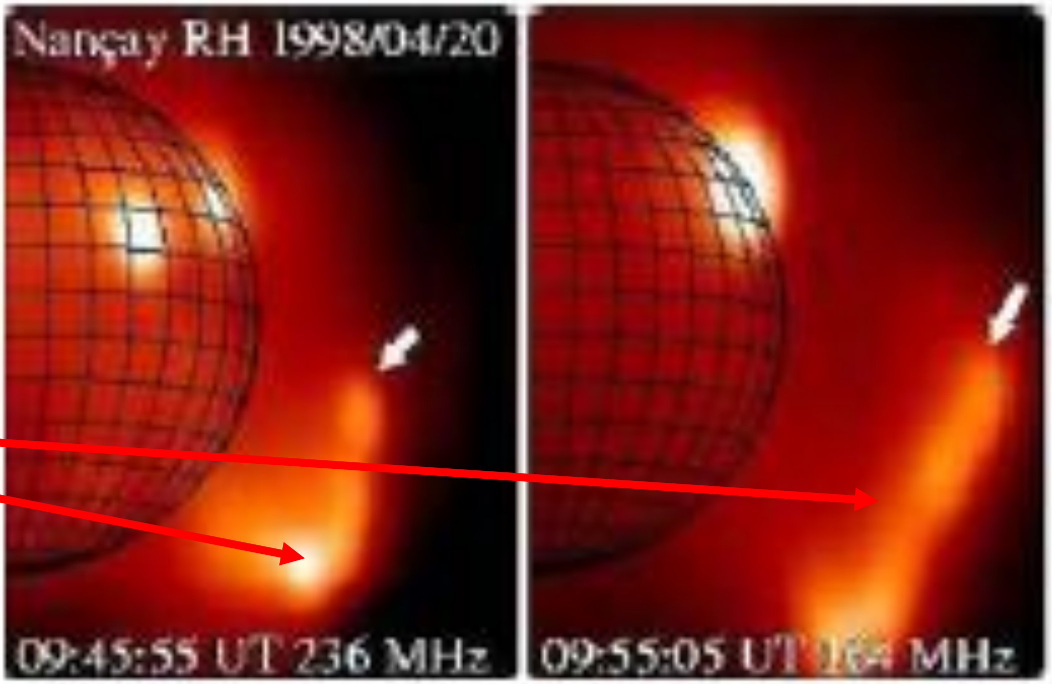
Exciter: shock waves

Type II bursts and shocks

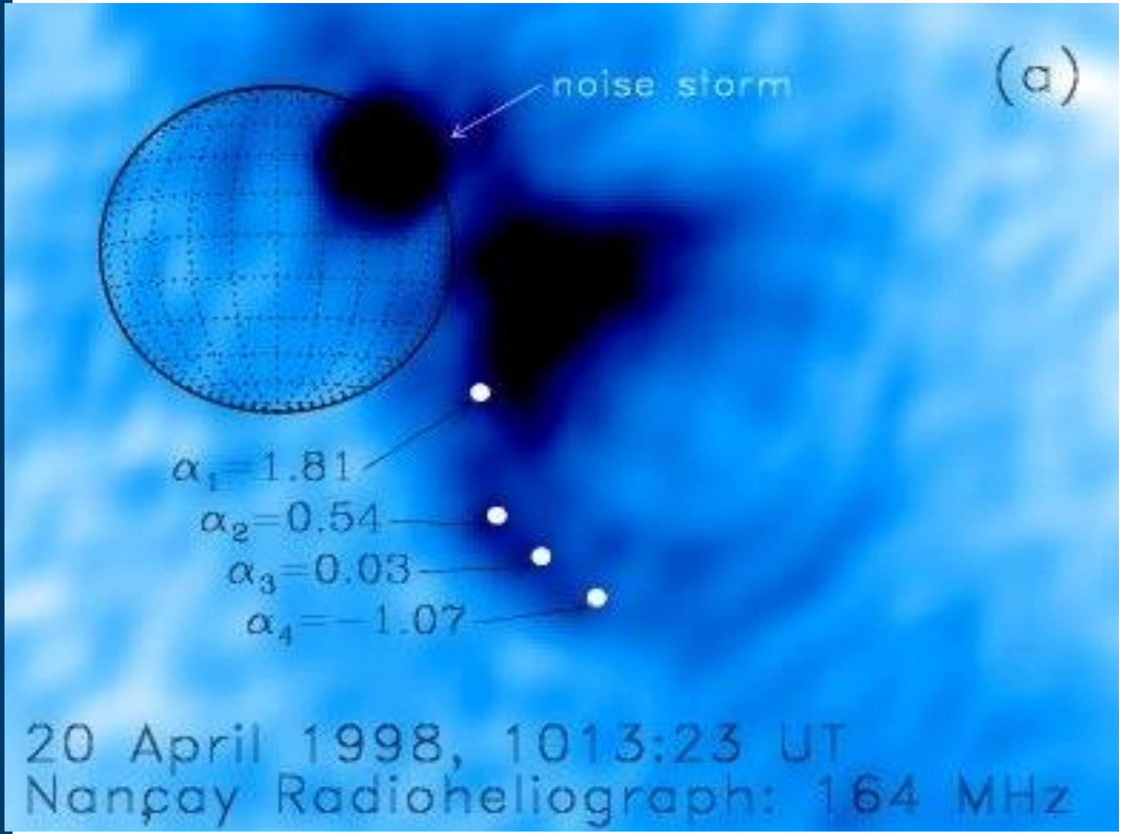


Formation and propagation of the shocks and CMEs

Type II radio burst ➔ prime diagnostic of outward-moving coronal shock waves



Radio emission from Coronal Mass Ejections



Radio emission is gyrosynchrotron from electrons trapped in weak-field structures:

→ electron energy distribution

→ magnetic field strength/direction

→ dynamic evolution of coronal structures

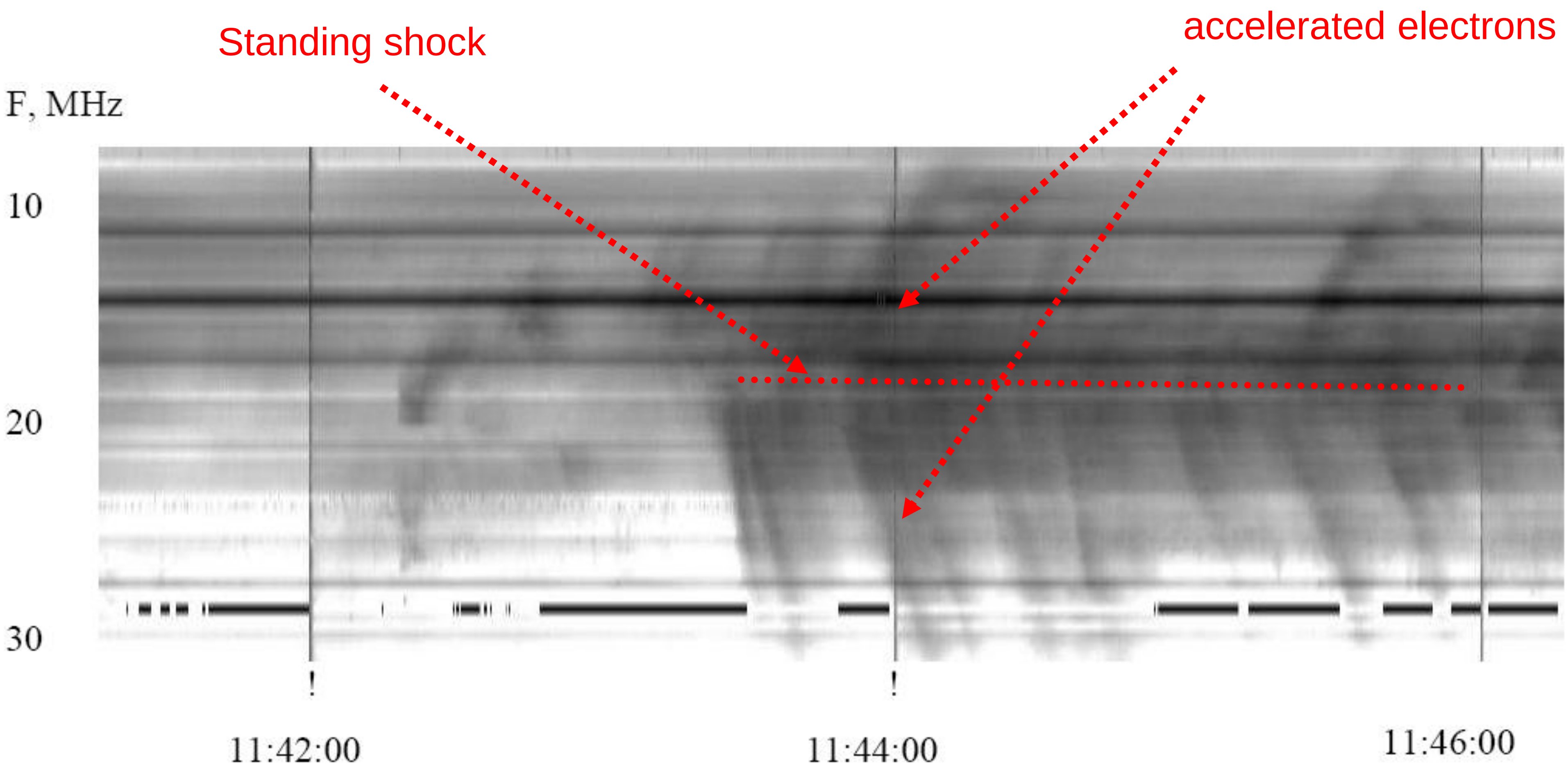
Image of a CME at 164MHz using the Nancay Radioheliograph (Bastian et al. 2001)

Key questions:

- What is CME/flare relationship?
- How do they develop and evolve into interplanetary disturbances?
- What are their effects on the surrounding solar/heliospheric plasma?

Shocks and energetic electrons

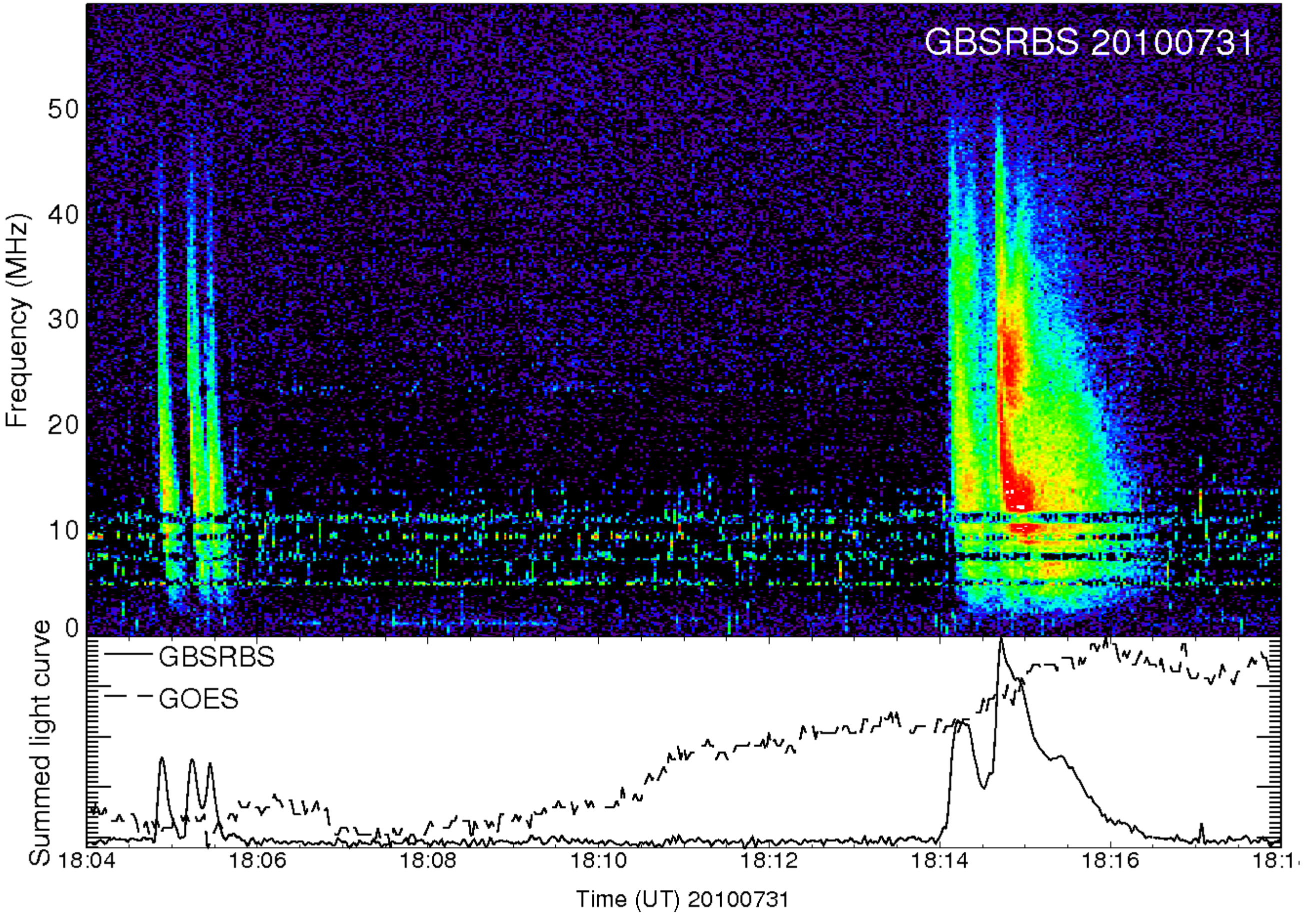
Type II with herring-bone structure: acceleration of electrons by shocks



