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INTRODUCTION TO RADIO EMISSION FROM THE SUN

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Talk outline

I) Radio emission – fundamentals

Radio spectrum
Optical thin/thick emission
Brightness temperature

II) Radio emission mechanisms

Free-free emission
Gyromagnetic emission
Plasma emission

III) Quiet Sun radio emission and radio imaging

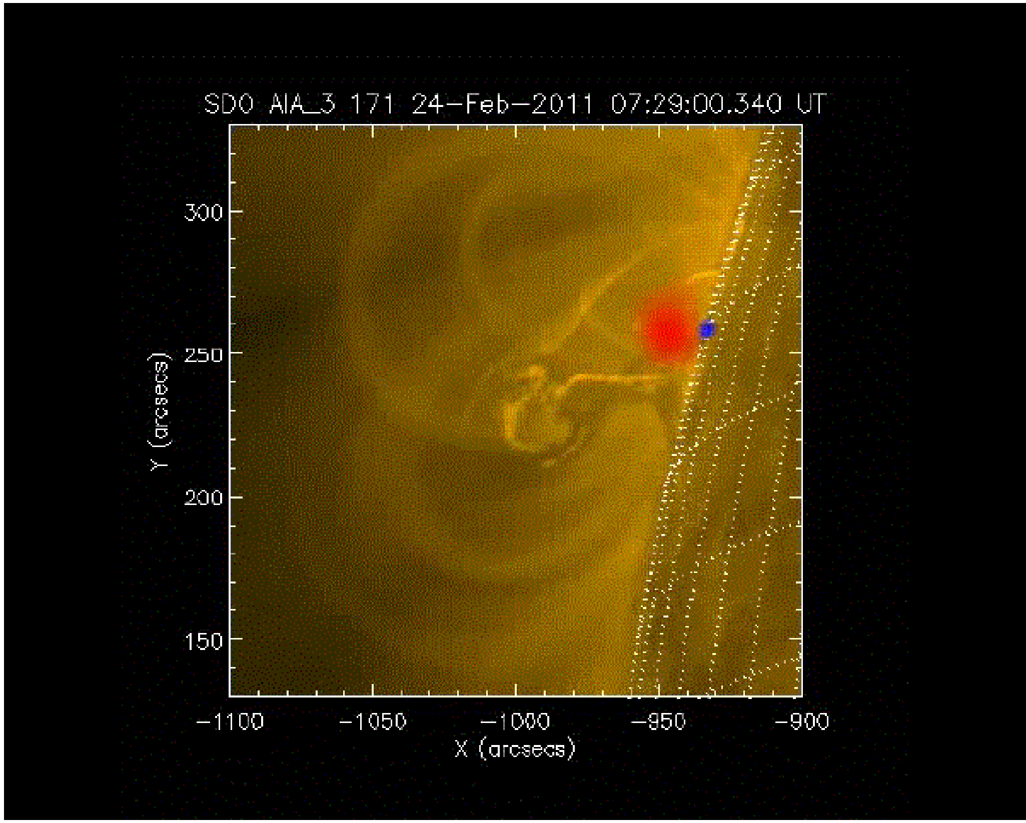
Temperature diagnostics of the low atmosphere
Magnetic field diagnostics

IV) Active Sun emission and solar radio burts

Dynamic spectrum
Types of solar radio bursts

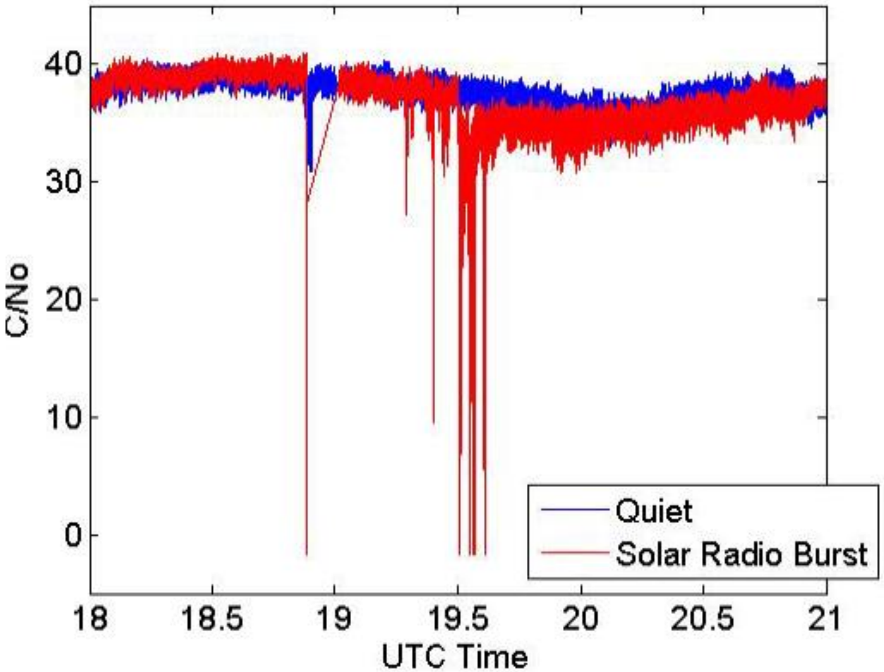
Motivation for radio observations of the Sun

1. Solar radio emission as a diagnostic to study **fundamental processes in solar atmosphere** (e.g. conversion of magnetic energy into particle energy, turbulence, particle acceleration, physics of shocks)



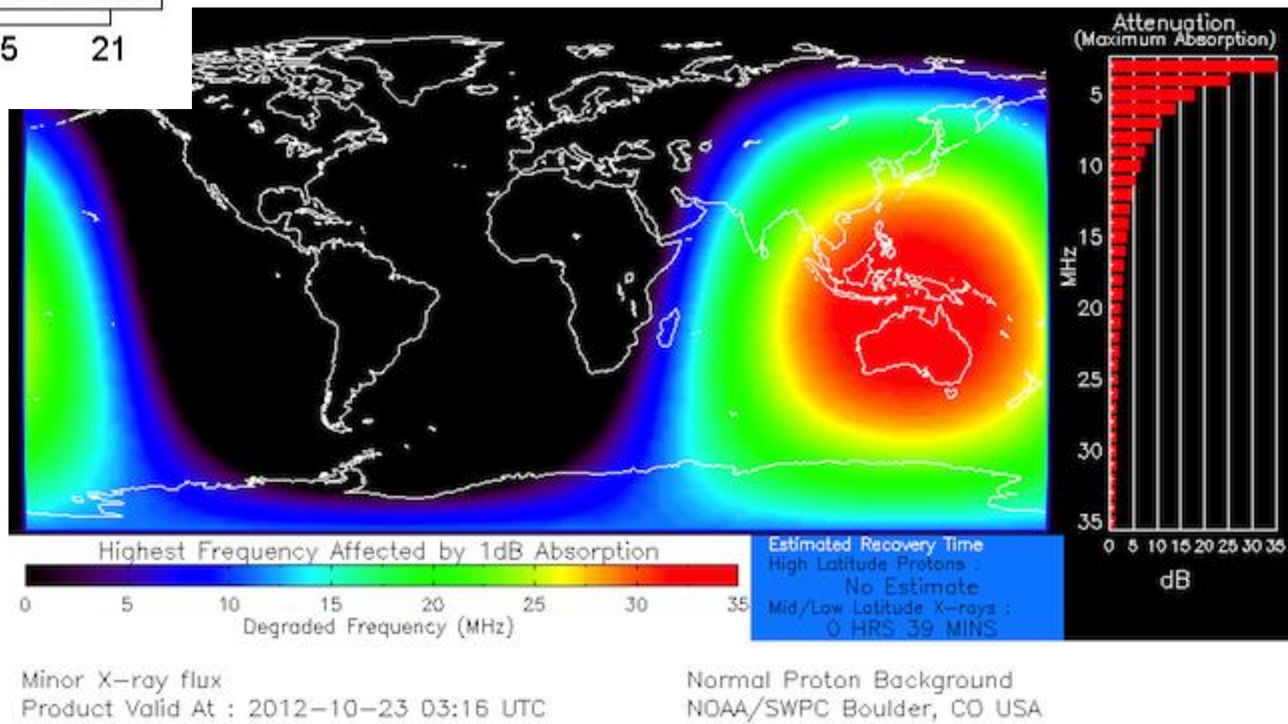
2. Sun-Earth connection and ‘space weather’

Solar flares and their impact



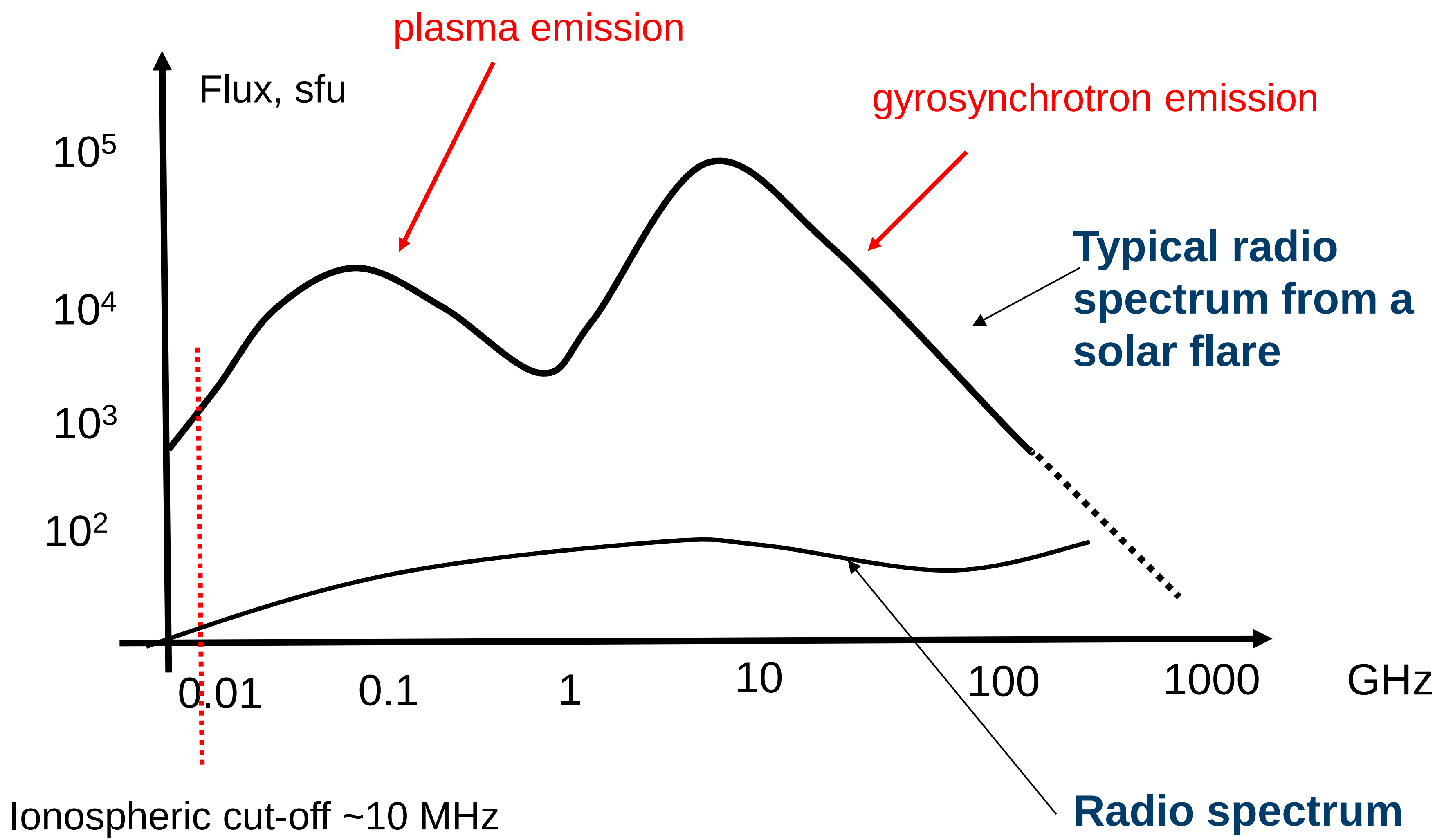
Most GPS receivers in the sunlit hemisphere failed for ~10 minutes. (P. Kintner) at Dec 6th, 2006
(tracking less than 4 s/c)
See Gary et al, 2008

Ionising radiation and impact on ionosphere



Radio emission – important basics

Solar radio emission



1 sfu = 10^4 Jansky

Brightness temperature

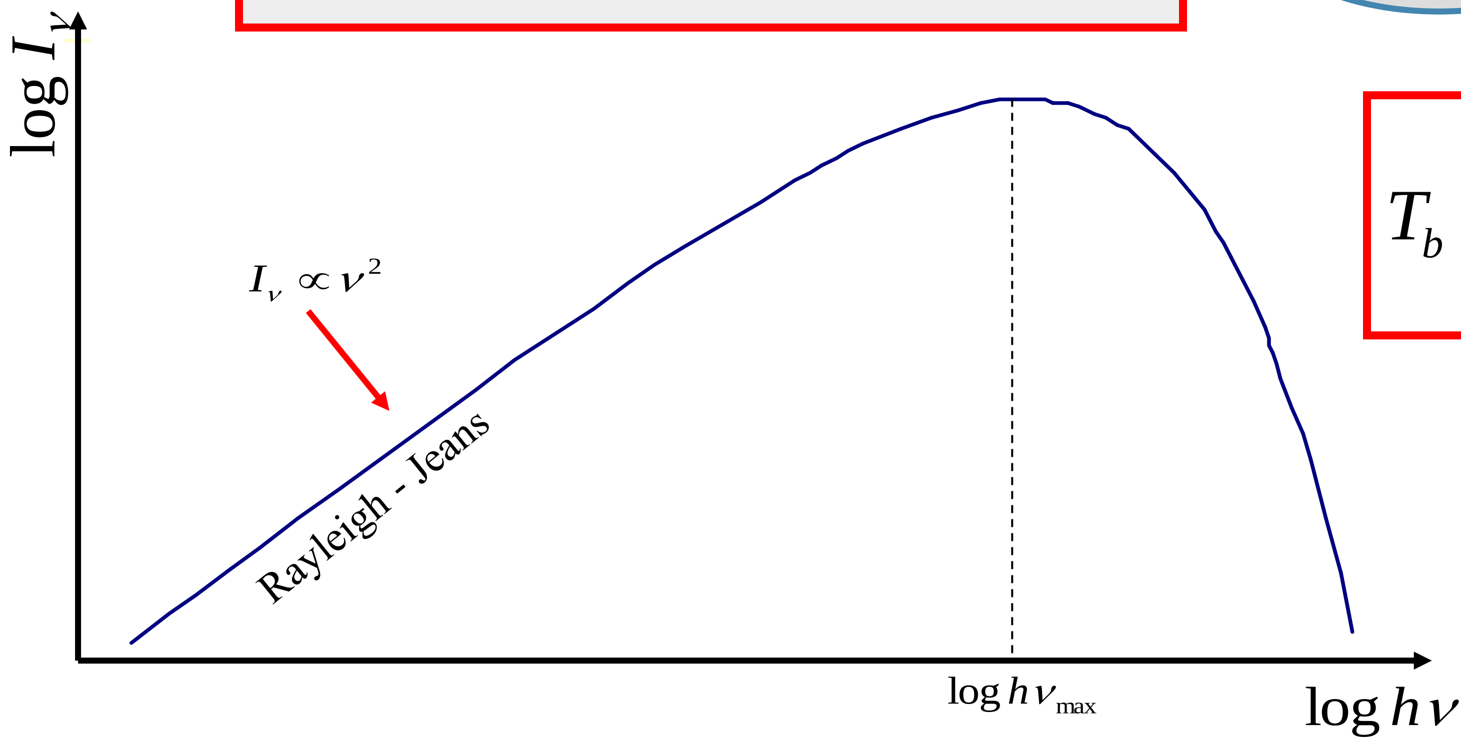
We can always make a definition, common in radio astronomy: Brightness temperature

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

Hence

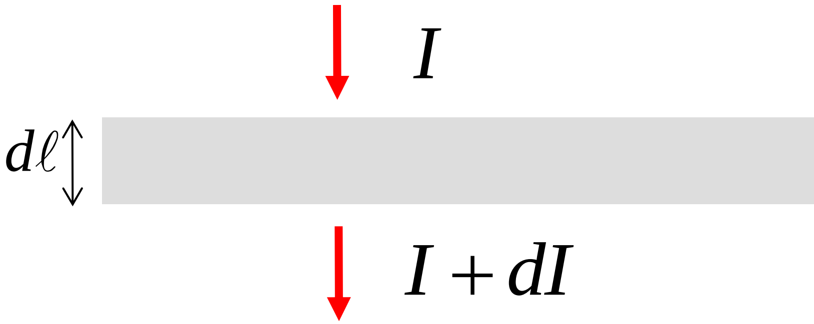
$$\boxed{I_\nu = \frac{2h\nu^3}{c^2\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]} \cong \frac{2\nu^2 kT}{c^2}}$$

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 $\quad I_{\text{obs}} = I_0\, e^{-\tau}$

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

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)*

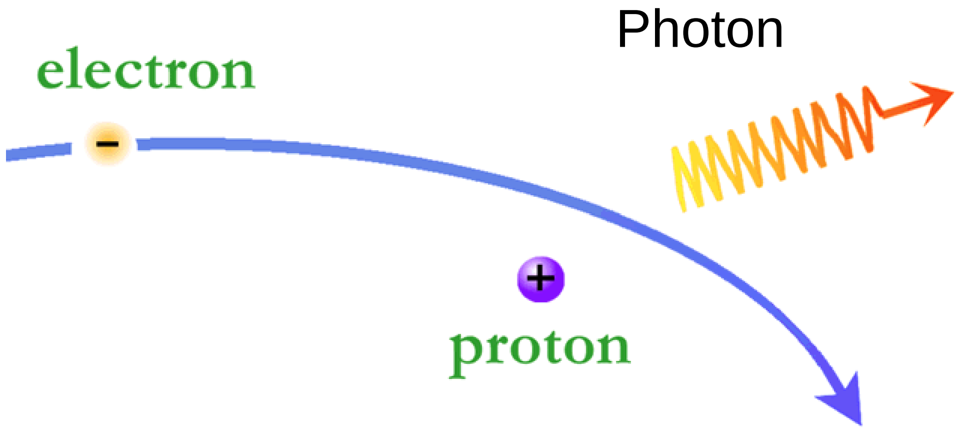
Coherent emission *due to wave-wave and wave-particle interaction*