Standing shock

accelerated electrons

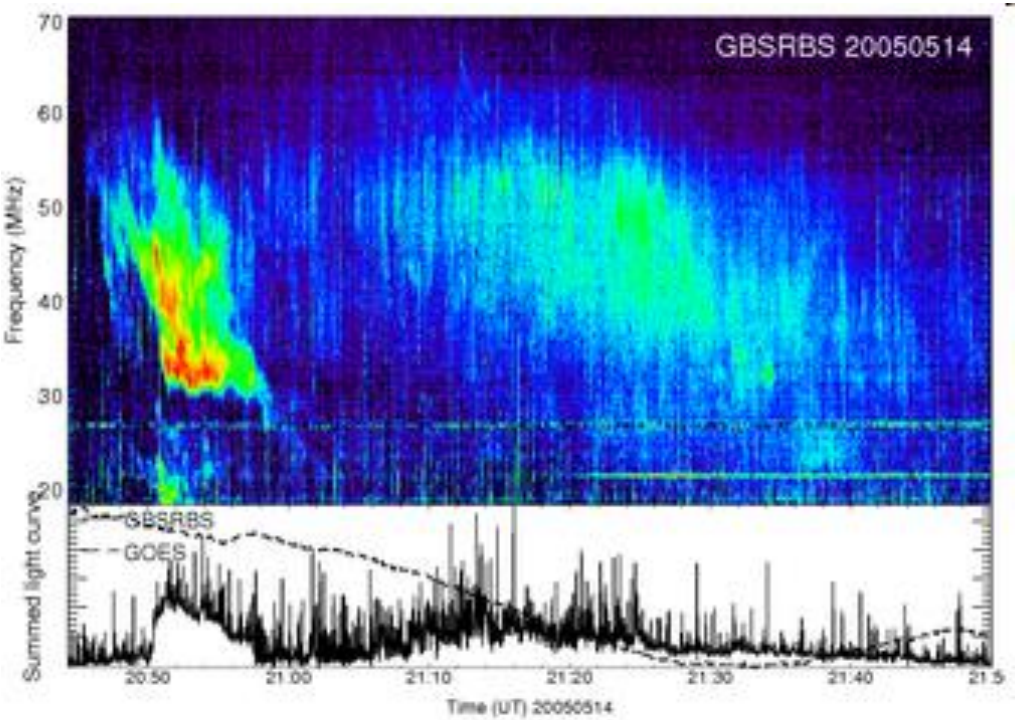
Type III and type V bursts



Emission mechanism: plasma emission

Exciter: energetic electron beams

Type IV



Emission mechanism: plasma emission

Exciter: trapped particles and wave particle interaction with MHD waves?

How are energetic particles produced?

For a single particle, the equation of motion (SI units)

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

The change of kinetic energy

$$m\mathbf{v}\frac{d\mathbf{v}}{dt} = \frac{d}{dt}\left(\frac{mv^2}{2}\right) = q\mathbf{v}\mathbf{E}$$

hence to have energy gain, we need q**vE**>0

Although the energy gain does not depend on **B** explicitly, it enters as an important parameter via **v*(t,r)*** – the evolution of the velocity in space and time.

Electric field acceleration

Let us consider electron in collisional plasma. For simplicity, we consider fields parallel to electron velocity:

$$m_e \, dv/dt = eE - \nu_c m_e v$$

where

$$\nu_c = \frac{e^4 n_e \ln \Lambda}{2\pi \varepsilon_0^2 m_e^2 v^3} = \frac{e^4 n_e \ln \Lambda}{2\pi \varepsilon_0^2 m_e^{\frac{1}{2}} (3kT)^{\frac{3}{2}}}$$

is a collisional frequency.

There is a critical velocity that sets right hand side to zero.

Electrons with the velocities larger than the critical are accelerated.

The process is called ***electron runaway***.

Assuming thermal distribution of electrons, there is critical electric field, called ***Dreicer field*** (Dreicer, 1959):

$$E_D = \frac{e^3 n_e \ln \Lambda}{6\pi \varepsilon_0^2 kT}$$

Acceleration: electric field

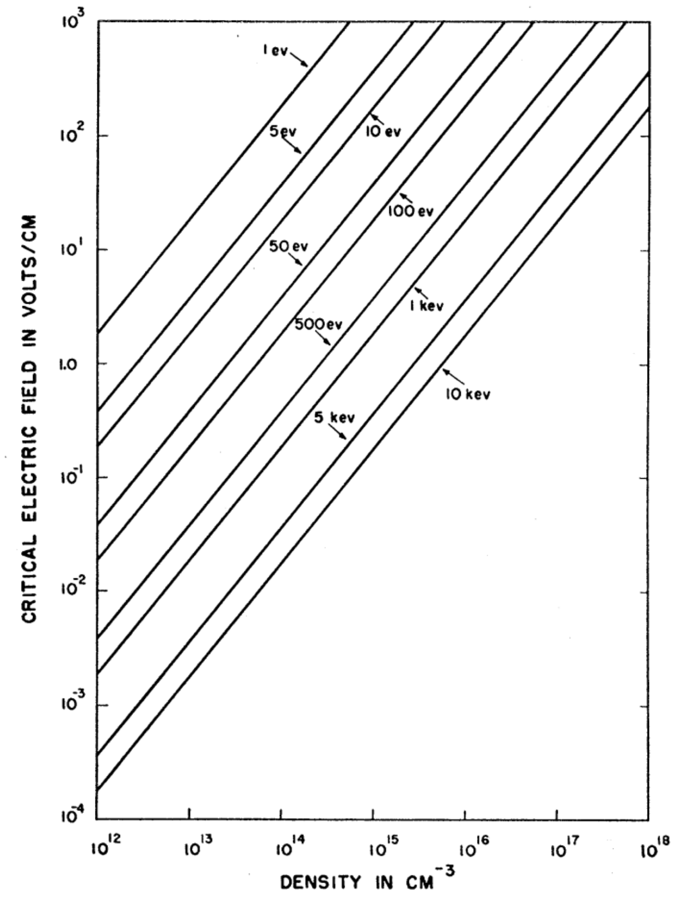


Figure: Dreicer field as a function of temperature and density (Dreicer, 1959)

Putting the constants, one finds:

$$E_D = 2 \times 10^{-13} \frac{n_e \ln \Lambda}{T} \, \mathrm{V\,m^{-1}}$$

where number density is measured in *particles per cubic meter* and temperature in K.

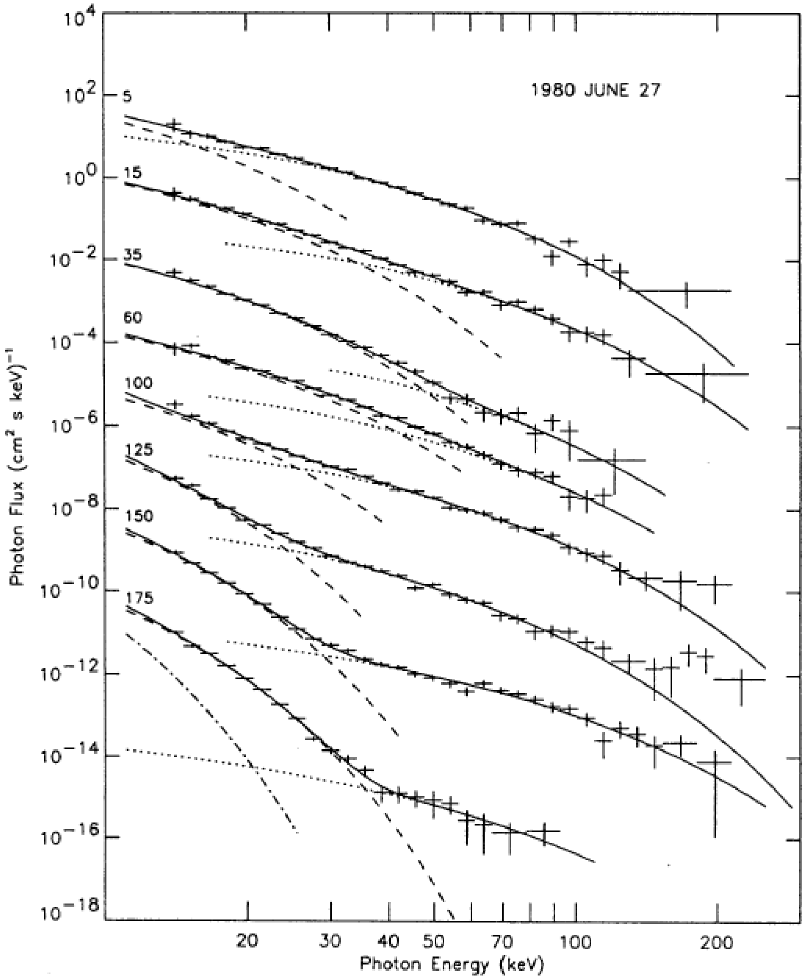
Typical values of Dreicer field in the solar corona ~0.01 V/m

DC electric field models can be categorized according to the electric field:

a) weak sub-Driecer
b) strong super-Driecer

Electric field acceleration: sub-Dreicer field

Runaway acceleration in sub-Dreicer fields has been applied to solar flares by a number of authors (Kuijpers (1981), Heyvaerts (1981), Holman (1985), etc)



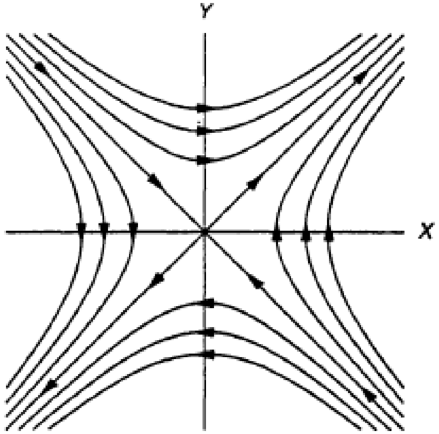
In principle, such models can explain observations, e.g. Benka and Holman (1994) demonstrate good spectral fits.

Open questions:

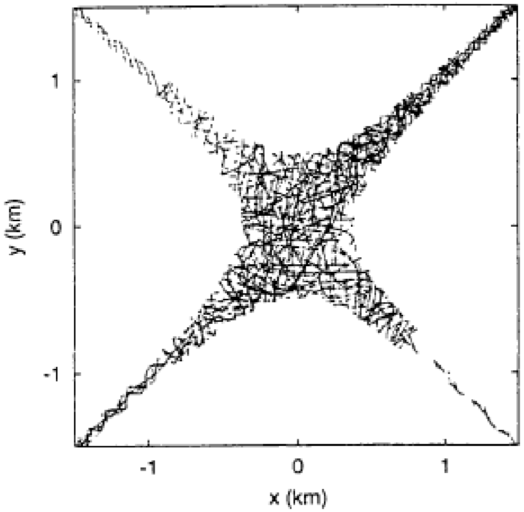
1) ***Stability of the involved DC currents***
2) ***Large scale fields e.g., the size of a loop 10^{10}cm***
3) ***Issues with return current***

Electric field acceleration: Super-Dreicer field

Models with super-Dreicer require smaller spatial scales (e.g. Litvinenko (1996, 2003) etc)



The energy spectrum of particles near an X-point is found to have a power-law functions $N(E) \sim E^{-a}$, a in the range 1.3-2.0

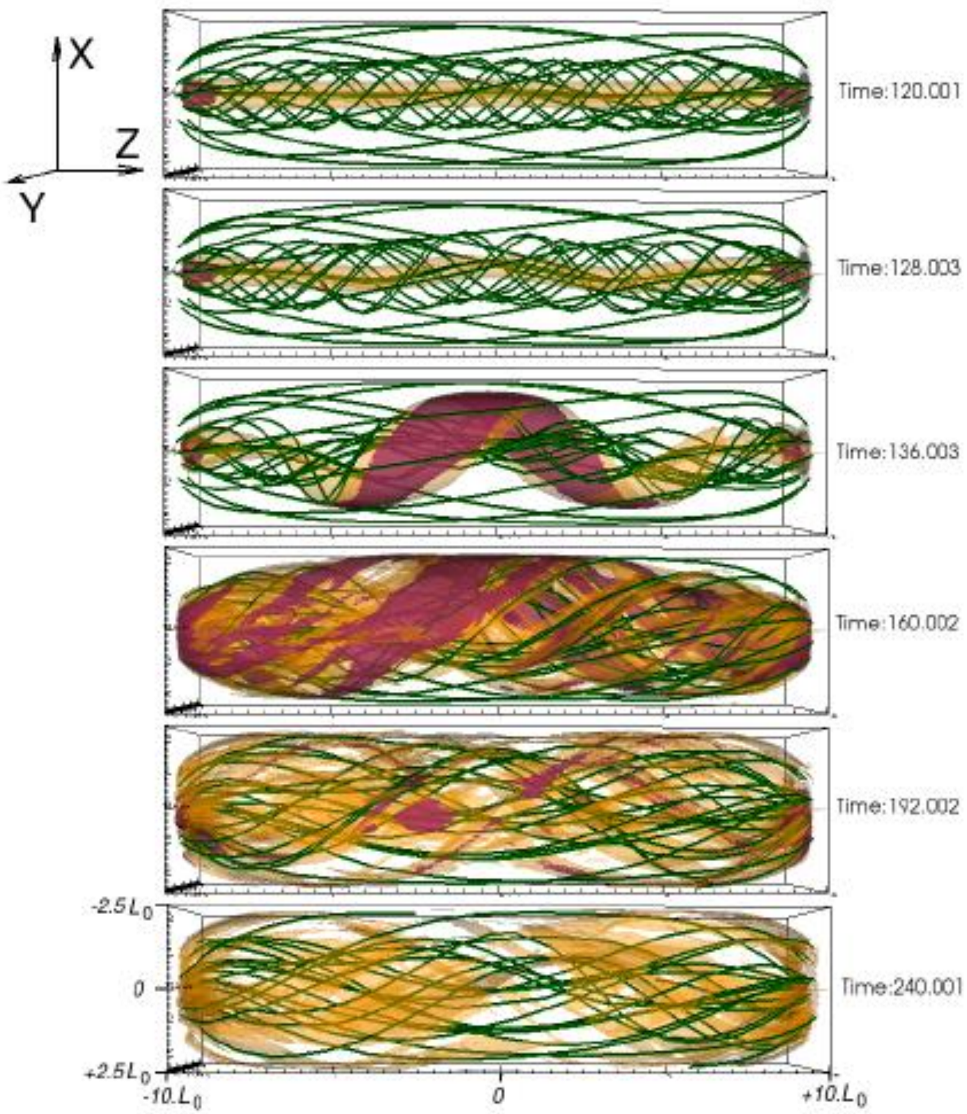


Sub-Dreicer fields might be responsible for bulk acceleration and super-Dreicer field from super-thermal seed (Aschwanden, 2006 as a book).

Open questions:

1) Supply of electrons
2) Consistency of the description

Extended acceleration scenario



Simulations by Gordovskyy, et al 2012

Are particles accelerated within the loop?