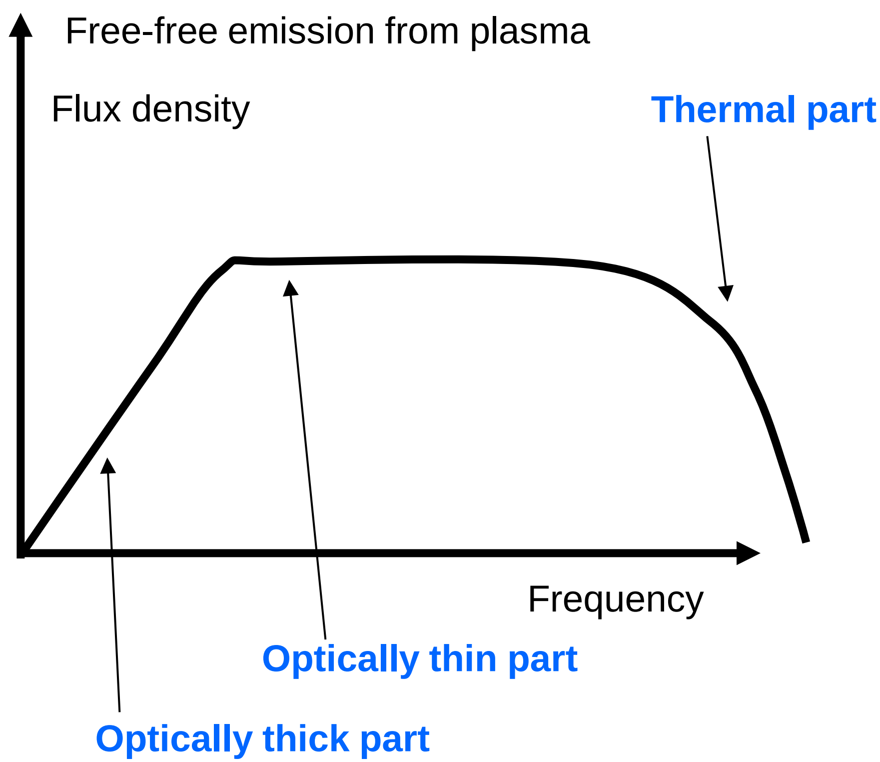
$$\nu_B = \frac{eB}{2\pi m_e c},$$ <= gyrofrequency

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

Free-free emission

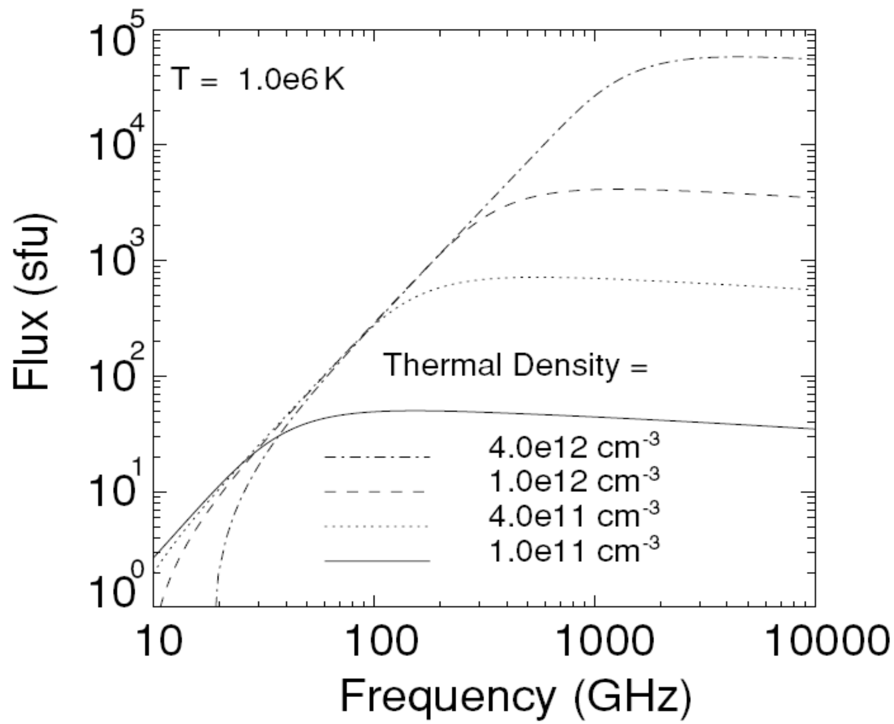
Photons are produced by **free-free transitions** of electrons – also known as **Bremsstrahlung** ('braking radiation')

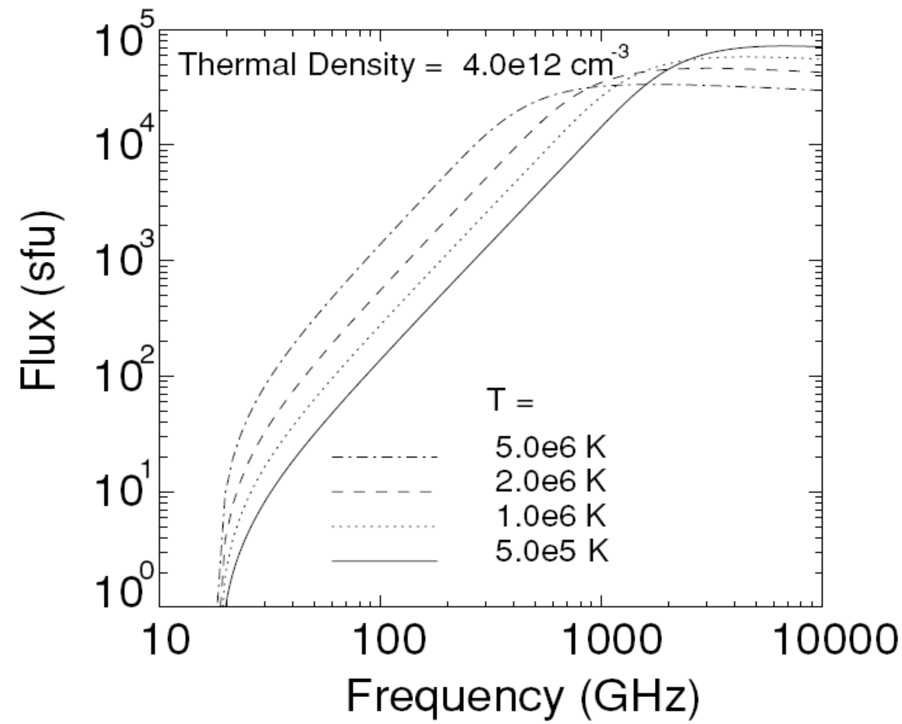




Free-free emission

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).

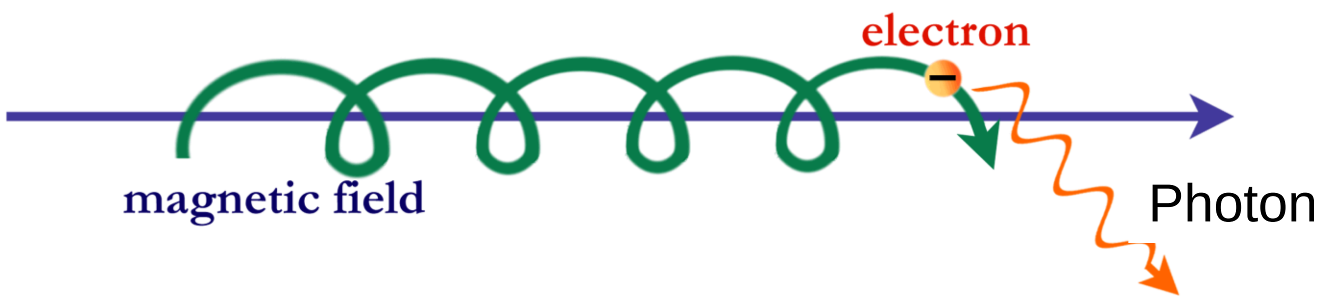




Thermal free-free radio spectra produced from a uniform cubic source with a linear size of 20’’ for $n_e = 10^{11}$ to 4×10^{12} cm^{-3} and T_e = 0.5–5 MK.

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.



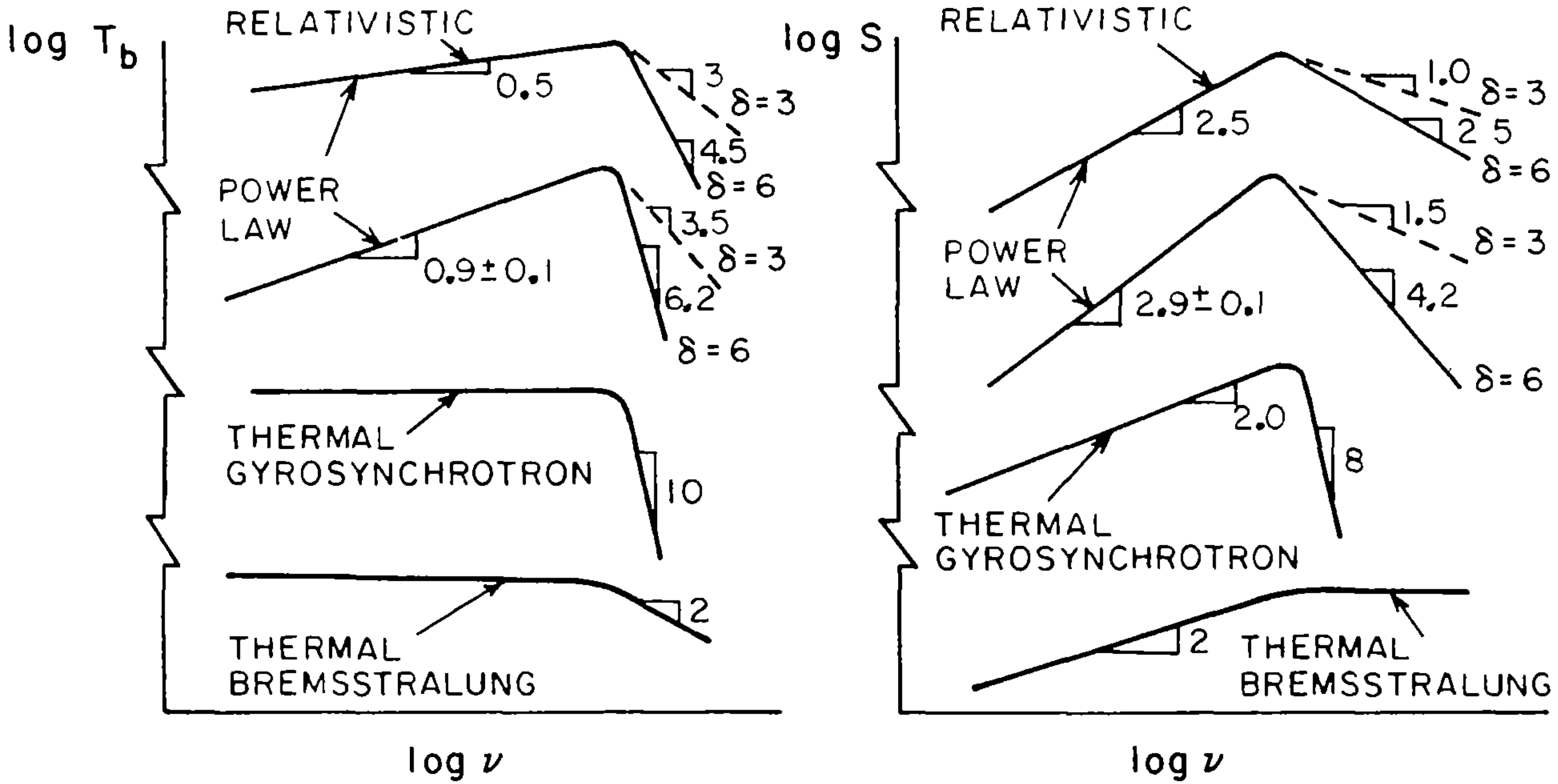
Electron cyclotron line has frequency

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

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

↓

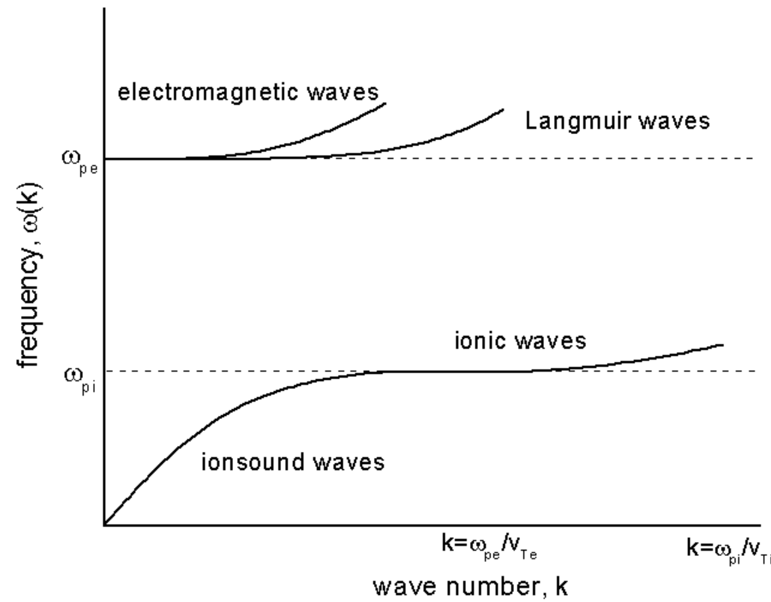
Wave-wave interactions

↓ Fundamental Radio emission

↓ Secondary waves

↓

Harmonic radio emission



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

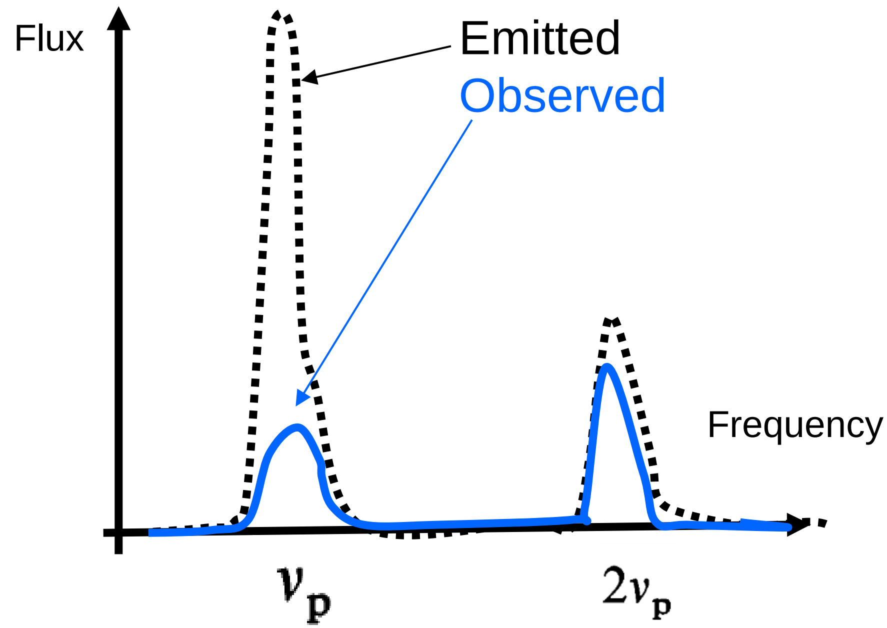
$$\nu_p = \omega_p/2\pi = [n_e e^2/\pi m_e]^{1/2} \approx 9000\ n_e^{1/2}$$

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)

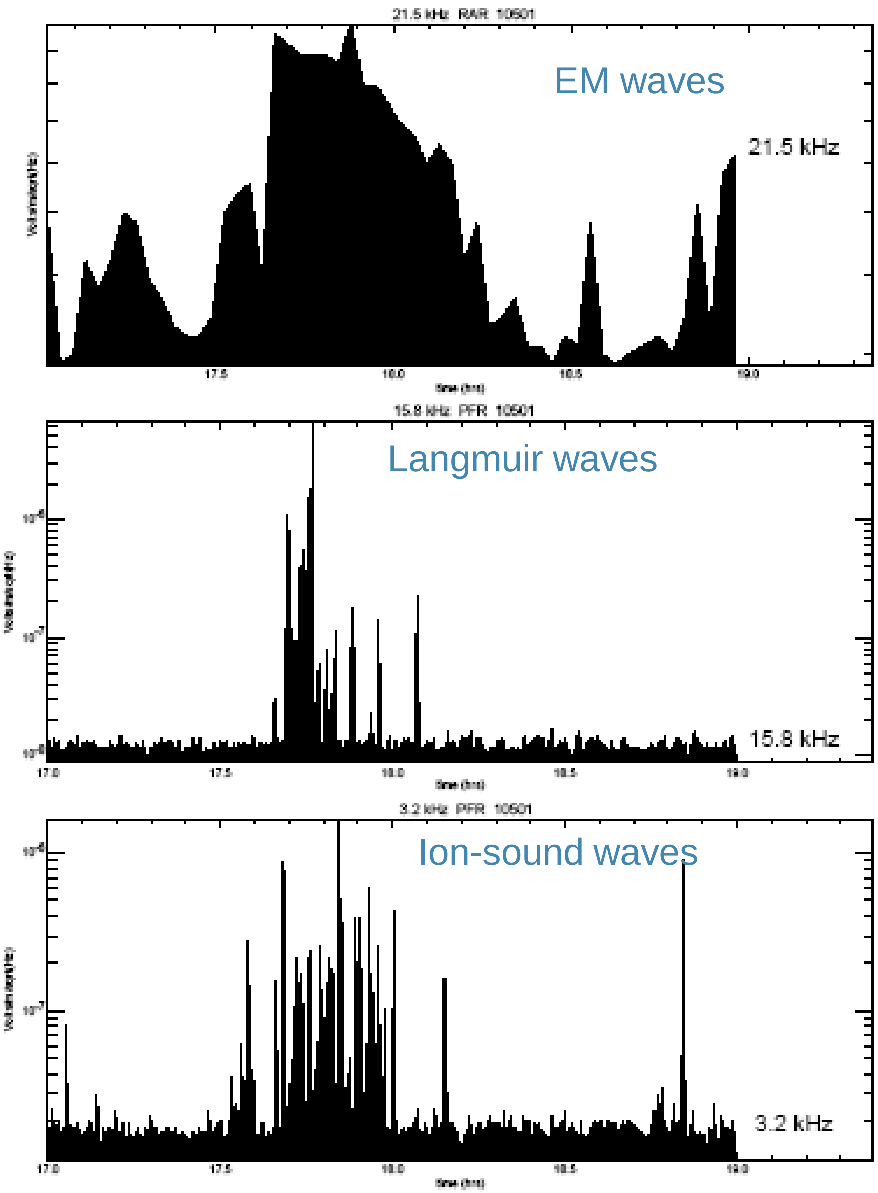
1) Decay and coalescence
   L =L'+S, L+L'=T
2) Scattering and coalescence
   L+i=L+i', L+L'=T

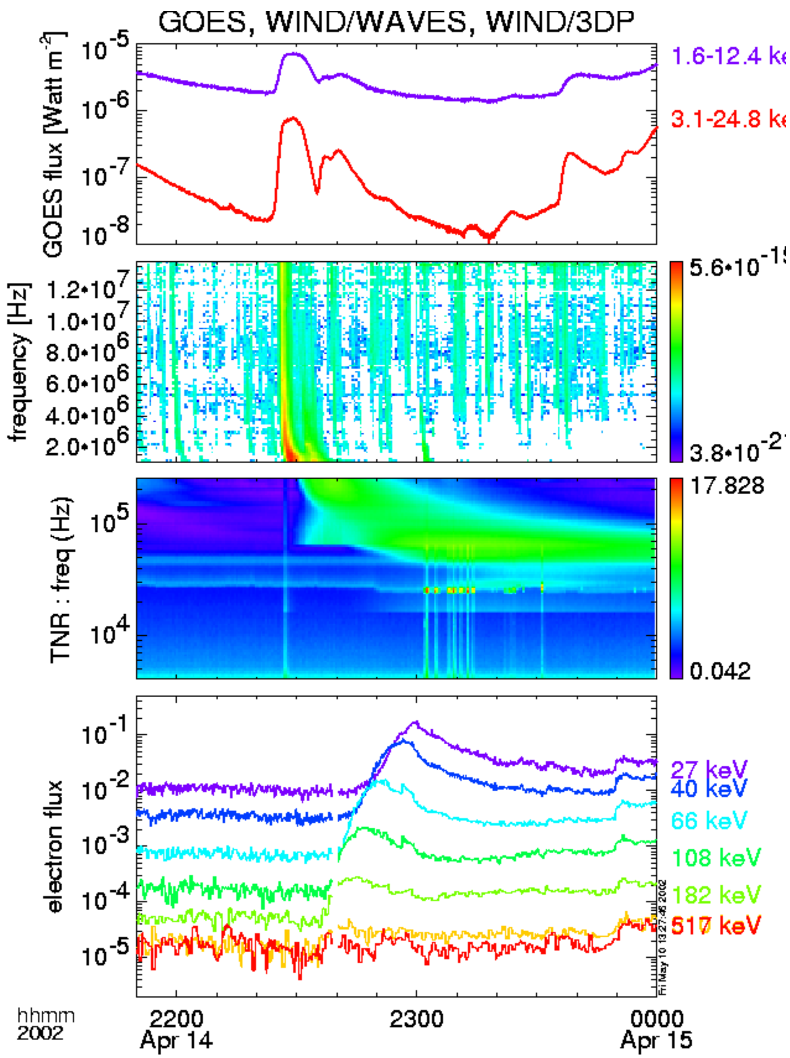
For each act of decay or coalescence we have the corresponding conservation laws for momentum and energy require:

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

Plasma and radio emission

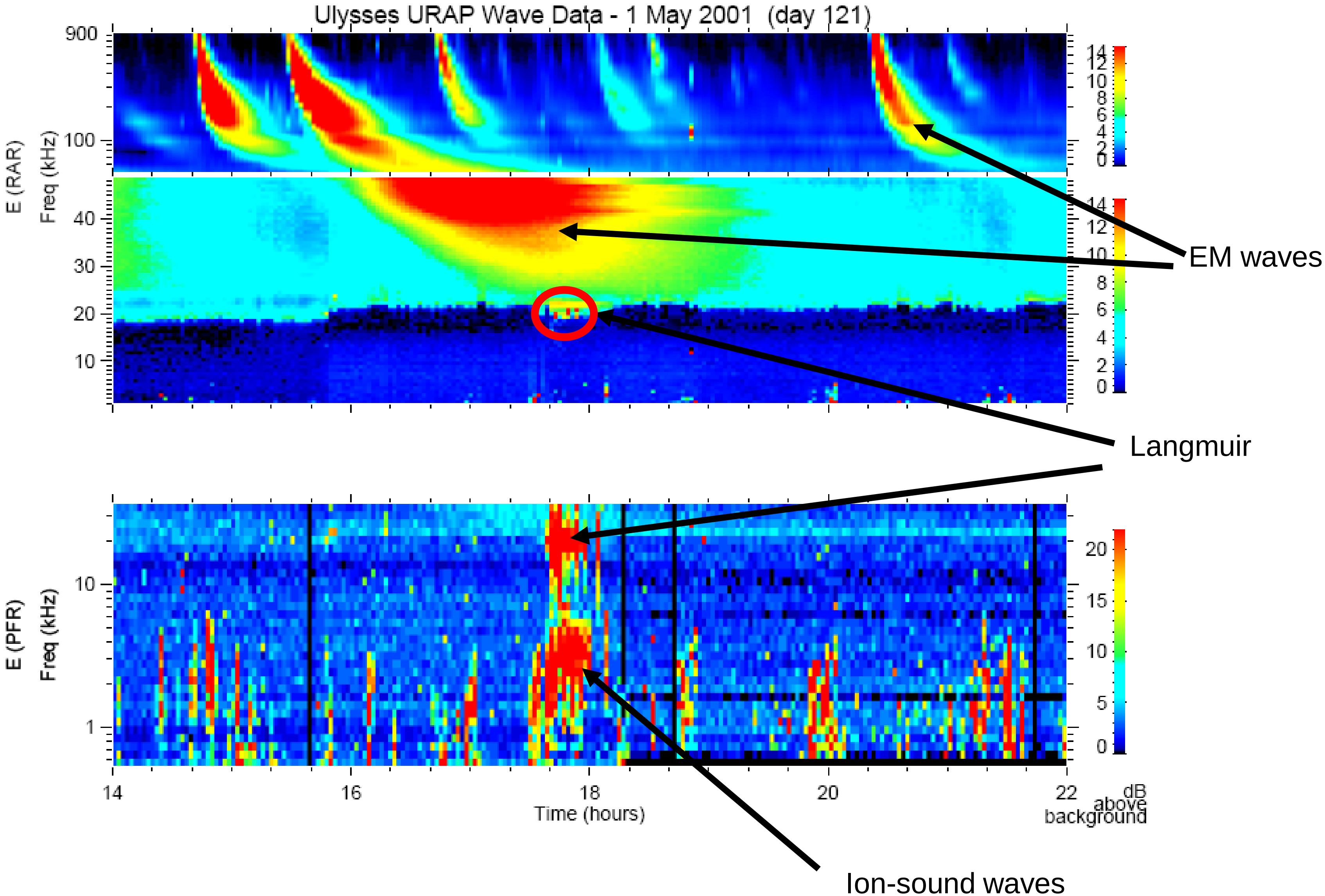
When do we need kinetic description?





Krucker et al 2007

When do we need kinetic description?



Description of N-particle system

Generally a system of **N** particles can be easily described by the system of **6xN** Hamiltonian equations:

$$\frac{\partial \mathbf{p_i}}{\partial t} = -\frac{\partial H(\mathbf{p_1}, ..., \mathbf{p_N}; \mathbf{r_1}, ..., \mathbf{r_N})}{\partial \mathbf{r}_i}, \qquad \frac{\partial \mathbf{r_i}}{\partial t} = \frac{\partial H(\mathbf{p_1}, ..., \mathbf{p_N}; \mathbf{r_1}, ..., \mathbf{r_N})}{\partial \mathbf{p}_i}$$

where $\mathbf{r_i}, \mathbf{p_i}$ are position and momentum of i-th particle

$H(\mathbf{p_1}, ..., \mathbf{p_N}; \mathbf{r_1}, ..., \mathbf{r_N})$ is a Hamiltonian of the system.

This description is exact. However, as soon as **N~10^{24}>>1** solution of the system becomes impossible to find and alternative methods of description should be applied.

Basics: Different types of plasma description

Test particles description: Exact solution for small number of individual particles while the rest of the particles are treated as an external slow varying media

Fluid description of plasma: plasma is assumed to be a continues media at ***L>>l***, where ***L*** is a scale of processes to consider, and ***l*** is the mean free path of a particle in a plasma. In classical fluid description ***L*** is the collisional length.

Classical kinetics is the study of the relationship between motion and the forces affecting motion introducing statistical tools for description.

… other methods or combination of the above

Distribution function

Kinetic description of plasma is based on *the distribution function* f**(t,r,p)** in phase space **(r,p)**.The value f(t,**r,p**)**drdp** is the average number of particle in the phase volume **drdp**, i.e. in the range (**r**,**r+dr**) and (**p**,**p+dp**). **Note:** the number of particles with **p**=$\mathbf{p}_0$ and **r=**$\mathbf{r}_0$ is equal to zero.

If we ignore collisions than each particle is a closed subsystem and the corresponding distribution function obeys *Liouville theorem* as a result of which we can write:

$$\frac{\mathrm{d}f(t,\mathbf{r},\mathbf{p})}{\mathrm{d}t} = 0$$

where the time derivative is a along a trajectory in the phase space.

Liouville and Boltzmann equations

Using equations of motion we derive:

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} + \mathbf{F}\frac{\partial f}{\partial \mathbf{p}} = 0.$$

The third term in this equation shows the influence of *an external field* on the the particles. When the interaction between particles cannot be neglected we have:

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} + \mathbf{F}\frac{\partial f}{\partial \mathbf{p}} = \left(\frac{\partial f}{\partial t}\right)_c$$

where $\left(\frac{\partial f}{\partial t}\right)_c$ is integral of collisions and the equations of this type kinetic are called *kinetic equations*.

The term in the right hand side of kinetic equations is a source or a sink of particles in the phase space volume **drdp**.

The main force acting on a particle in a plasma is electromagnetic.

If the collisional term in the right hand side is a small value and the kinetic equations will take the form

$$\frac{\partial f_{e,i}}{\partial t} + \mathbf{v}\frac{\partial f_{e,i}}{\partial \mathbf{r}} + q_{e,i}\left(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B}\right)\frac{\partial f_{e,i}}{\partial \mathbf{p}} = 0$$

where **E, B** are the average values of electric and magnetic field respectively. This equation was first derived by *Vlasov* in 1937.

This equation should be completed with the system of Maxwell equations,

$$\nabla\mathbf{B} = 0, \quad \nabla\mathbf{D} = 4\pi\rho, \quad \nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla\times\mathbf{H} = \frac{4\pi}{c}\mathbf{j} + \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t}$$

and with the sources

$$\rho = \sum_j q_j \int f_j \mathrm{d}\mathbf{p}, \quad \mathbf{j} = \sum_j q_j \int \mathbf{v} f_j \mathrm{d}\mathbf{p}$$

Who is this person?

We first linearize ***Vlasov equations*** by separating out zero and first order

$$f = f_0 + \delta f, \quad E = 0 + \delta E, \quad \text{etc.}$$

Avoiding the terms of second order, we have

$$\frac{\partial \delta f_{e,i}}{\partial t} + \mathbf{v}\frac{\partial \delta f_{e,i}}{\partial \mathbf{r}} + q_{e,i}\left(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B}\right)\frac{\partial f_{0,e,i}}{\partial \mathbf{p}} = 0$$

Since isotropic distribution function depends only on absolute value of **p**, for such function df/d**p** is parallel to **p**=m**v**, and thus the last term is zero.

We also assuming perturbations to vary as

$$\delta f, \delta E, \delta B, \text{etc.} \sim exp(i\mathbf{k}\mathbf{r} - i\omega t)$$

Waves in un-magnetized plasma

Together with Maxwell equations we have:

$$-i\omega\delta f_{e,i}+i\mathbf{vk}\delta f_{e,i}-e\mathbf{E}\frac{\partial f_{0,e,i}}{\partial\mathbf{p}}=0$$

$$i\mathbf{k}\mathrm{B}=0,\quad i\mathbf{k}\mathrm{D}=4\pi\rho,\quad ik\times\mathbf{E}=\frac{i\omega}{c}\mathrm{B},\quad i\mathbf{k}\times\mathbf{H}=\frac{4\pi}{c}\mathbf{j}-\frac{i\omega}{c}\mathrm{D}$$

$$\rho=-e\sum_j\int\delta f_j\mathrm{d}\mathbf{p},\quad \mathbf{j}=-e\sum_j\int\mathbf{v}\delta f_j\mathrm{d}\mathbf{p}.$$

where plasma is considered neutral.

Recall from Electromagnetism: $\mathbf{D}=\varepsilon\mathbf{E}$

Solving the system of equations we can find ***dielectric tensor***:

$$\varepsilon_l(\omega,\mathbf{k})=1-\sum_j\frac{4\pi e^2}{k^2}\int\mathbf{k}\frac{\partial f}{\partial\mathbf{p}}\frac{d\mathbf{p}}{(\mathbf{kv}-\omega)}$$

$$\varepsilon_t(\omega,\mathbf{k})=1-\sum_j\frac{2\pi e^2}{\omega}\int\mathbf{v}_\perp\frac{\partial f}{\partial\mathbf{p}_\perp}\frac{d\mathbf{p}}{(\mathbf{kv}-\omega)}$$

Waves in un-magnetized plasma

$$\varepsilon_l(\omega,\mathbf{k}) = 1 - \sum_j \frac{4\pi e^2}{k^2}\int \mathbf{k}\frac{\partial f}{\partial \mathbf{p}}\frac{d\mathbf{p}}{(\mathbf{kv}-\omega)}$$

$$\varepsilon_t(\omega,\mathbf{k}) = 1 - \sum_j \frac{2\pi e^2}{\omega}\int \mathbf{v}_\perp\frac{\partial f}{\partial \mathbf{p}_\perp}\frac{d\mathbf{p}}{(\mathbf{kv}-\omega)}$$

dispersion relation

We want to solve this system of equations to find $\omega = \omega(k)$:

However, the integrals have a pole $\omega = kv$, , and the actual value depends on the path: above, below the pole or the average of two. We take the path above the pole i.e. add a small value $\omega \to \omega + i0$ This rule was suggested by ***Landau*** in 1946 and is named after him.

$$\int_{-\infty}^{\infty} \frac{f(z)dz}{z-i0} = \mathrm{PV}\int_{-\infty}^{\infty}\frac{f(z)dz}{z} + i\pi f(0)$$

Landau rule

Obviously integrals have a pole $\omega = kv$, but the actual value depends on the path: above, below the pole or the average of two. We take the path above the pole i.e. add a small value $\omega \to \omega + i0$ This rule was suggested by ***Landau*** in 1946 and is named after him.

$$\int_{-\infty}^{\infty} \frac{f(z)dz}{z - i0} = \mathrm{PV} \int_{-\infty}^{\infty} \frac{f(z)dz}{z} + i\pi f(0)$$

Principal Value

Comes from Residue

This gives us

$$\varepsilon(\omega, \mathbf{k})_l = 1 - \sum_j \frac{4\pi e^2}{k^2} \int \mathbf{k} \frac{\partial f}{\partial \mathbf{p}} \frac{d\mathbf{p}}{(\mathbf{kv} - \omega - i0)}$$

$$\varepsilon_t(\omega, \mathbf{k}) = 1 - \sum_j \frac{2\pi e^2}{\omega} \int \mathbf{v}_\perp \frac{\partial f}{\partial \mathbf{p}_\perp} \frac{d\mathbf{p}}{(\mathbf{kv} - \omega - i0)}$$

Maxwellian plasma

Let us apply Maxwellian distribution to the expressions of the previous section:

$$f(p) = \frac{n_{e,i}}{(2\pi m T_{e,i})^{1/2}} \exp\left(-\frac{p^2}{2mT_{e,i}}\right)$$

Substituting Maxwell distribution we immediately obtain

$$\varepsilon_l(\omega,k) = 1 + \sum_j \frac{1}{k^2\lambda_{Dj}^2}\left[1 + F\left(\frac{\omega}{\sqrt{2}kv_{Tj}}\right)\right]$$

$$\varepsilon_t(\omega,k) = 1 + \sum_j \frac{\omega_{pj}^2}{\omega^2} F\left(\frac{\omega}{\sqrt{2}kv_{Tj}}\right)$$

$$\lambda_{Dj} = \sqrt{\frac{T_j}{4\pi e^2 n_j}}, \quad v_{Tj} = \sqrt{\frac{T_j}{m_j}}, \quad \omega_{pj} = \sqrt{\frac{4\pi e^2 n_j}{m_j}}$$

$$F(x) = \frac{x}{\sqrt{\pi}} \int\limits_{-\infty}^{\infty} \frac{\exp(-z^2)dz}{z - x - i0}$$ is *plasma dispersion function*

Landau damping

Let us consider an imaginary part of dielectric tensor

$$\mathrm{Im}\varepsilon(\omega, \mathbf{k})_l = -\sum_j \frac{4\pi^2 e^2}{k^2} \int \mathbf{k}\frac{\partial f}{\partial \mathbf{p}} \delta(\omega - \mathbf{k}\mathbf{v}) d\mathbf{p}$$

It says that the waves in plasma are damped even in the collisionless plasma. For Maxwellian distribution we have

$$\gamma_k \approx -\sqrt{\frac{\pi}{8}} \sum_j \frac{\omega_{pj}}{(k\lambda_{Dj})^3} \exp\left(-\frac{1}{2(k\lambda_{Dj})^2}\right)$$

The damping is not randomization of collisions, but a transfer of wave energy into resonant oscillation of particles. Note that
For $k\lambda_{De} > 1$ the damping rate would exceed frequency of oscillations.