Multiple current sheets
Vlahos et al 1998, Turkmani et al, 2005, Hood et al, 2008, Browning et al 2008, Gordovskyy et al, 2012

Plasma turbulence acceleration
Sturrock, 1966, Melrose, 1968
Miller et al 1997, Petrosian et al, 1994; Bian et al, 2012

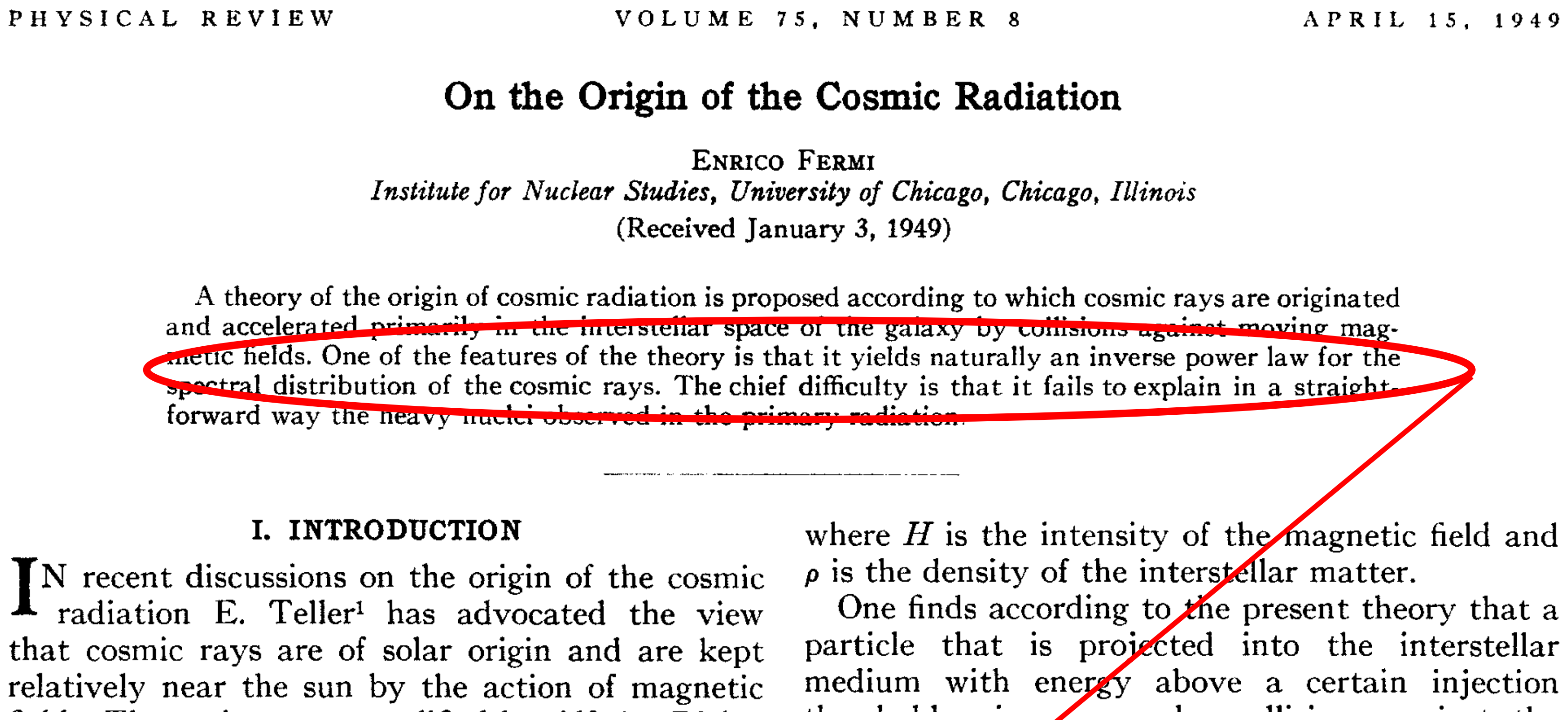
Fermi acceleration

Observation of cosmic energetic particles

The story started in 1936. Austrian physicist V. Hess measured radiation level in 1912 balloon experiment.

Interesting enough, *C.T.R. Wilson observed radiation with cloud chamber experiment (1902) in a railway tunnel near Peebles, Scotland.* However, concluded that the radiation cannot be cosmic.

Fermi acceleration



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On the Origin of the Cosmic Radiation

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(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic

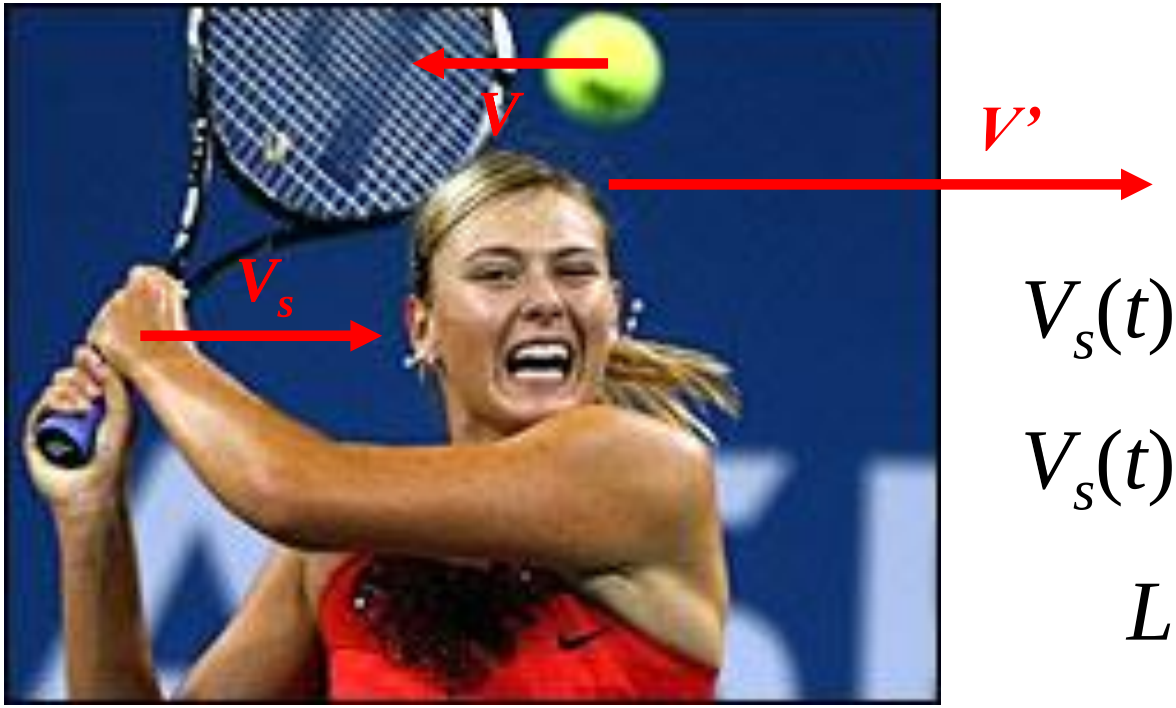
where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar medium with energy above a certain injection

Fermi (1949) explained the acceleration of cosmic-ray particles by reflection on moving magnetic clouds.

Naturally explains ***inverse power-law distributions***.