Langmuir waves

The dispersion relation for longitudinal electrostatic oscillations:

$$\varepsilon(\omega, k)_l = 0$$

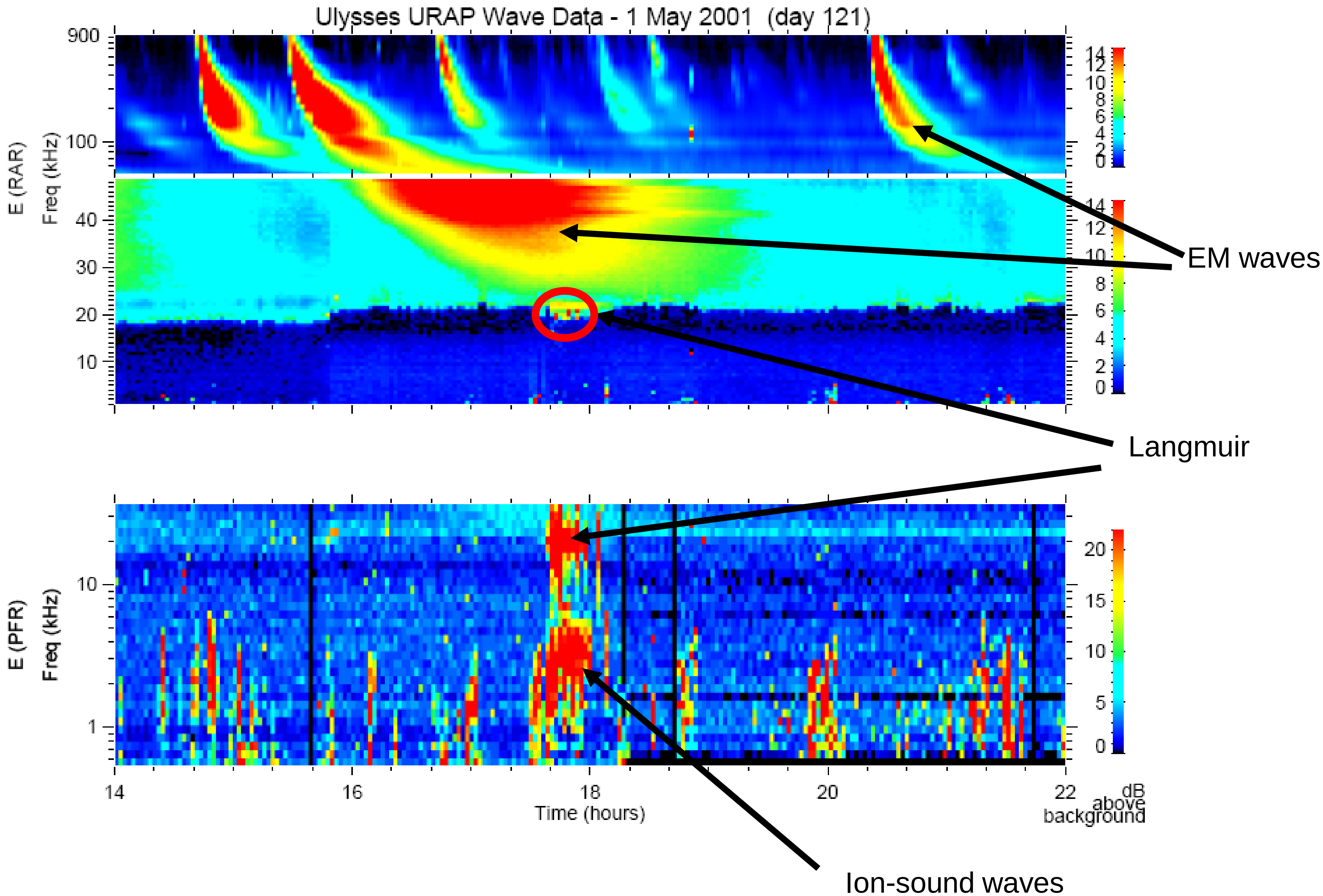
In the limit $\omega >> kv_{Te} >> kv_{Ti}$ we find for the real part

$$\omega(k)_l = \omega_{pe}(1 + \frac{3k^2\lambda_{De}^2}{2})$$

which is the dispersion relation for *Langmuir waves*. The imaginary part of the frequency is

$$\gamma(k) = -0.5\omega_{pe}\mathrm{Im}\varepsilon(\omega, k)$$

In-situ observations of Langmuir waves



Electromagnetic waves

For transverse waves the dispersion relation is given by

$$\omega^2 = c^2k^2/\varepsilon_t$$

High frequency waves $\omega \gg kv_{Te}$ orresponds to ordinary electromagnetic waves. We find

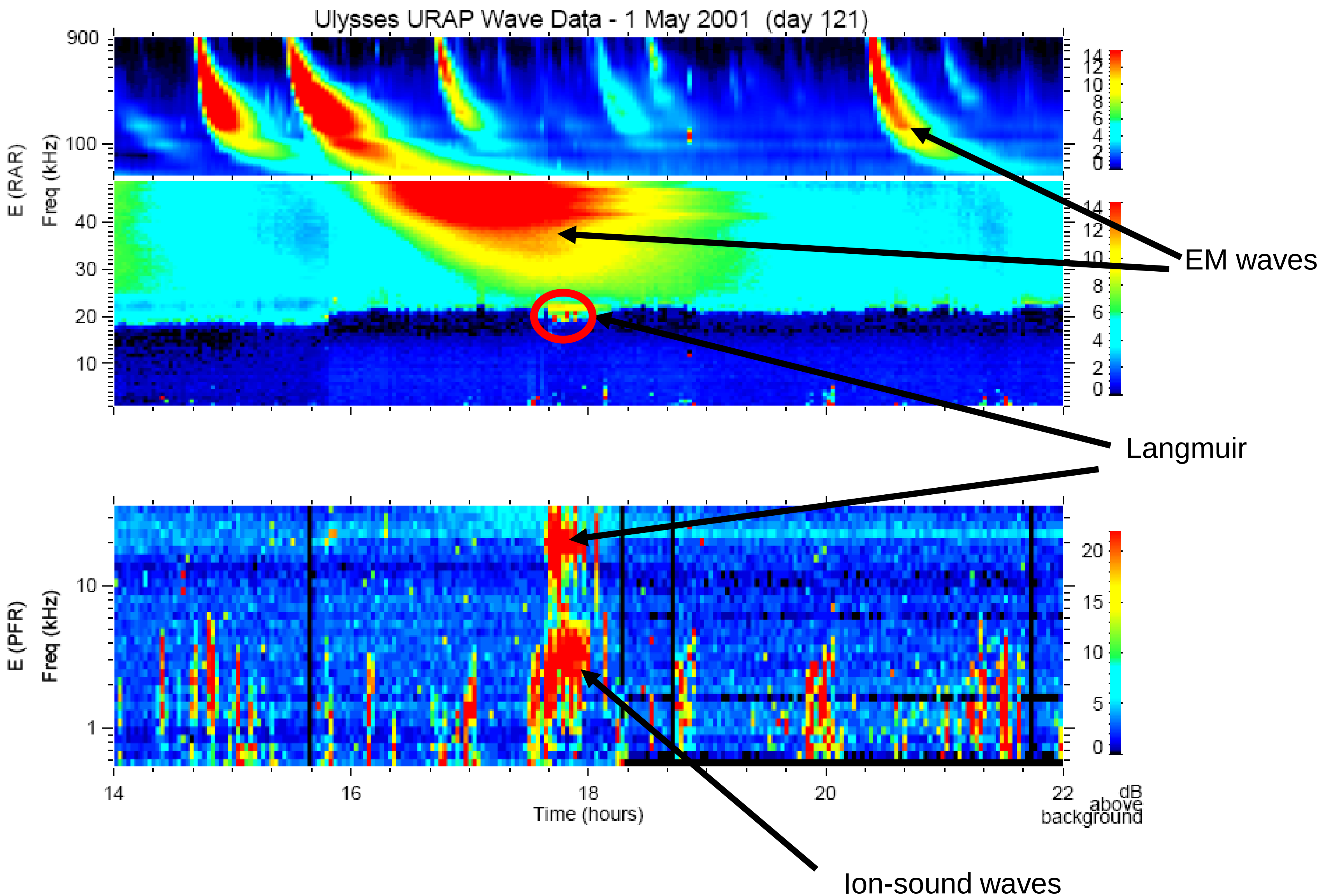
$$\omega(k)_t^2 = \omega_{pe}^2 + k^2c^2$$

This relation is correct for all values of **k**. Note Landau damping is does not exist since phase velocities are greater than speed of light.

For low frequency waves ions again are not important and the solution has only imaginary part and no waves can propagate

$$\omega(k)_t = -i\sqrt{\frac{2}{\pi}}\frac{k^3c^2v_{Te}}{\omega_{pe}^2}$$

Radio waves



Ulysses URAP Wave Data - 1 May 2001 (day 121)
E (RAR)
Freq (kHz)
900
100
40
30
20
10
E (PFR)
Freq (kHz)
10
1
14
16
18
20
22
Time (hours)
dB above background
EM waves
Langmuir
Ion-sound waves

Let us consider the range $kv_{Ti} << \omega << kv_{Te}$ have the solution of dispersion equation in the form

$$\omega(k)_s^2 = \omega_{pi}^2 \frac{k^2\lambda_{De}^2}{1+k^2\lambda_{De}^2}$$

These waves are called *ion-sound waves*. For $k\lambda_{De} << 1$ have

$$\omega(k)_s = k\sqrt{\frac{T_e}{M}}$$

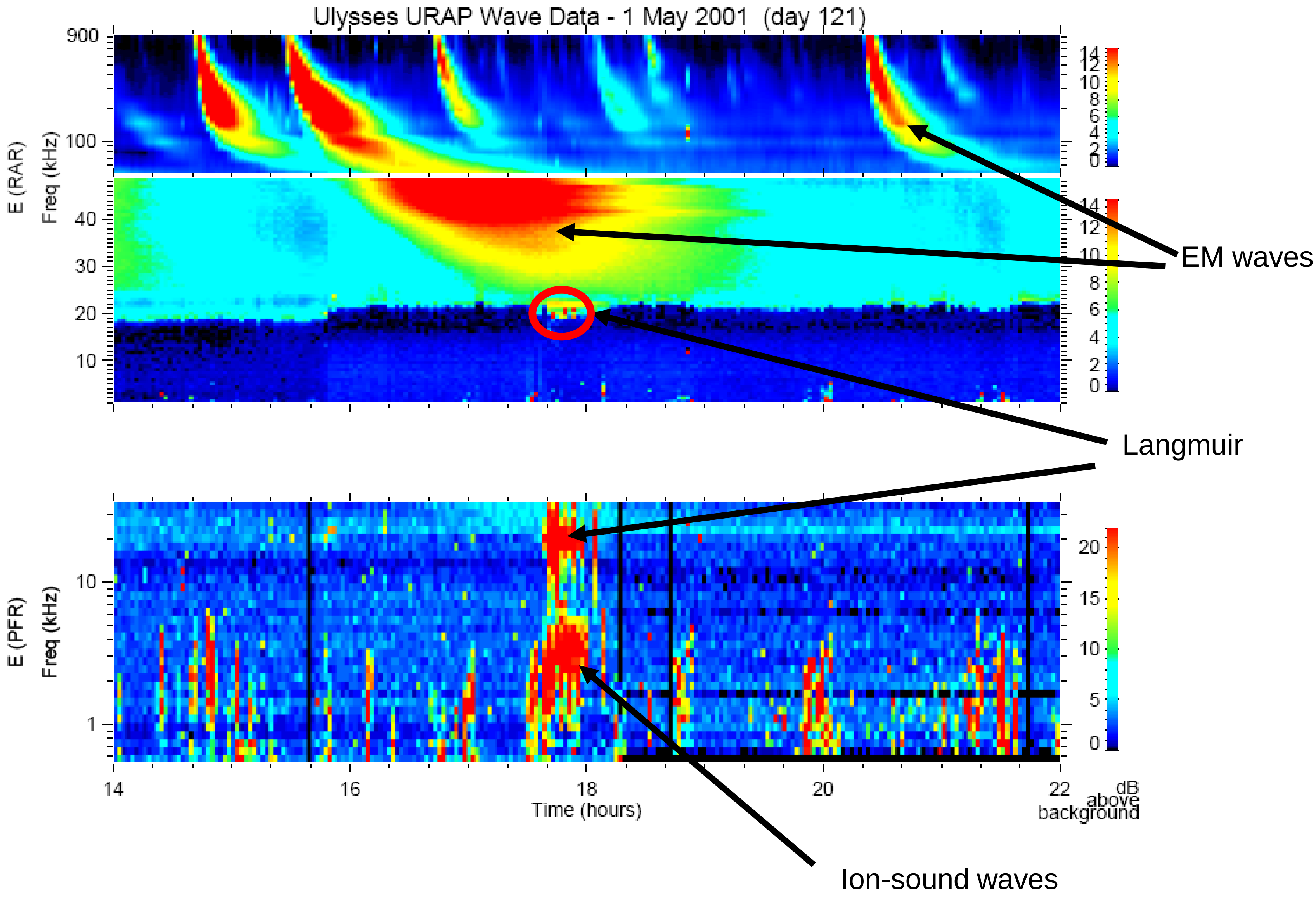
with the dispersion as for ordinary sound waves.

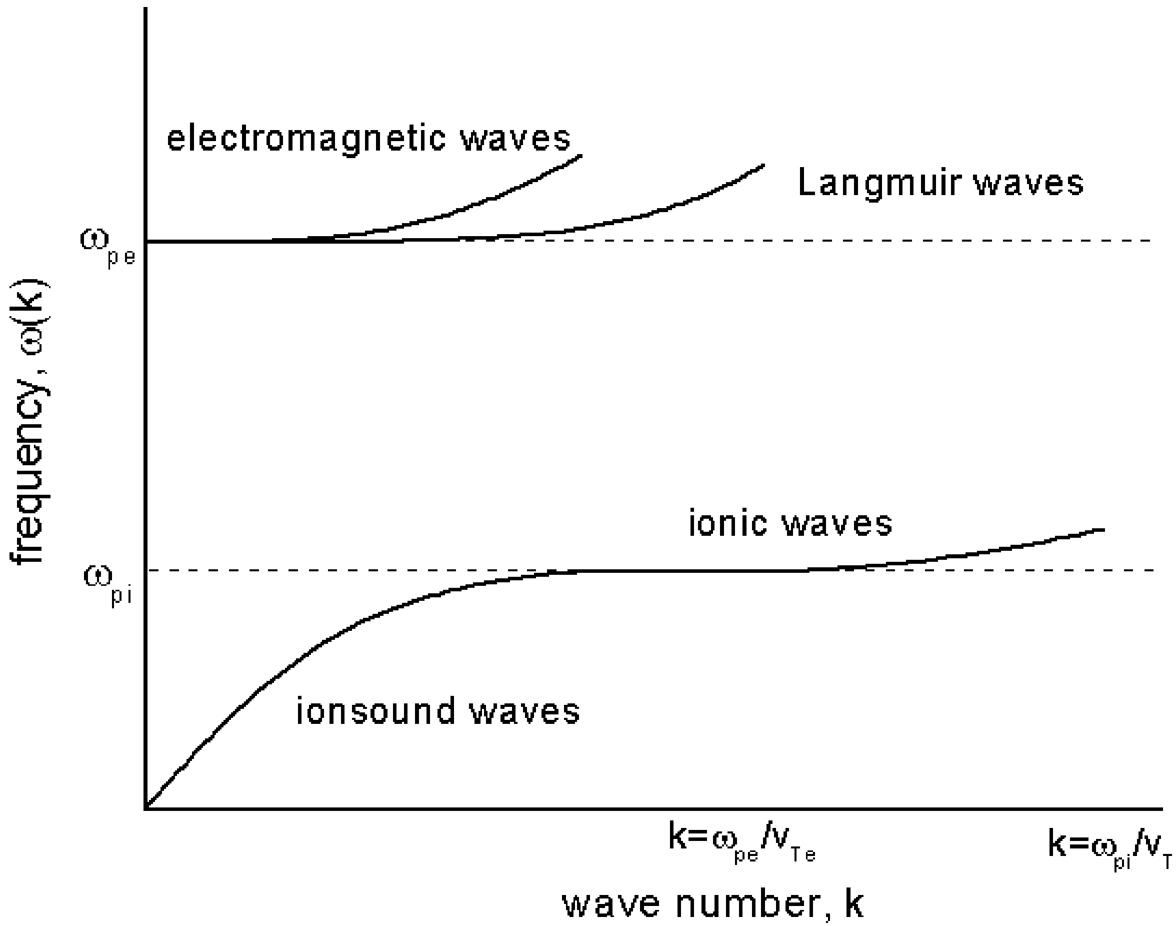
This waves are subject to strong damping. The rate accounting only electrons is

$$\gamma(k)_s = \omega\sqrt{\frac{\pi m}{8M}}$$

Note that these waves require $T_e >> T_i$

Ion-sound waves





electromagnetic waves
Langmuir waves
ωpe
frequency, ω(k)
ionic waves
ωpi
ionsound waves
k=ωpe/vTe
k=ωpi/vTi
wave number, k

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

Recall Landau damping: $$\mathrm{Im}\varepsilon(\omega, \mathbf{k})_l = -\sum_j \frac{4\pi^2 e^2}{k^2} \int \mathbf{k} \frac{\partial f}{\partial \mathbf{p}} \delta(\omega - \mathbf{k}\mathbf{v}) d\mathbf{p}$$

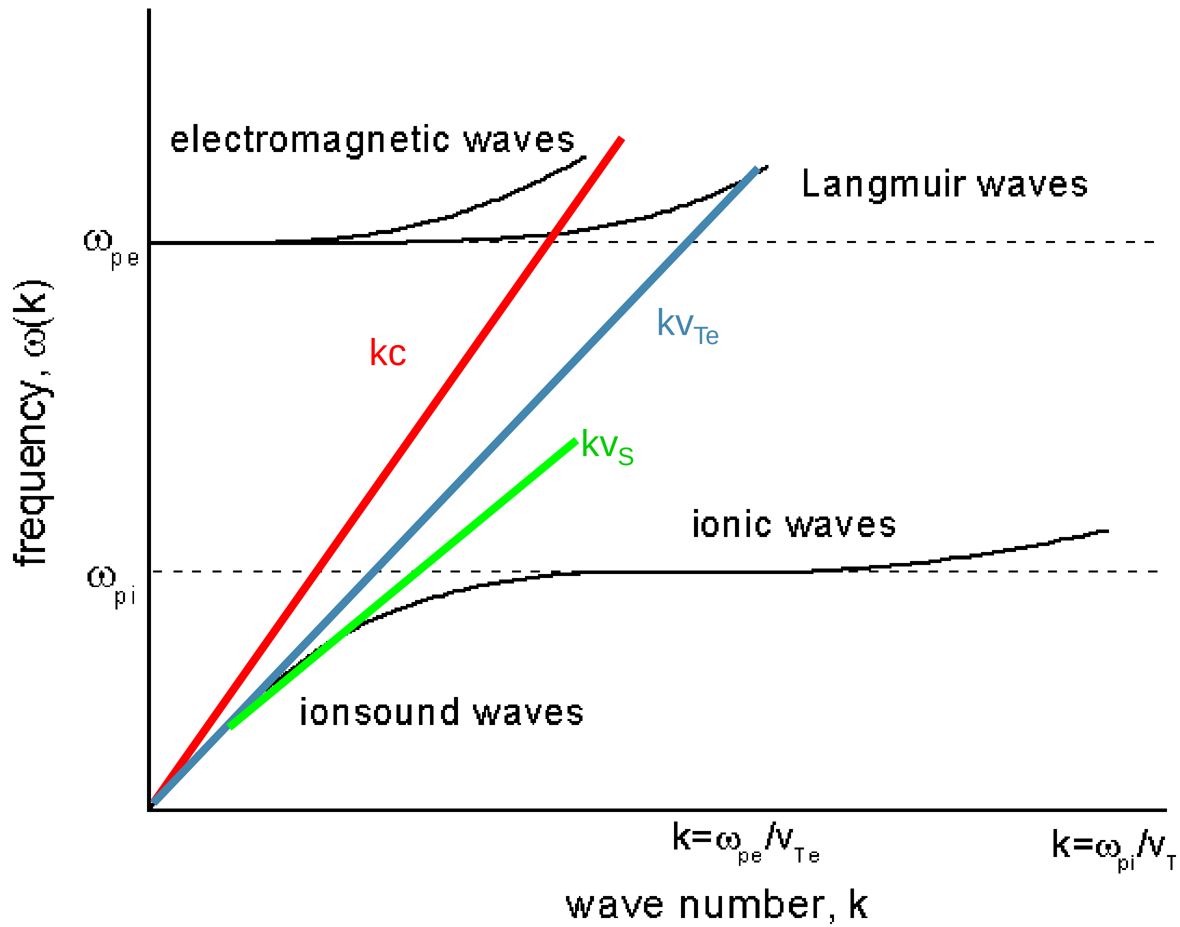
For unmagnetised plasma – Cherenkov resonance:

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

In magnetised plasma –cyclotron resonance possible:

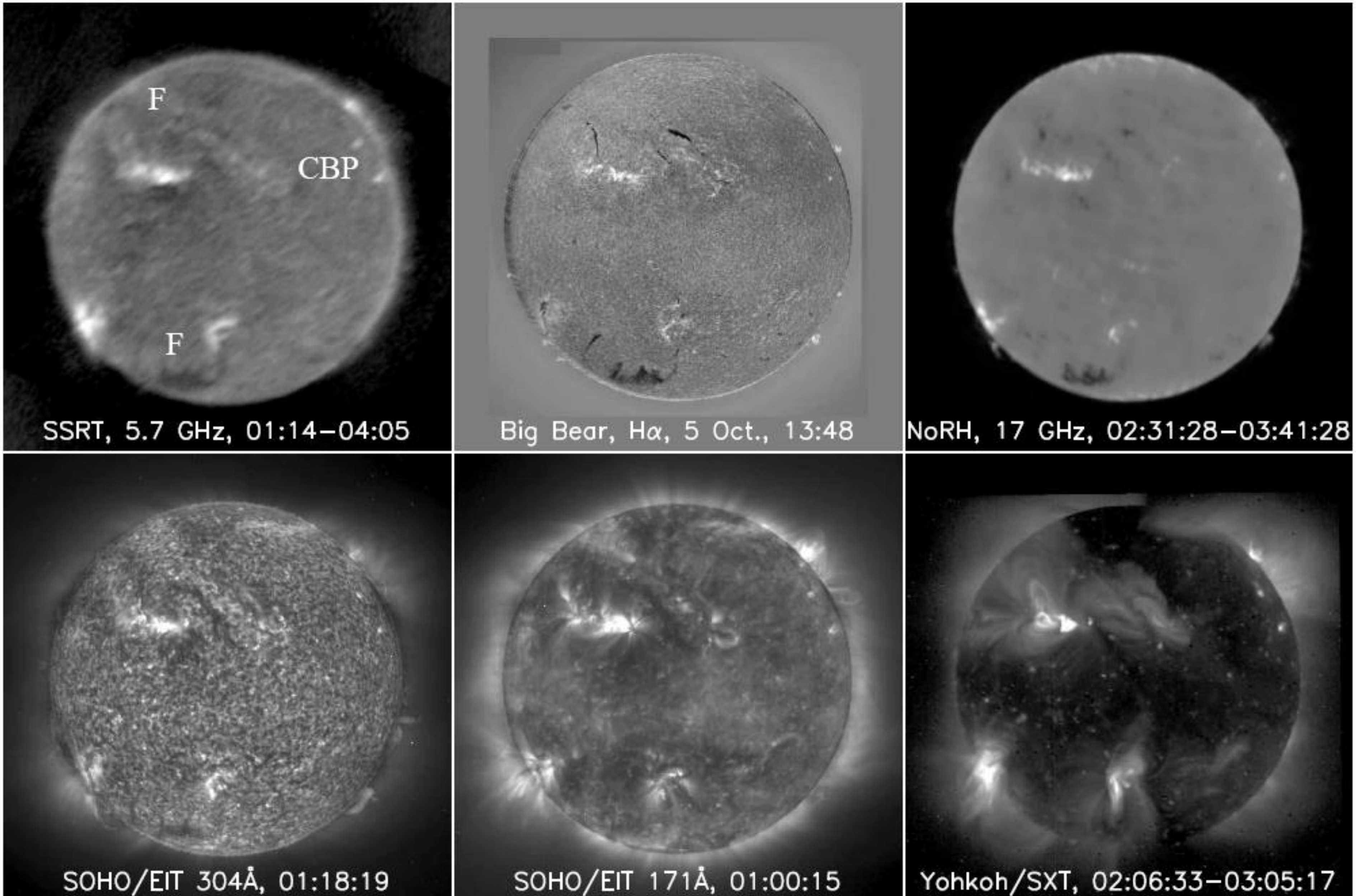
$$\omega - s\Omega - k_{\|} v_{\|} = 0,$$

Cherenkov resonance condition



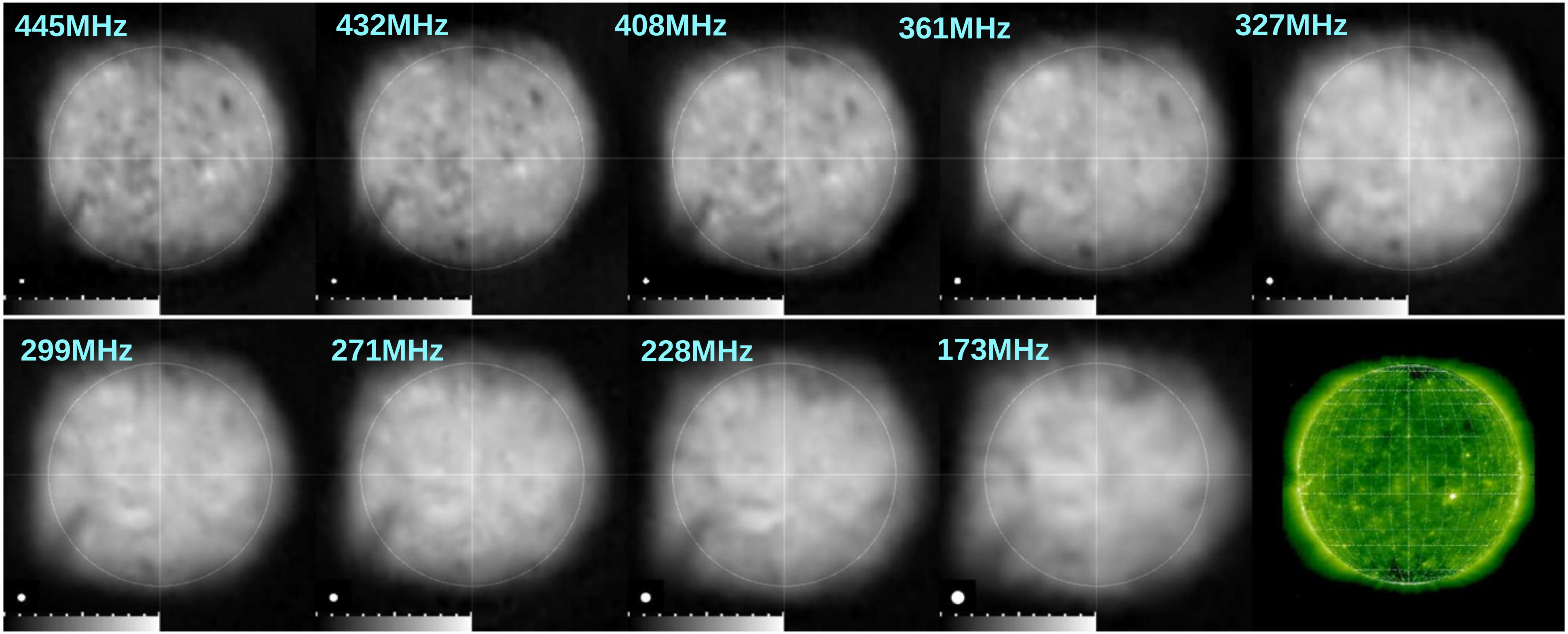
Radio emission from quiet Sun

Multi-frequency Sun



From Grechnev et al, 1998

Quit Sun – meter wavelengths



NRH Images of the Sun on 2008 June 6 (near solar minimum) at 445, 432, 408, 361, 327, 299, 271, 228, 173 MHz, together with a 195 Å image from EIT on board *SOHO* (*from Mercier & Chambe, 2009*).

Quiet corona – Temperature vs frequency

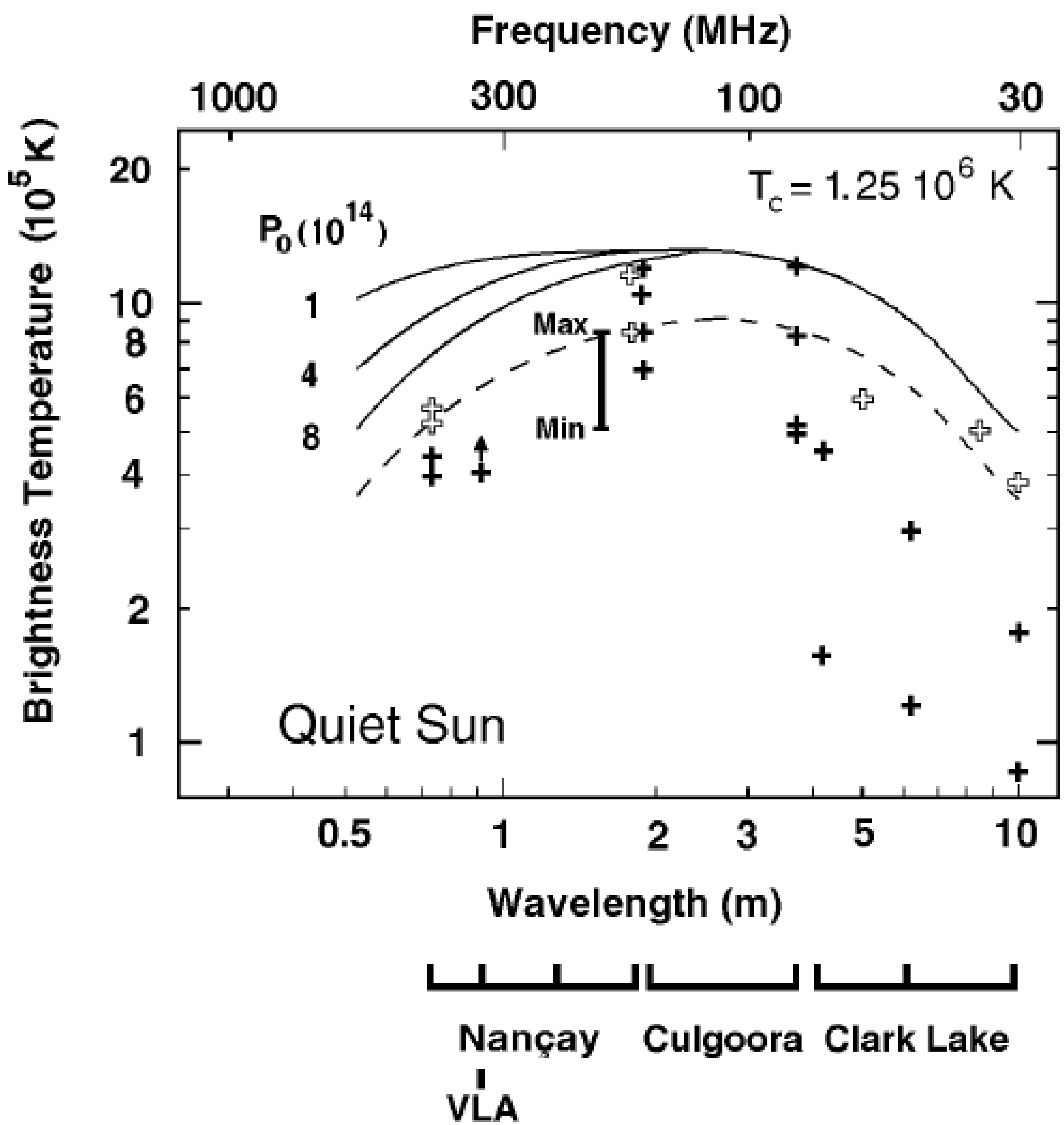
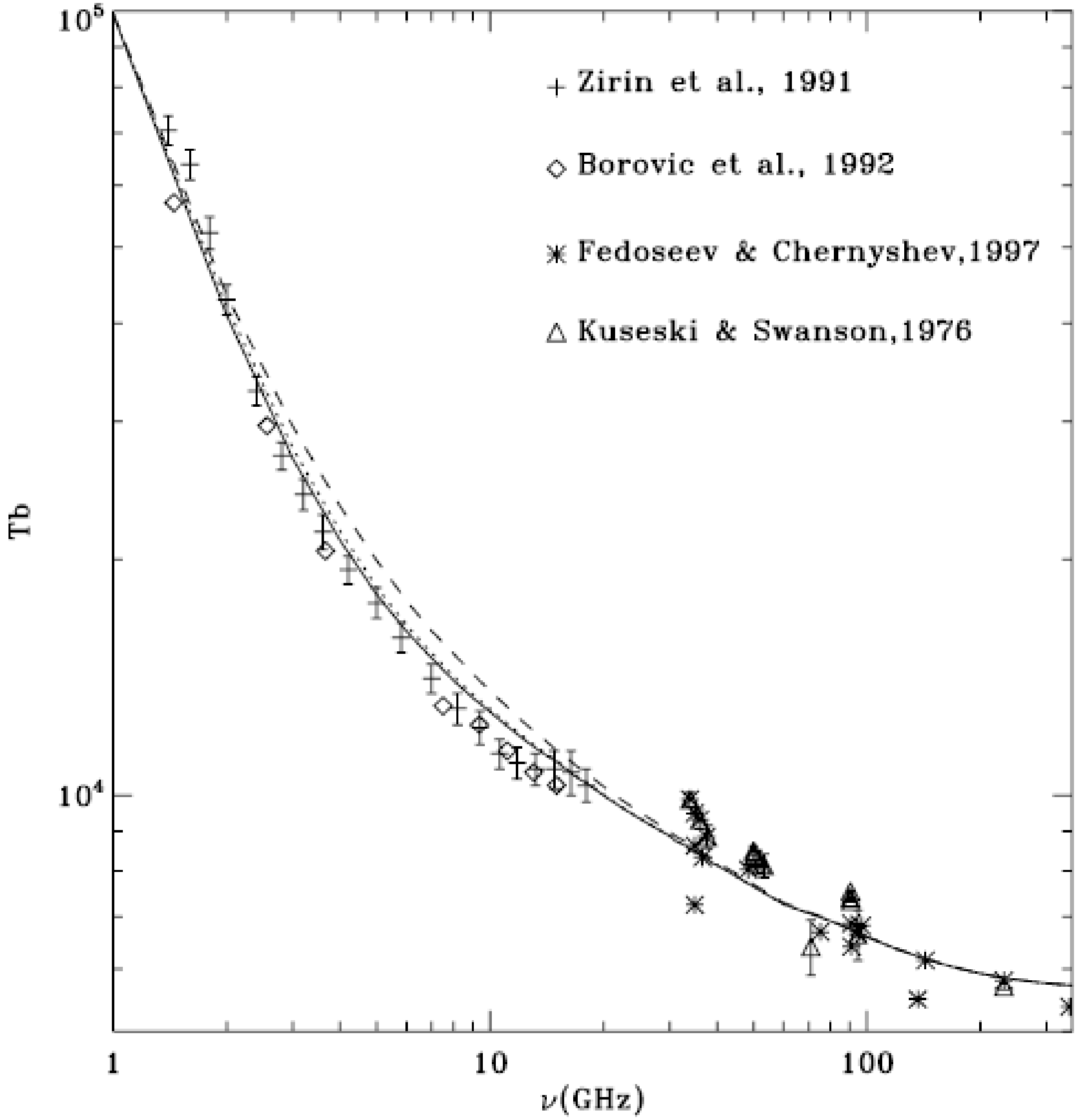


Figure: Brightness temperatures observed in the quiet. The open crosses are estimates obtained without two-dimensional observations. Chambe's model (1978) is given for comparison. (*from Lantos, 1998*)

Chromosphere: Brightness temperature vs frequency



Observed brightness temperature as a function of frequency (from Landi et al, 2008).