Acceleration



$$V' = V + 2V_s(t)$$

$V_s(t) > 0 \Rightarrow$ energy gain

$V_s(t) < 0 \Rightarrow$ energy loss

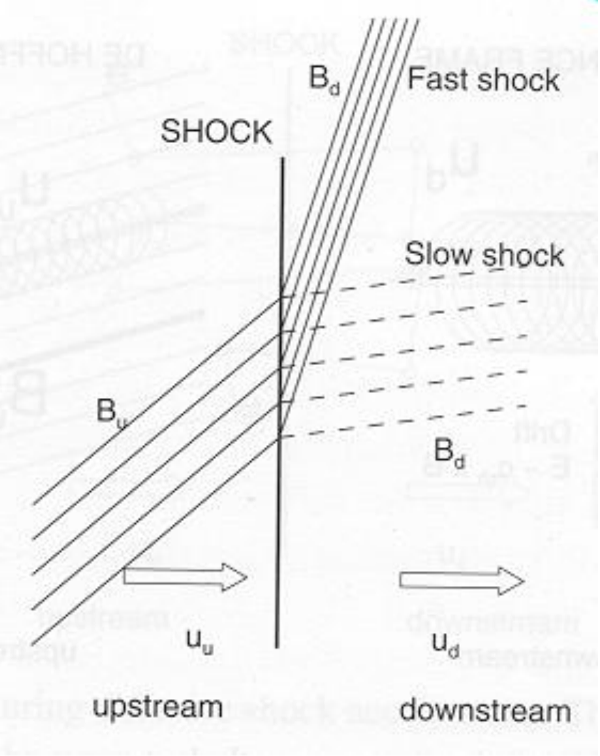
Let $V_s(t) = A\cos(\omega t)$

Net energy gain: $\langle V' \rangle^2 - \langle V \rangle^2 = 2A^2$

No energy change in the frame of the racket!

1) Exchange of energy per collision is small
2) Head-on collisions are more frequent

Shock acceleration



If $\mathbf{c_{sh}}$ is the velocity of the shock structure (e.g. magnetic field acting as a mirror) then the change in particle energy for one collision is

$$\Delta\varepsilon = -2\varepsilon \frac{\mathbf{c}_{sh} \cdot \mathbf{v}_{\|}}{c^2} \, ,$$

The probability of head-on collision is proportional to v+$\mathbf{c_{sh}}$ while the probability of overtaking collision is proportional to v-$\mathbf{c_{sh}}$

Taking into account the probabilities the average gain per collision is

$$< \Delta\varepsilon > \approx \frac{\mathrm{v} + c_{sh}}{2\mathrm{v}} \Delta\varepsilon - \frac{\mathrm{v} - c_{sh}}{2\mathrm{v}} \Delta\varepsilon \approx 2 \frac{c_{sh}^2}{c^2} \varepsilon \, .$$

The energy change proportional to the velocity of the shock is ***first order Fermi acceleration***; proportional to the square is called ***second order of Fermi acceleration*** (original Fermi model).

Power-law distribution

The average rate of energy gain can be written

$$\frac{d\varepsilon}{dt} \approx \frac{2c_{sh}^2}{\tau_{coll}\, c^2}\varepsilon, \quad \Rightarrow \quad \varepsilon(t_A) = \varepsilon_0 \exp\left(\frac{t_A}{\tau_G}\right),$$

where we introduced "collisional" time.

Let ***E*=*bE*$_0$** be the average energy of the particle after one collision and ***P*** be the probability that the particle remains within the acceleration region after one collision. Then after ***k*** collisions, there are **$N=N_0P^k$** particles with energies above ***E*=*b*^{k}*E*$_0$**. Eliminating ***k*** one finds

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P/\ln b}$$

Therefore we find $N(E)dE \propto E^{-(1+(\ln P/\ln b))}dE$

It can be shown that that the spectral index should be >=2.

Acceleration in flares and CMEs

In solar physics, first-order Fermi acceleration is often called shock-drift acceleration (Priest, 1982; Aschwanden, 2006 etc)

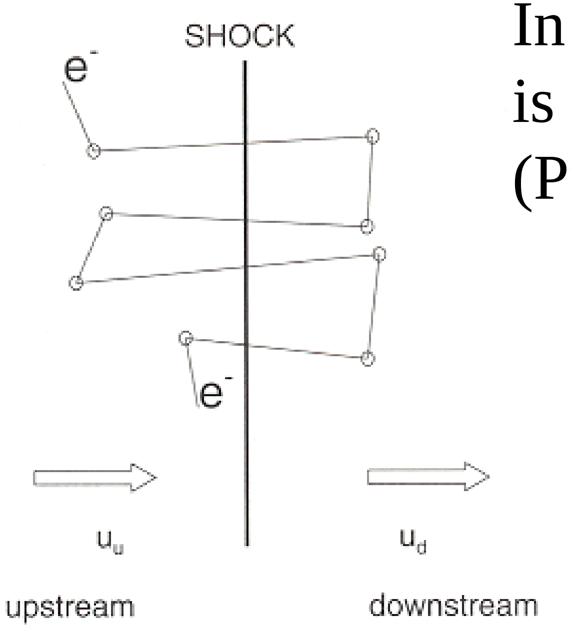
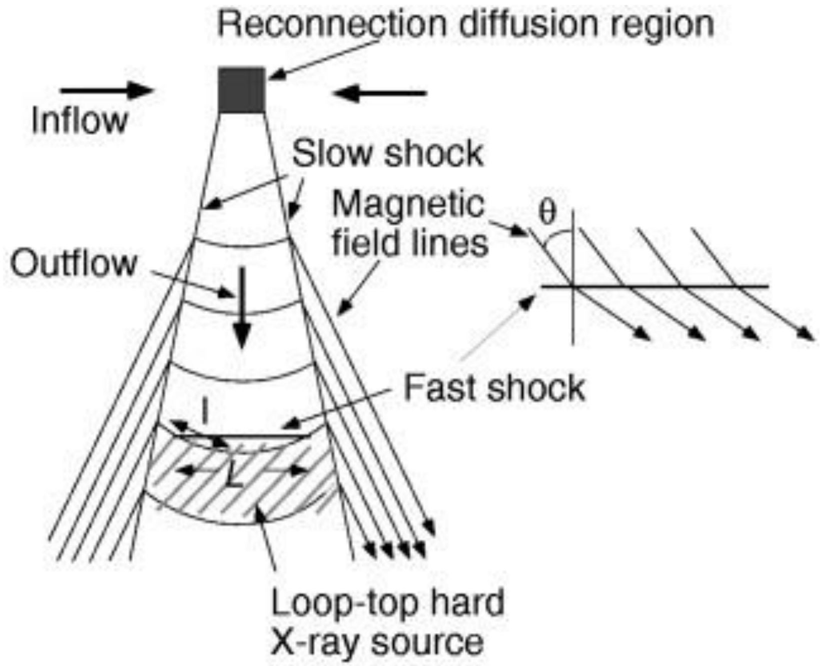


Figure: Diffusive shock acceleration (second-order Fermi acceleration)



Open questions:

1) Large areas required
2) Number of accelerated electrons

First-order acceleration is viable for 10-100 keV electrons under certain conditions and the energy gain is sufficiently fast (Tsuneta & Naito, 1980)