Solar chromosphere dynamics – cm wavelengths

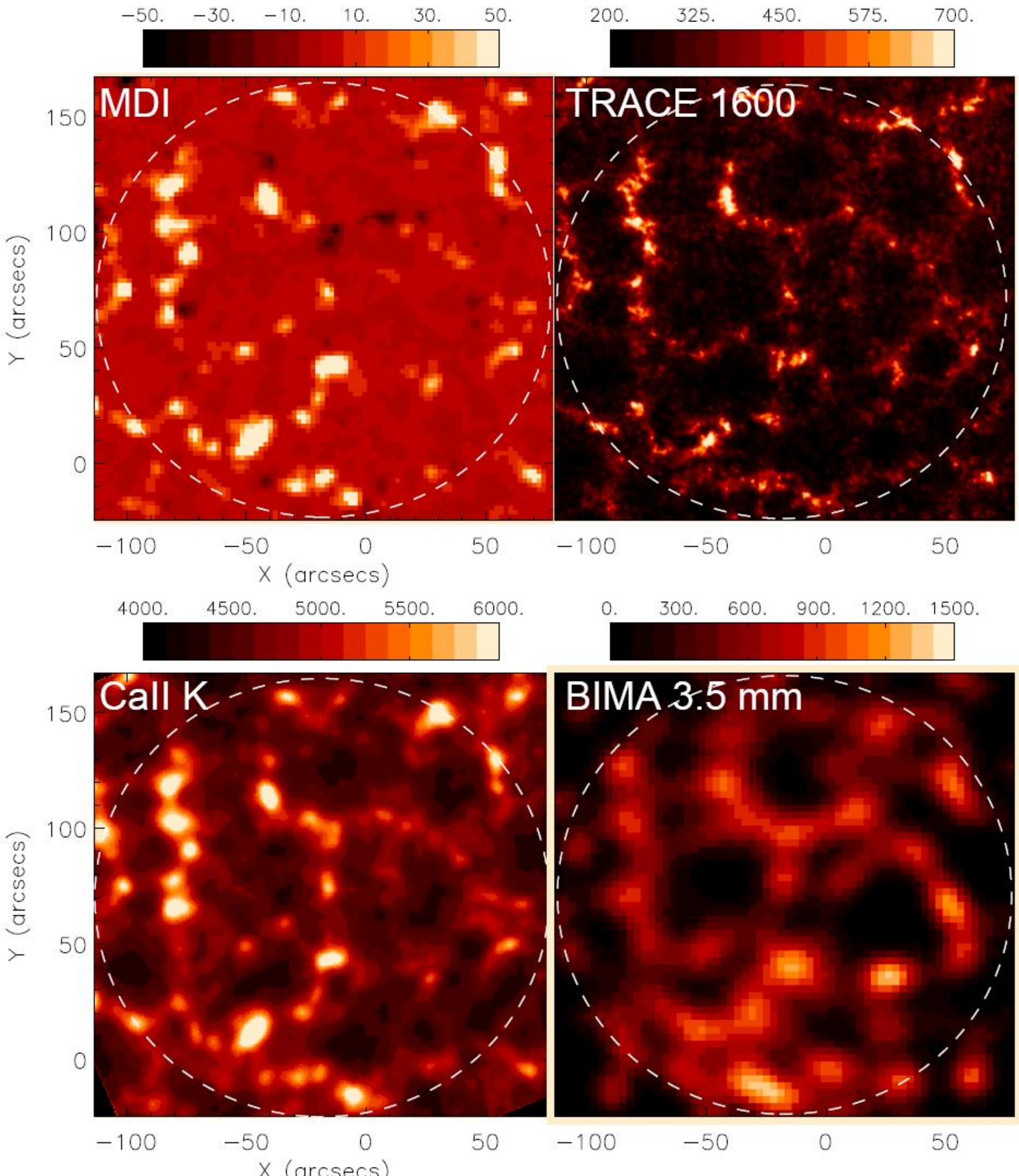
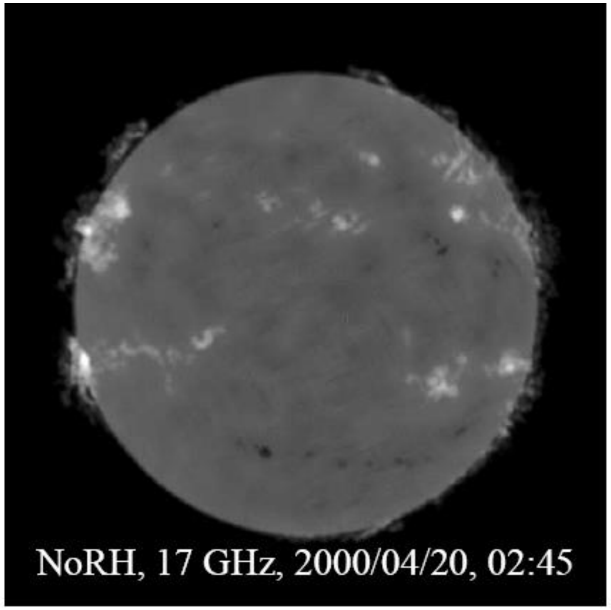
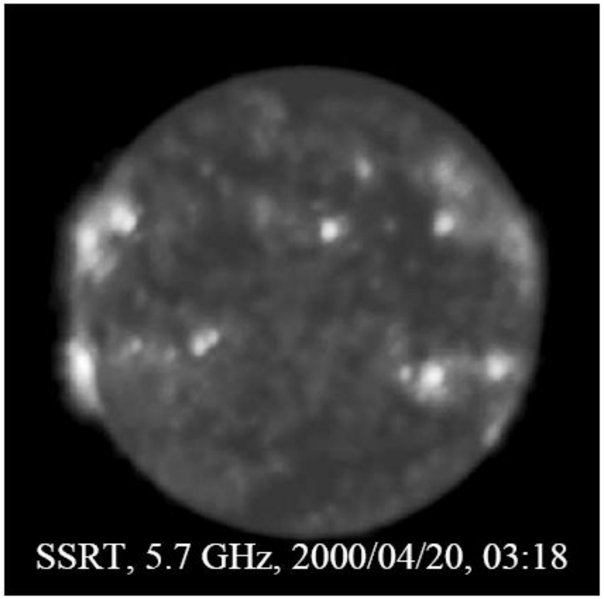


Figure: The solar chromosphere at the centre of the Sun's disk at 4 different wavelengths on May 18, 2004. From top left to bottom right: MDI longitudinal photospheric magnetogram, UV 1600 A image from TRACE, CaII K line center image from BBSO and radio image at 3.5 mm (90 GHz). (*from Loukitcheva et al, 2009*)

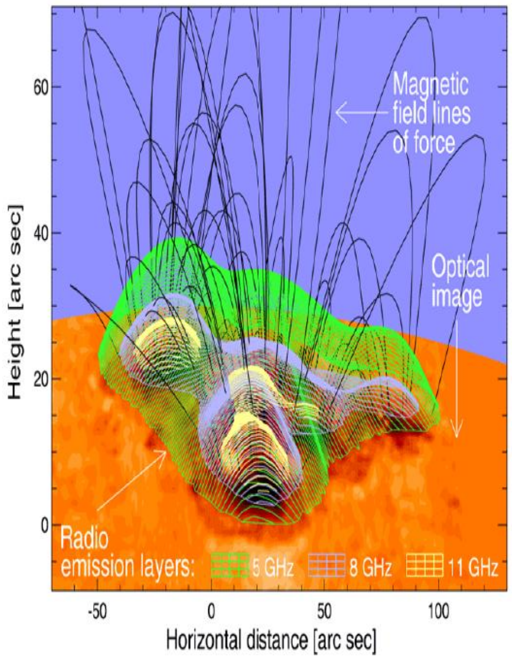
Quiet Sun – what can we learn?





Radio diagnostics of solar chromosphere and lower corona:

Free-free emission -> Temperature and Emission measure
Thermal Gyrosynchrotron -> Magnetic fields

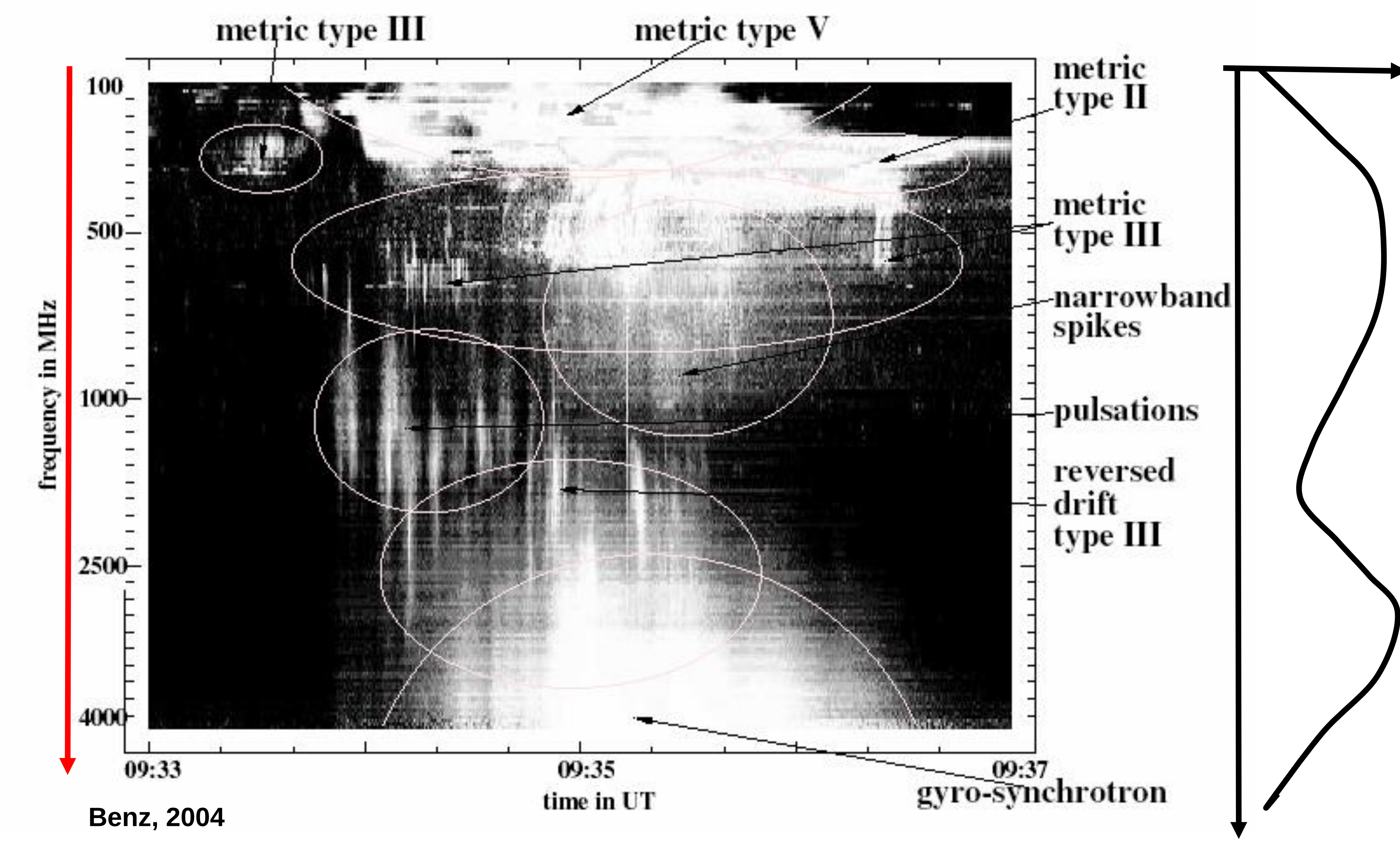


Lee et al 1998; Bastian et al, 2006

Radio emission from solar flares

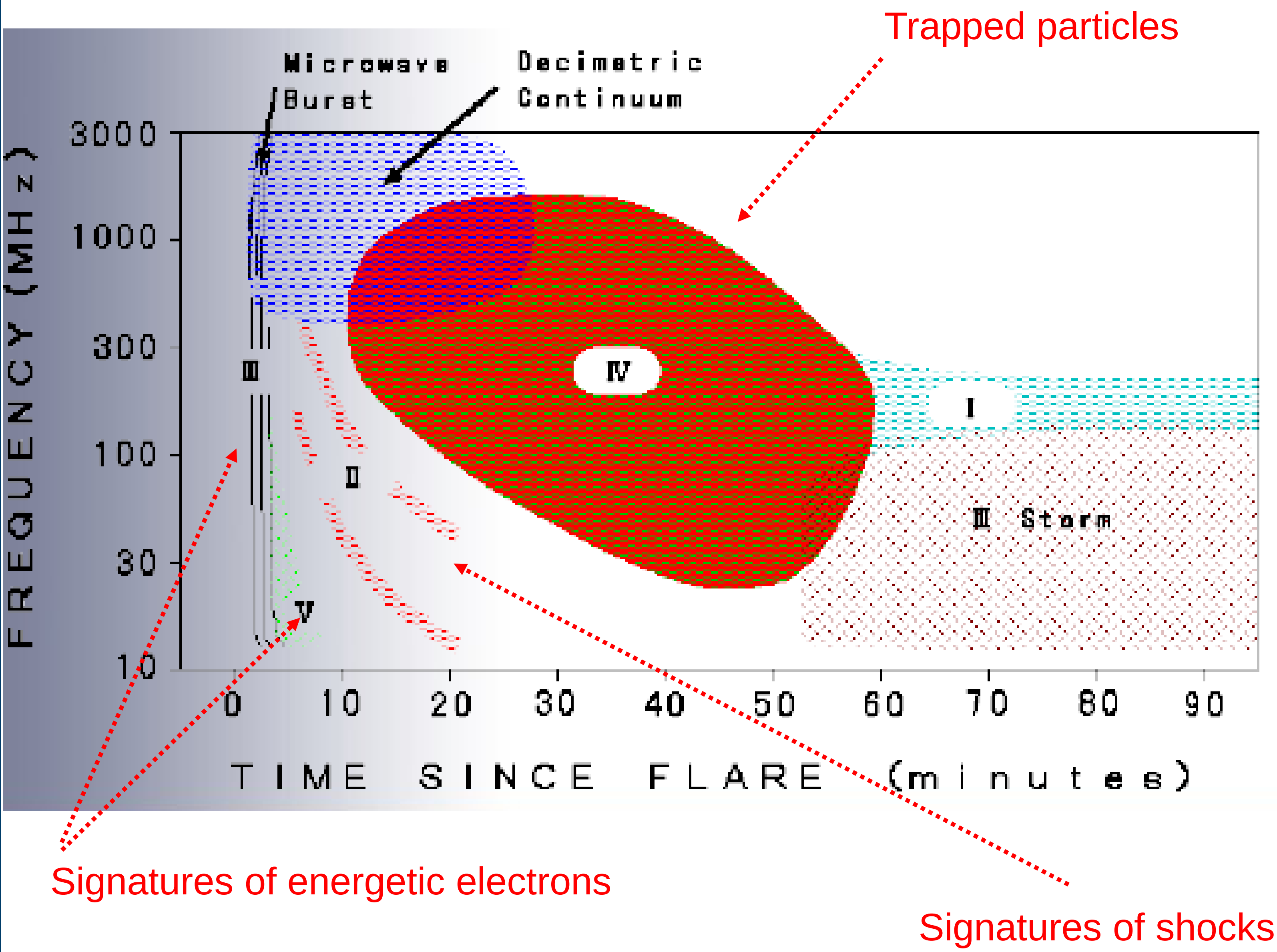
Solar radio emission is complex!