Resonant condition

The resonant condition is when *the wave has zero frequency in the rest frame of particle*:

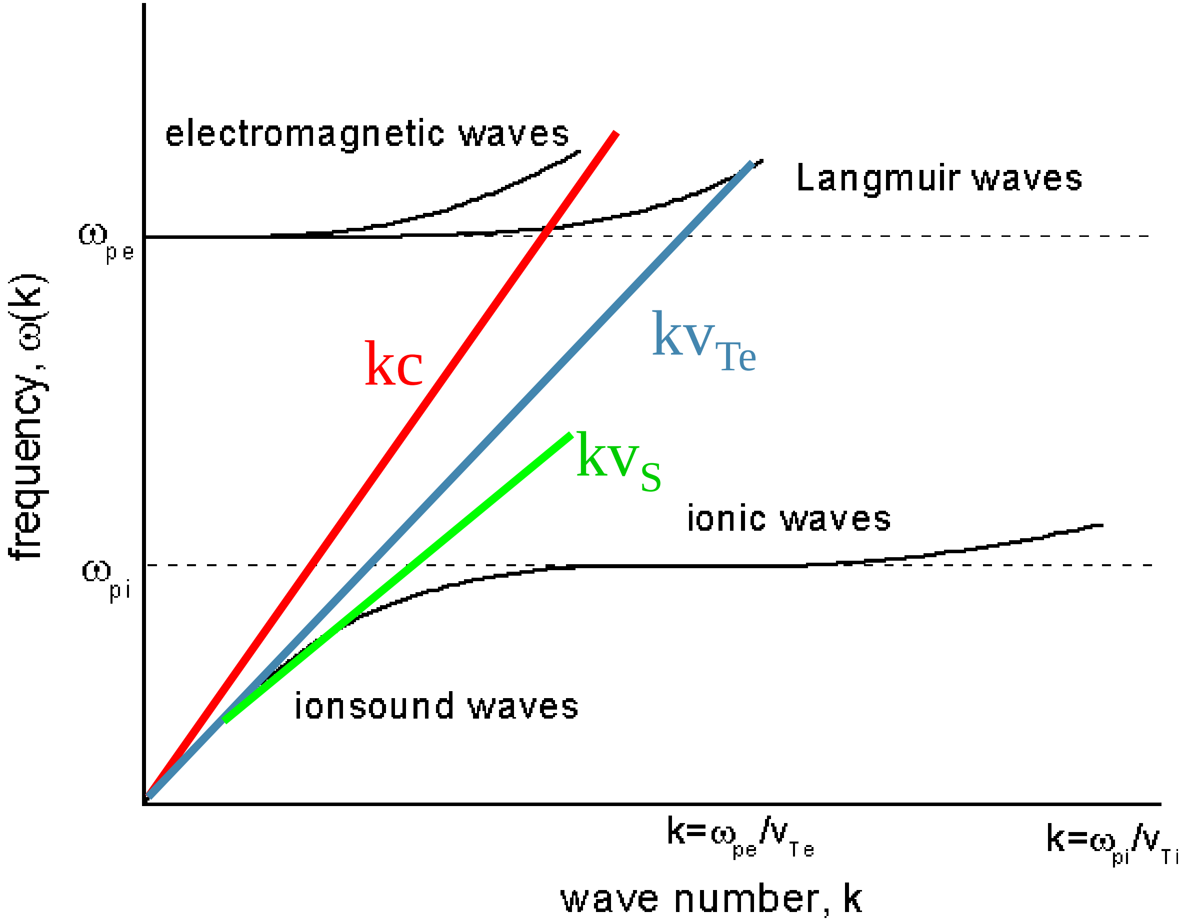
Cherenkov resonance (unmagnetised plasma):

$$\omega - \boldsymbol{k} \cdot \boldsymbol{v} = 0$$

Cyclotron resonance (magnetised plasma):

$$\omega - s\Omega - k_{\|}v_{\|} = 0,$$

Resonance condition in unmagnetised plasma



Acceleration

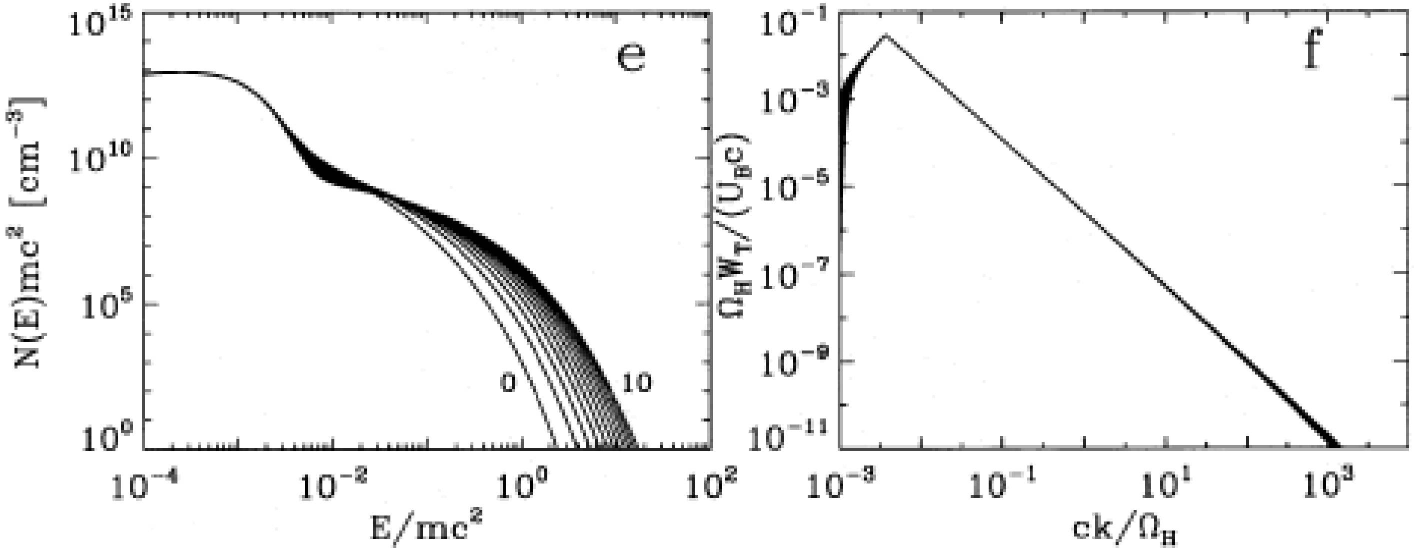


Figure: Electron energy spectrum and the spectral density of fast mode waves (Miller et al., 1996)