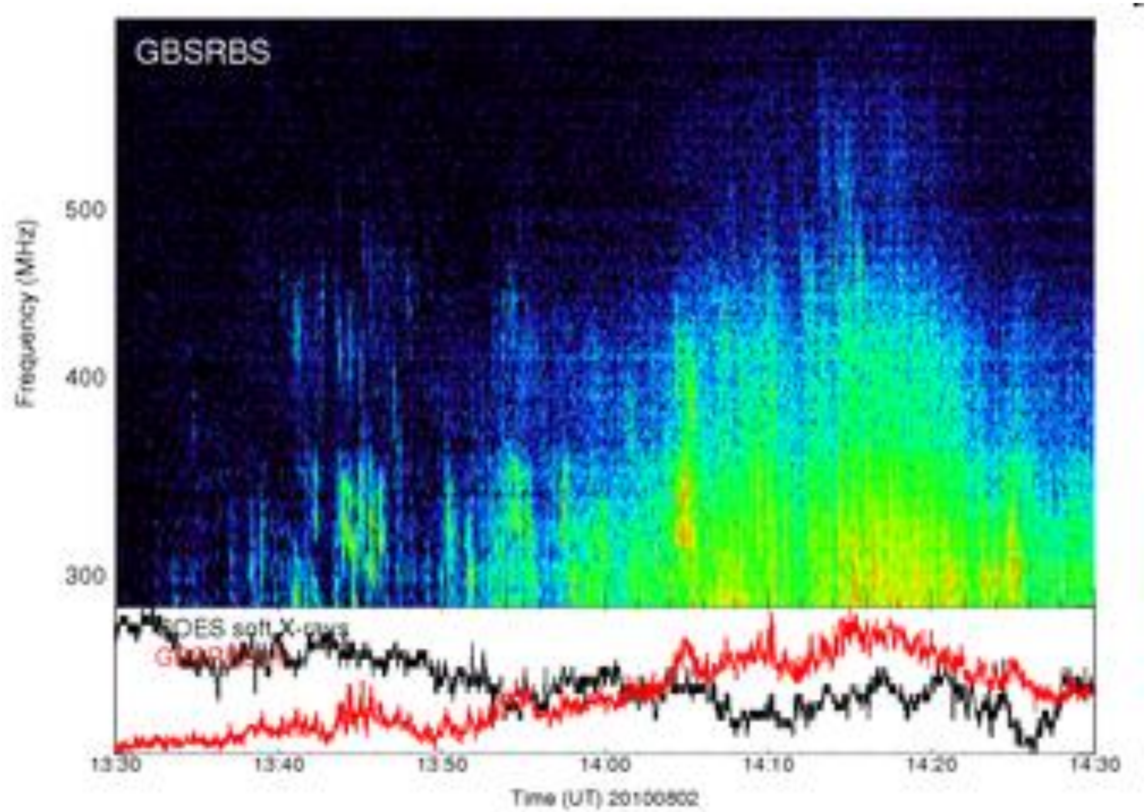
A typical dynamic spectrum of an active Sun



Benz, 2004

Source of information about various processes

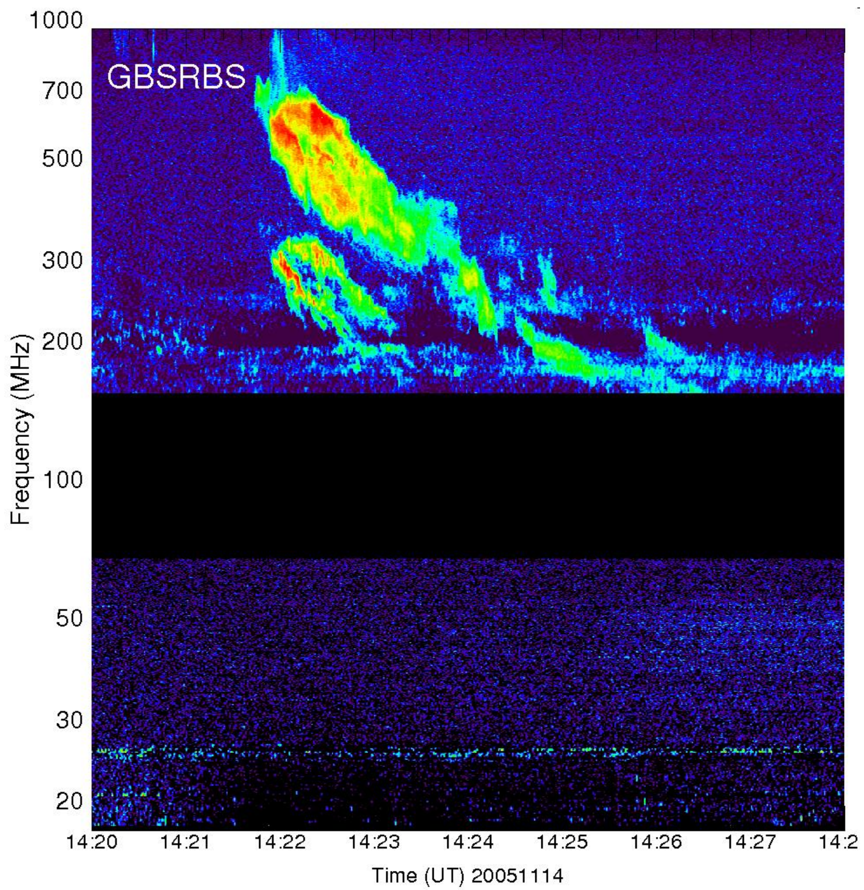




Emission mechanism: plasma emission

Exciter: hot plasma with non-thermal tail?

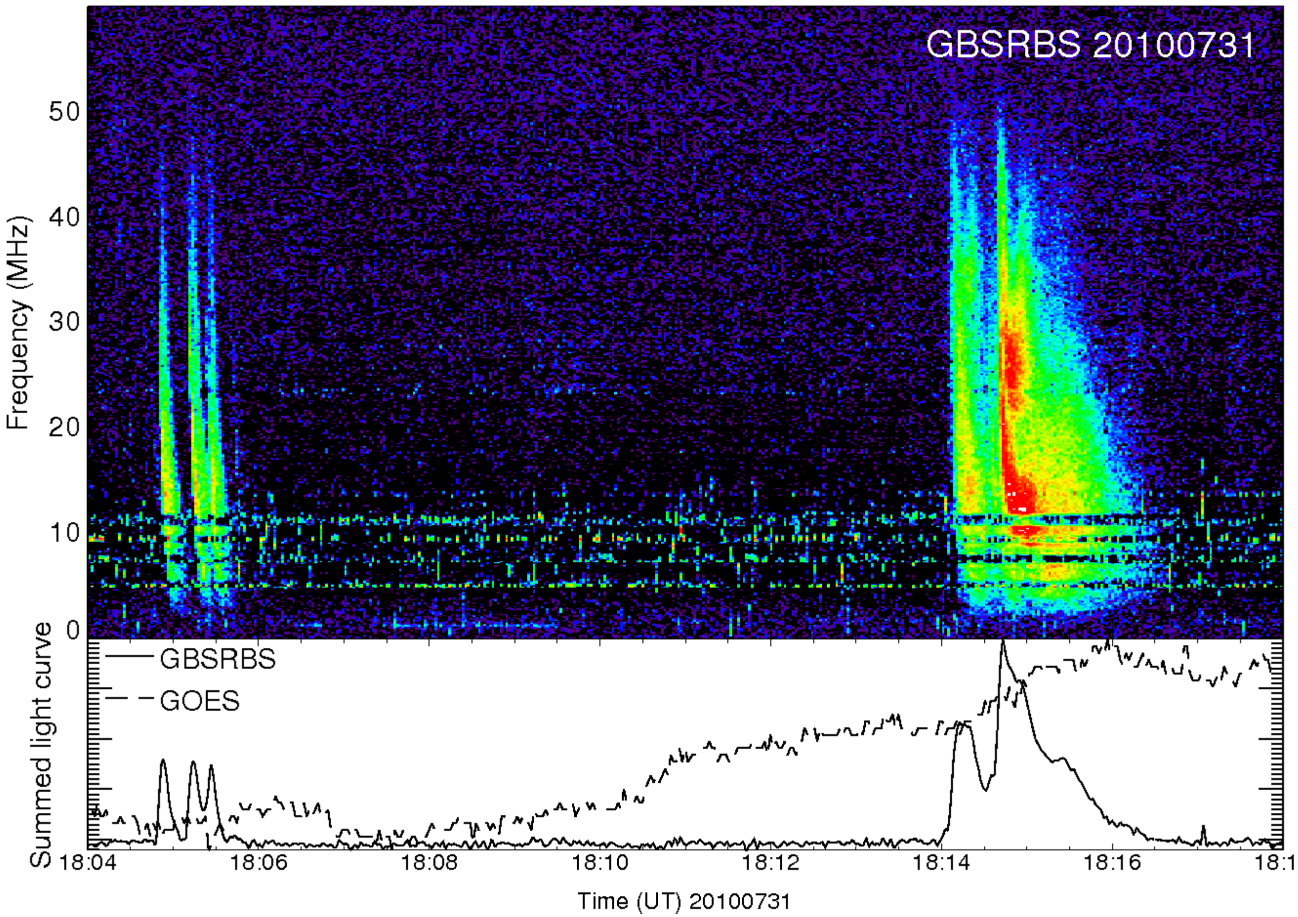
Type II



Emission mechanism: plasma emission

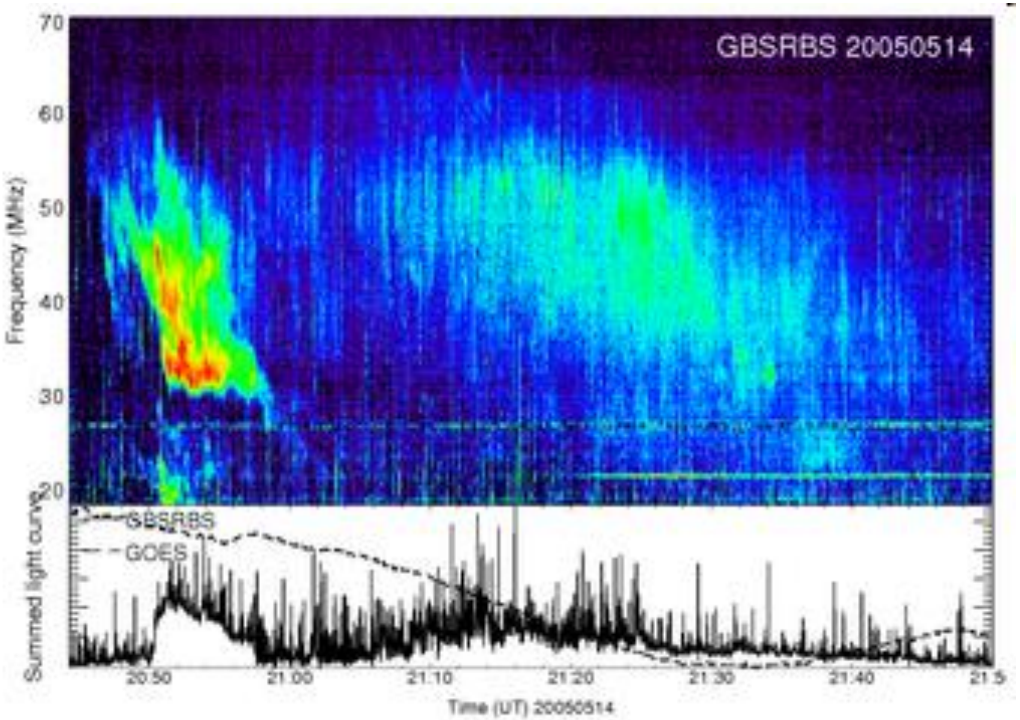
Exciter: shock waves

Type III and type V bursts



Emission mechanism: plasma emission

Exciter: energetic electron beams

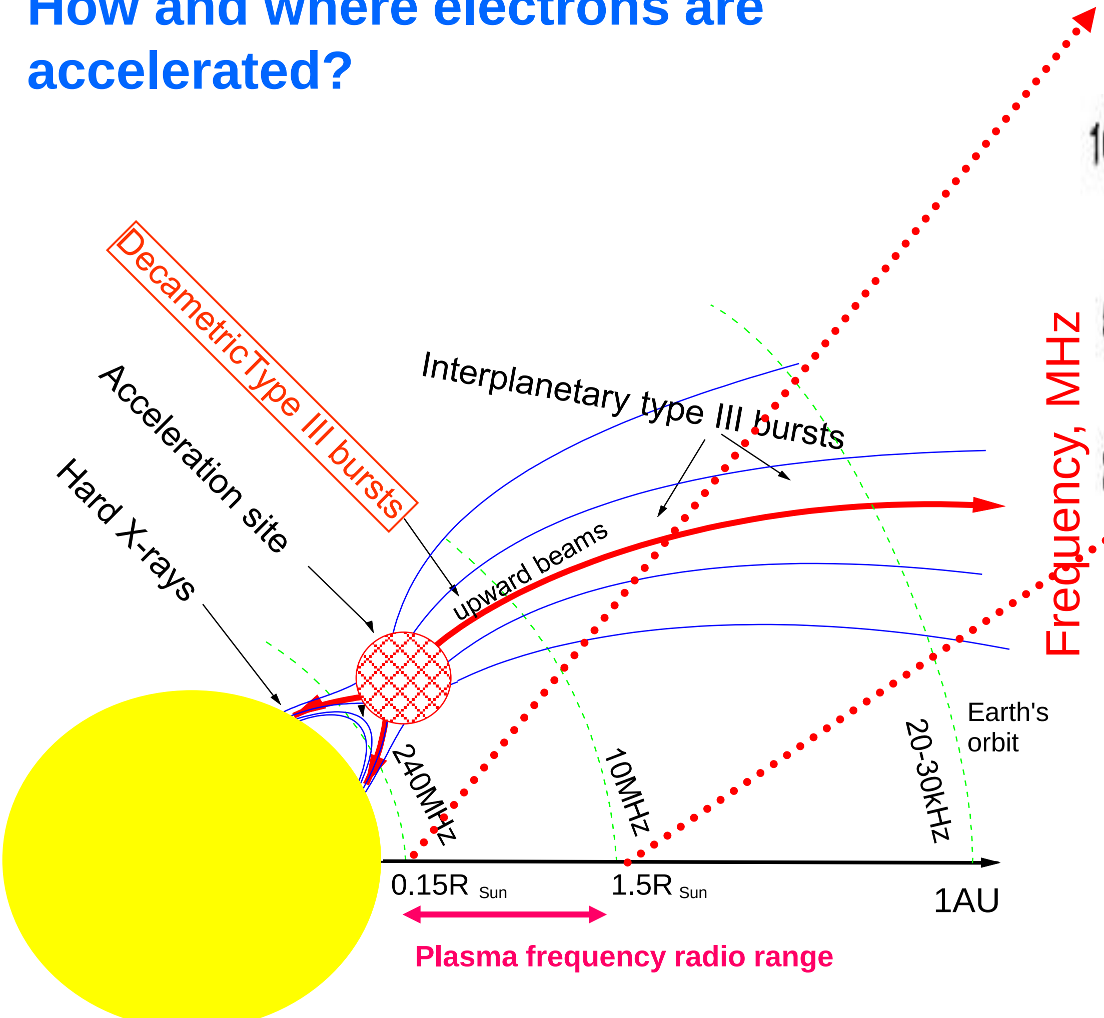


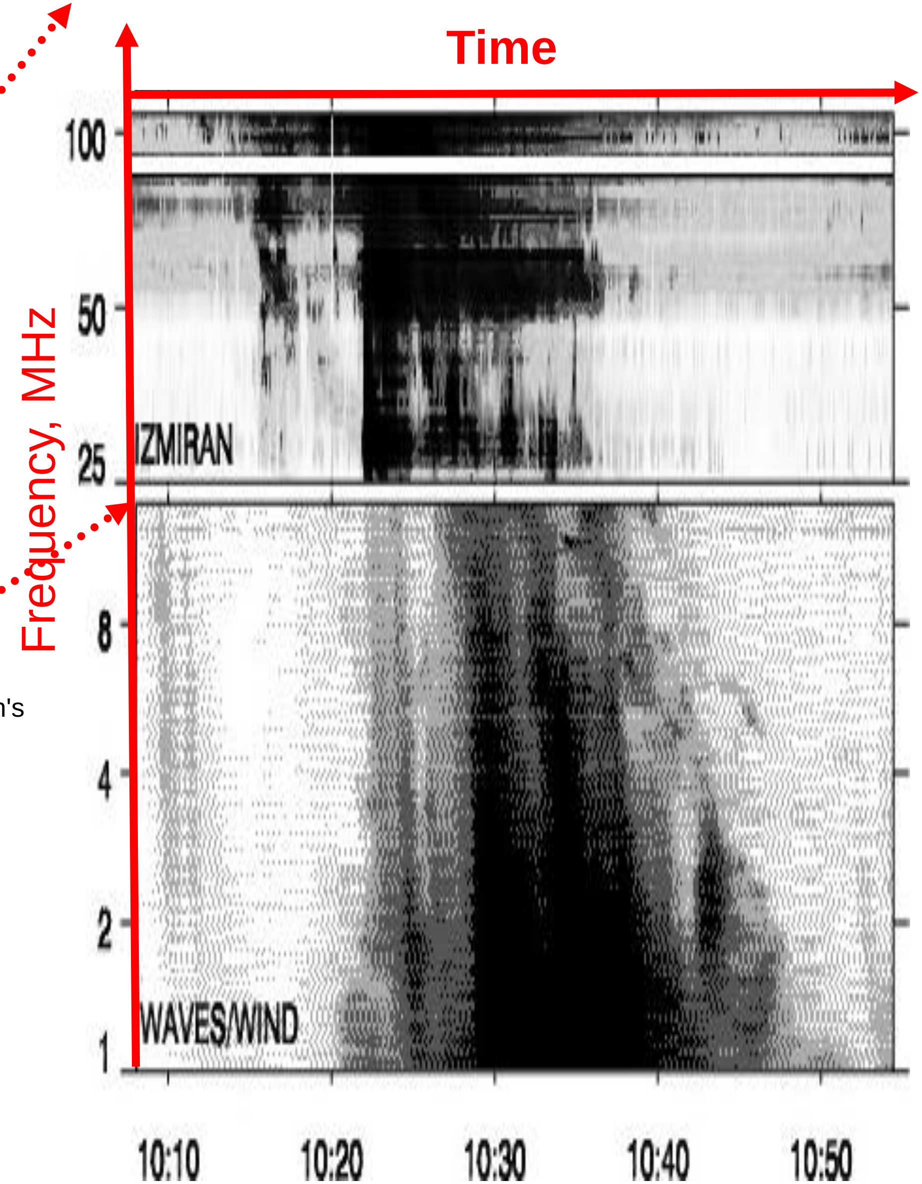
Emission mechanism: plasma emission

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

What can we learn from radio emission?