Various models have been developed to model acceleration of electrons by whistler waves (e.g., Hamilton & Petrosian, 1992; Miller, 1996, 1997)

$$\omega - k_{\|} v_{\|} - l\Omega/\gamma = 0,$$

Solar flare acceleration

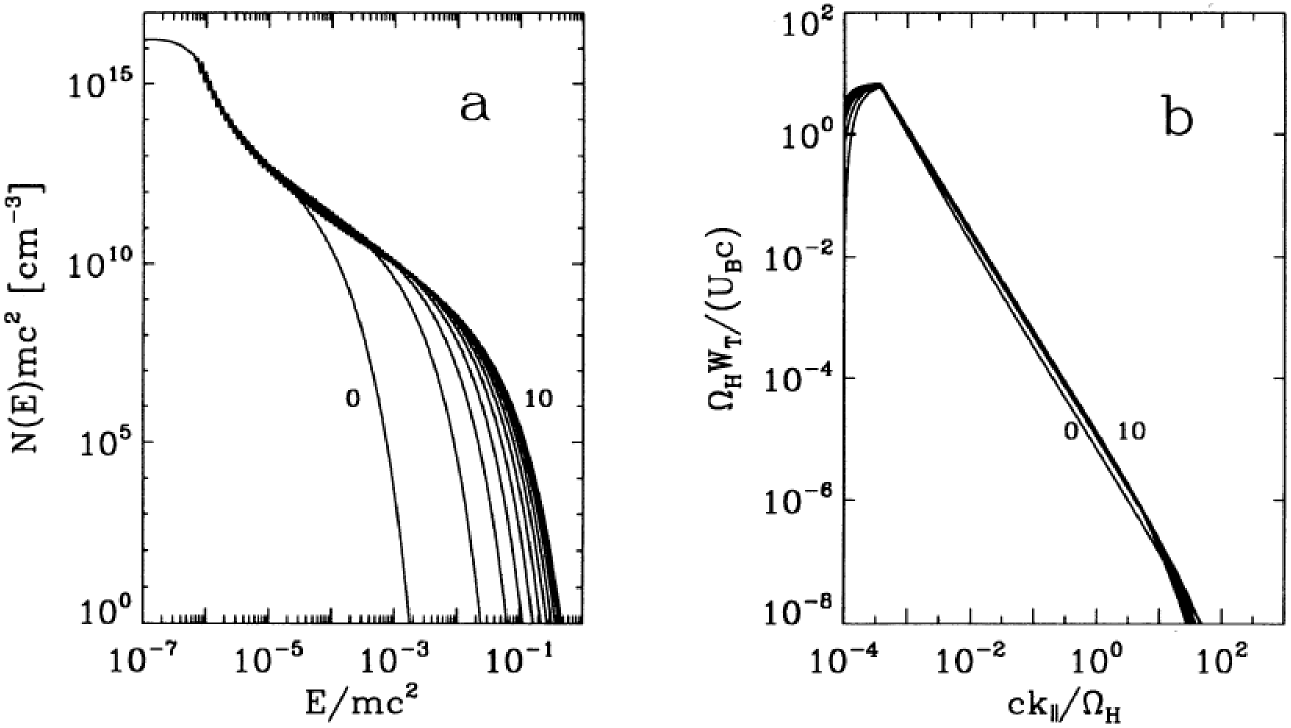
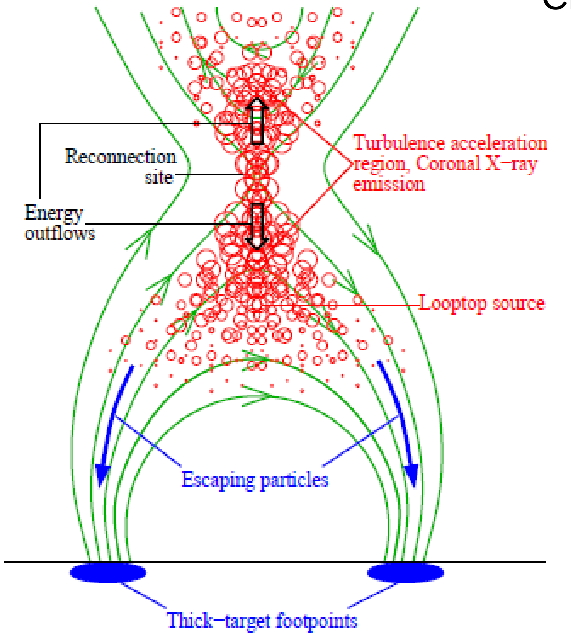


Figure: Proton distribution function and Alfven waves (Miller & Roberts, 1995)

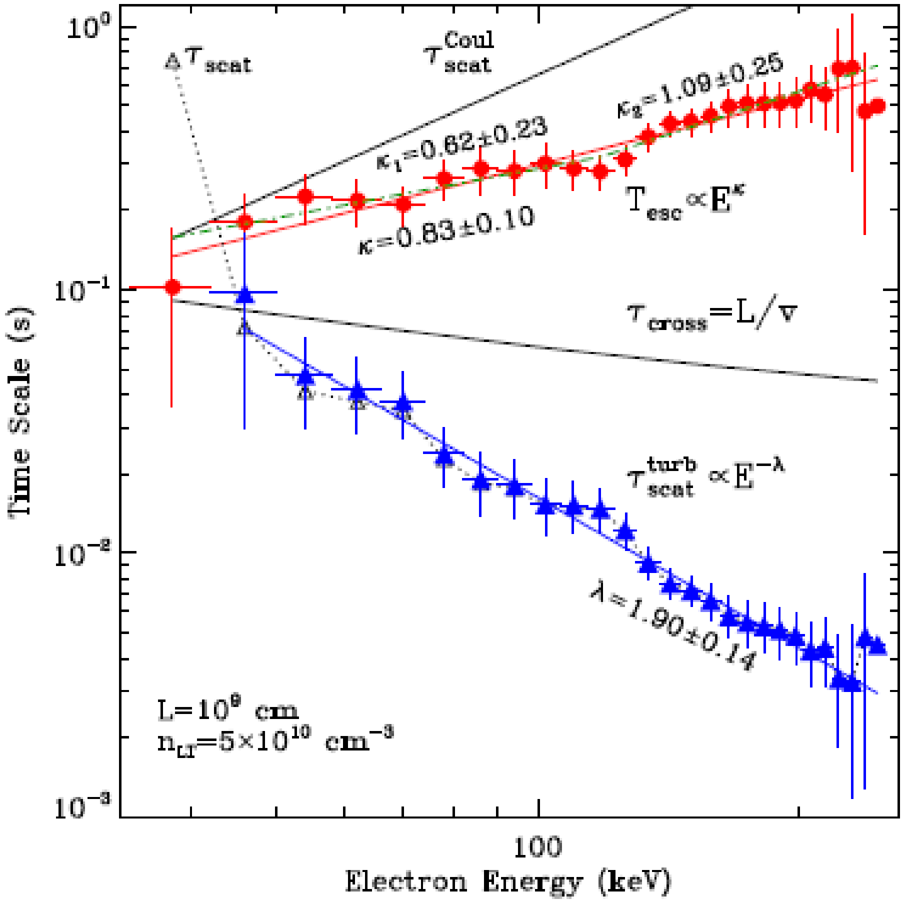
Stochastic acceleration naturally explains enhancement of heavy ions.

Open questions: relatively strong turbulence and its origin

Stochastic acceleration model tests



Liu et al 2008, Petrosian 2012


Chen & Petrosian, 2010-2013

Reasonable agreement with SA model

=> Although it requires rather steep spectrum of turbulence,
And interestingly scattering timescale is rather large at low energies
=> Transport is treated rather simplistically

Energetic particles

Energetic particles are good emitters of X-ray, gamma-rays and radio waves

⇒ Diagnostics of energetic particles

Large number of particles are accelerated in solar flares, CMEs. The energetic particles are observed from the Sun to the Earth.

The exact mechanism of particle acceleration is still not known. A number of mechanisms are considered each with advantages and disadvantages.