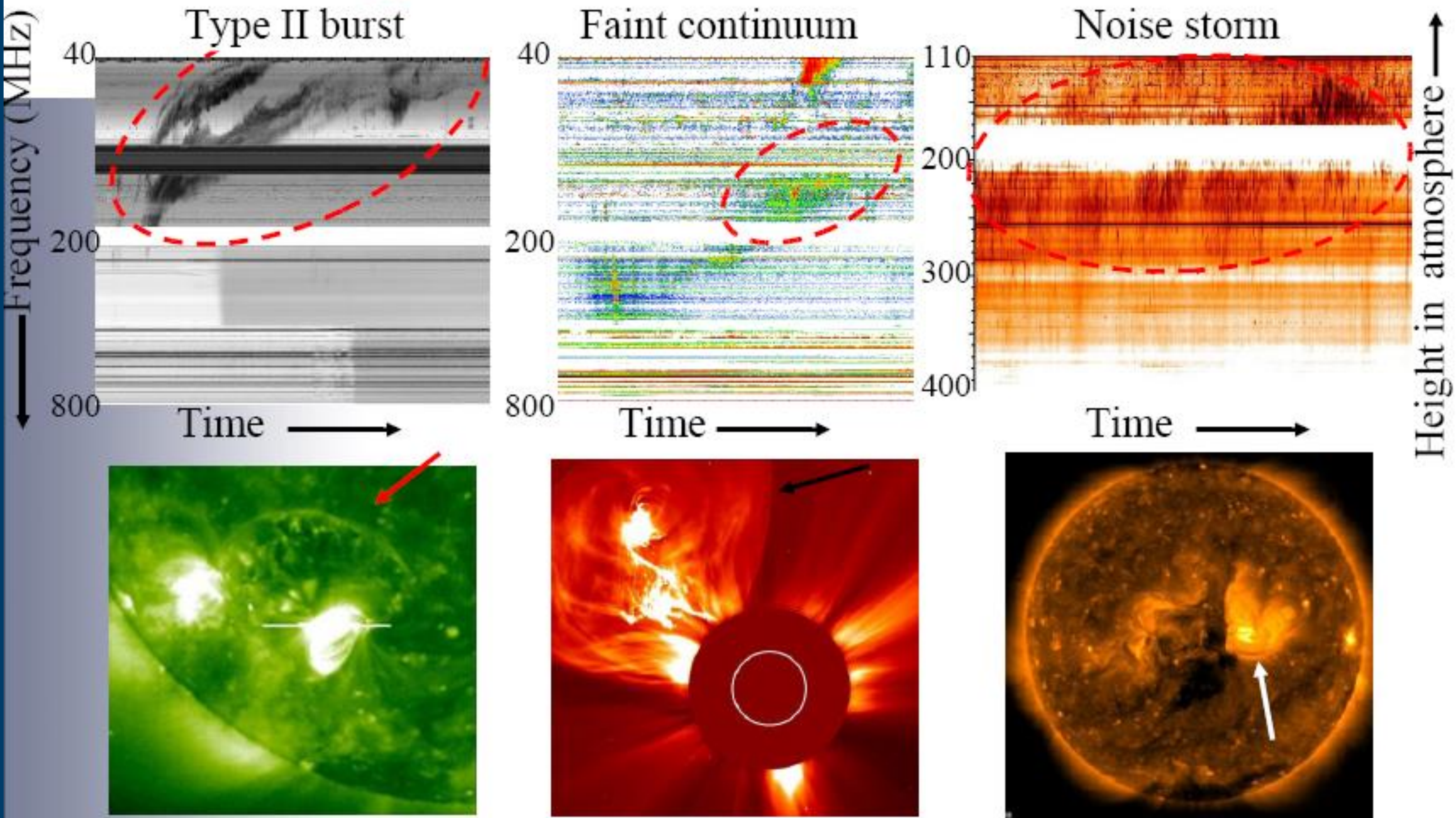
How and where electrons are accelerated?





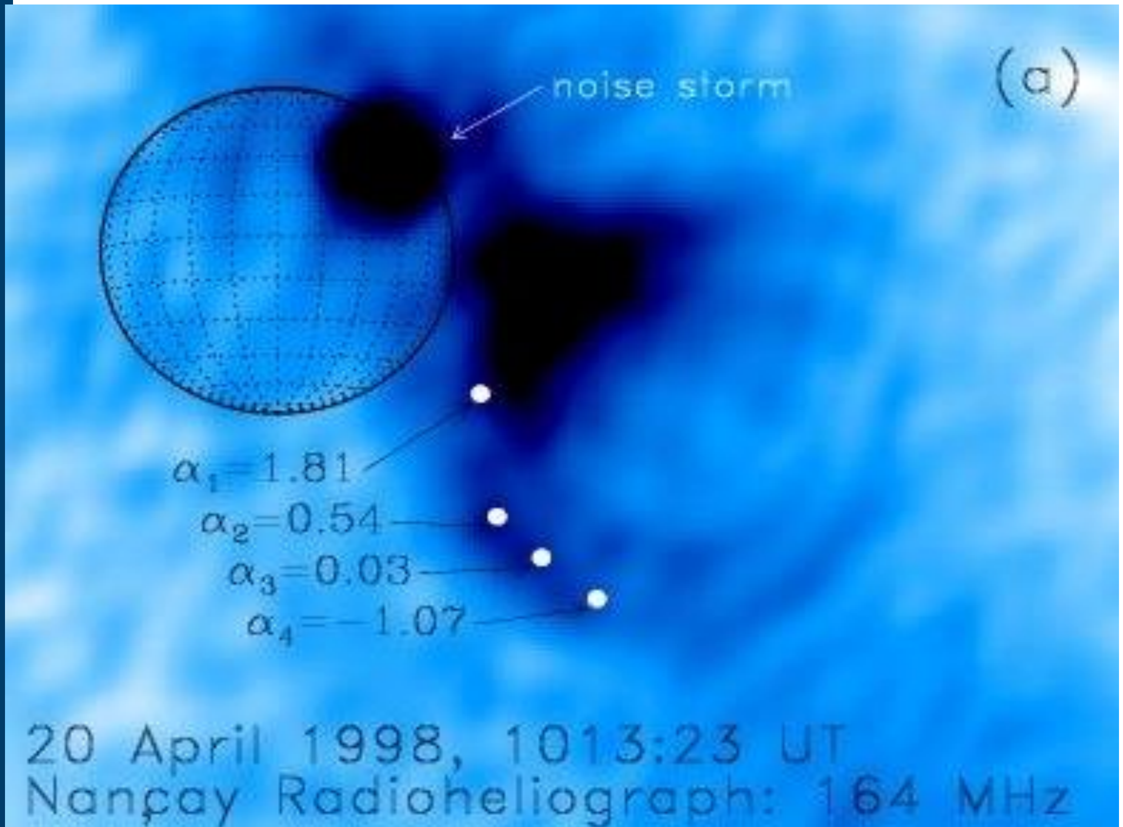
$$\nu_p = \sqrt{\frac{n_e e^2}{\pi m_e}},$$ <= plasma frequency

Shocks, continuum, active regions



- Large shock wave
- Coronal mass ejection
- AR/coronal heating?

Radio emission from Coronal Mass Ejections

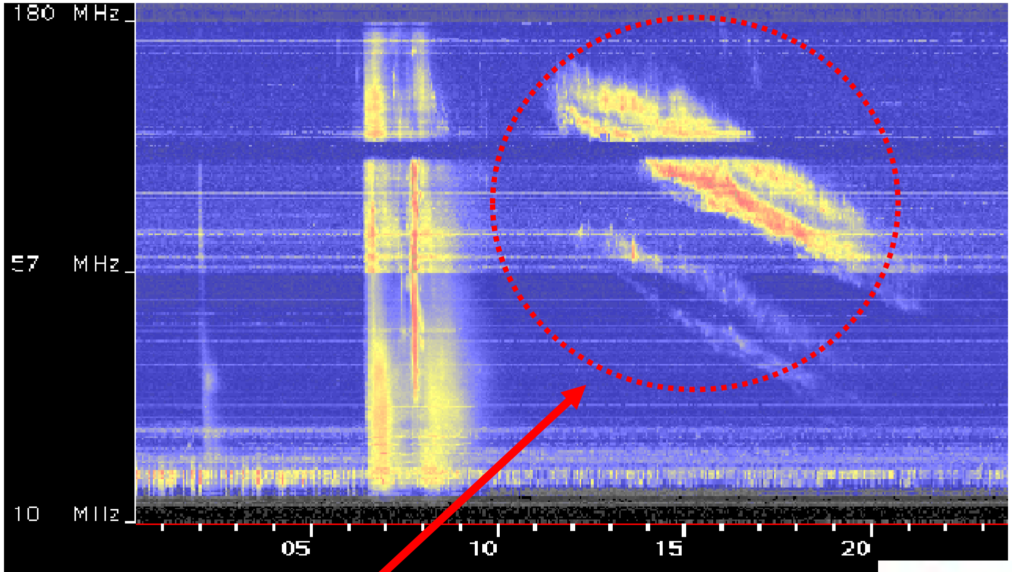


Radio emission is gyrosynchrotron from electrons trapped in weak-field structures:
→ electron energy distribution
→ magnetic field strength/direction
→ dynamic evolution of coronal structures

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

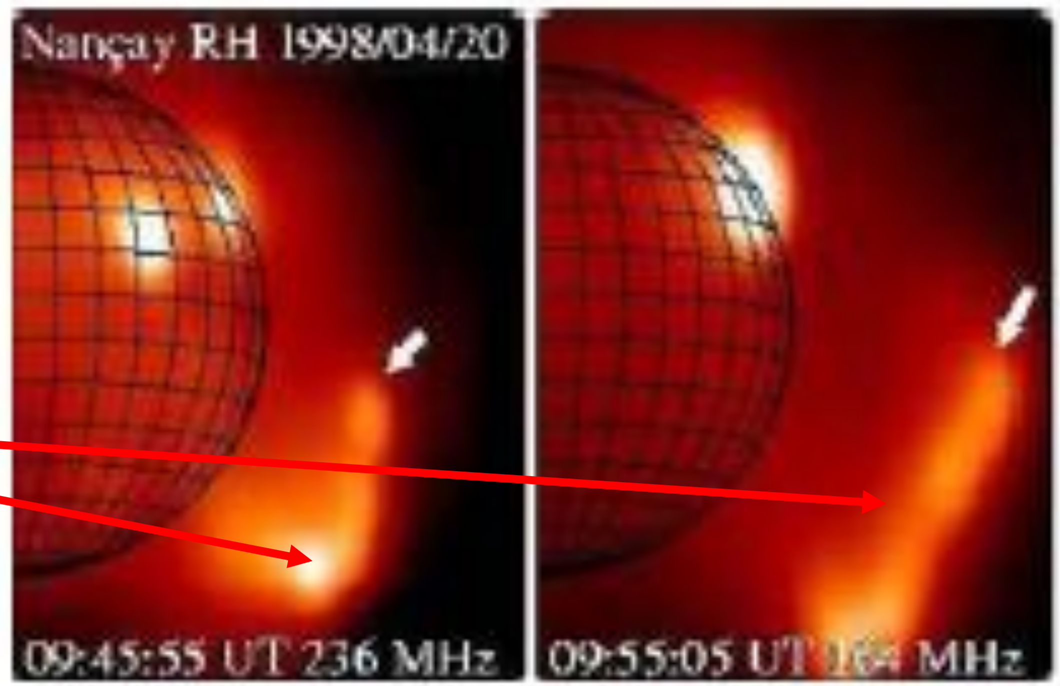
Key questions:
- What is CME/flare relationship?
- How do they develop and evolve into interplanetary disturbances?
- What are their effects on the surrounding solar/heliospheric plasma?

Type II bursts and shocks

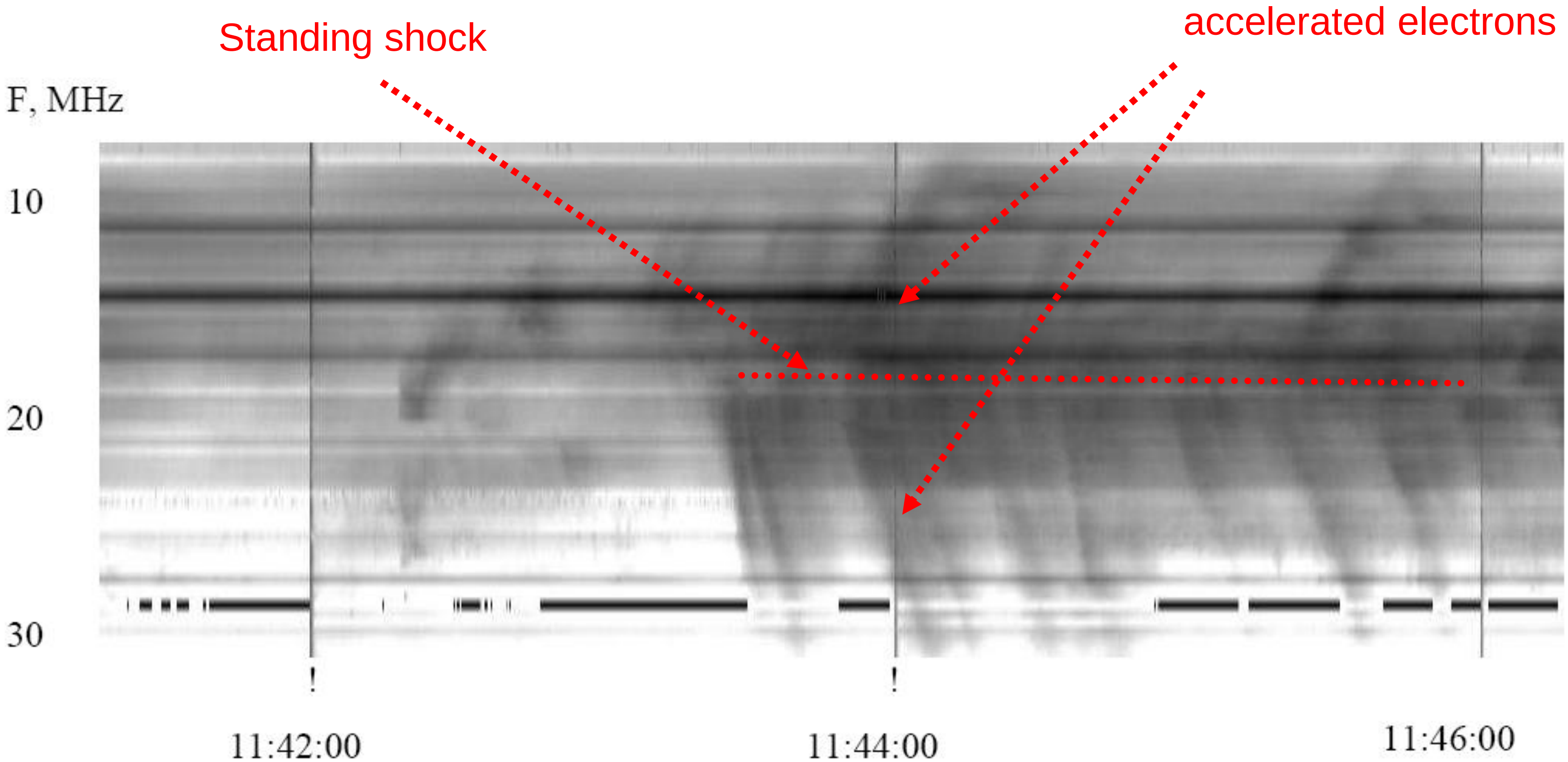


Formation and propagation of the shocks and CMEs

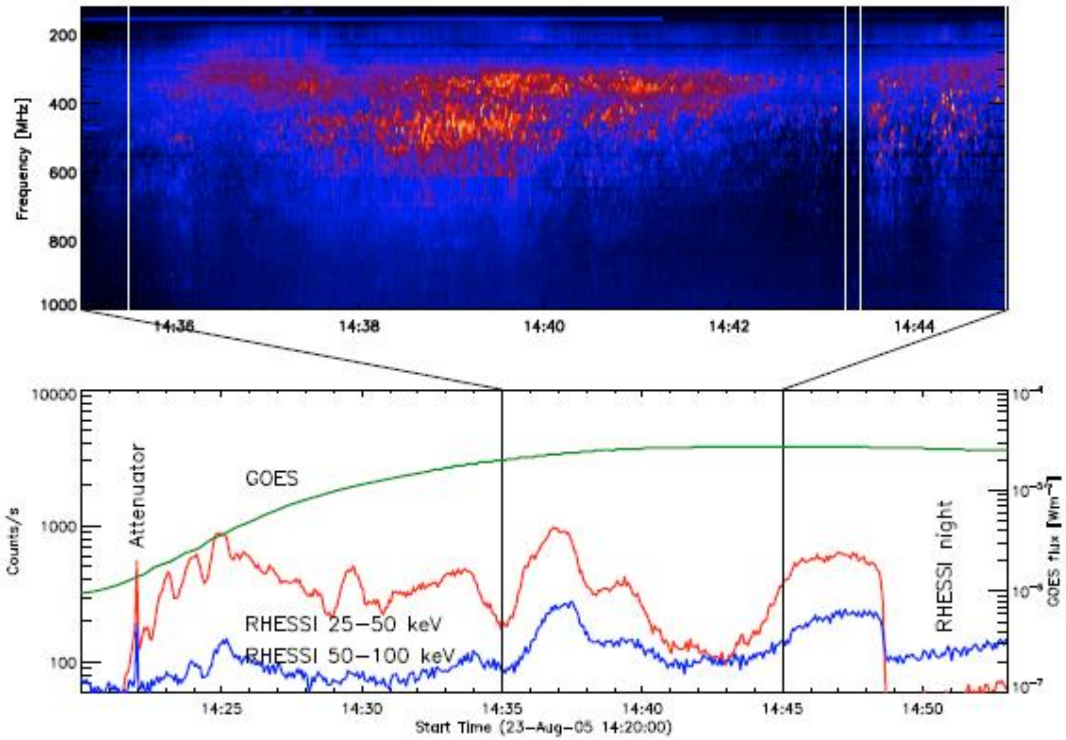
Type II radio burst ➔ prime diagnostic of outward-moving coronal shock waves



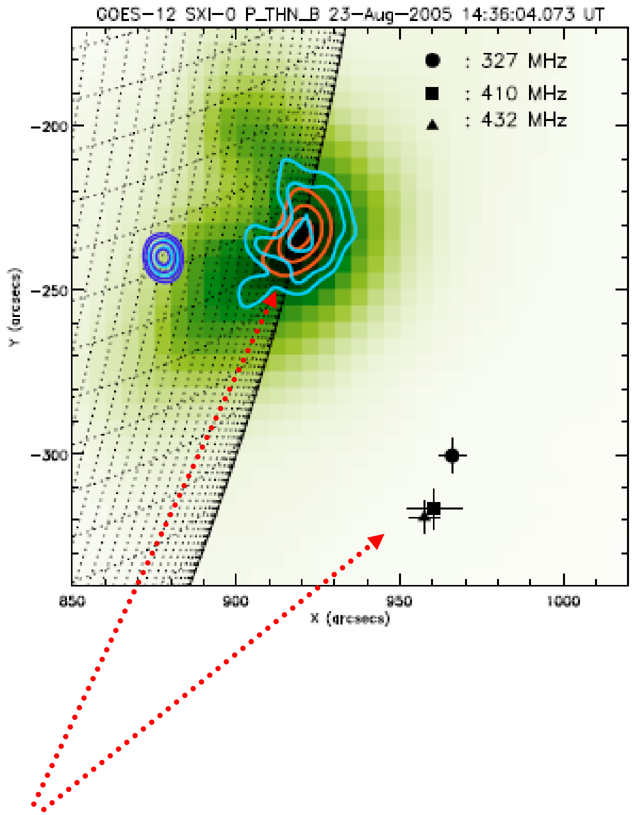
Type II with herring-bone structure: acceleration of electrons by shocks



Spikes



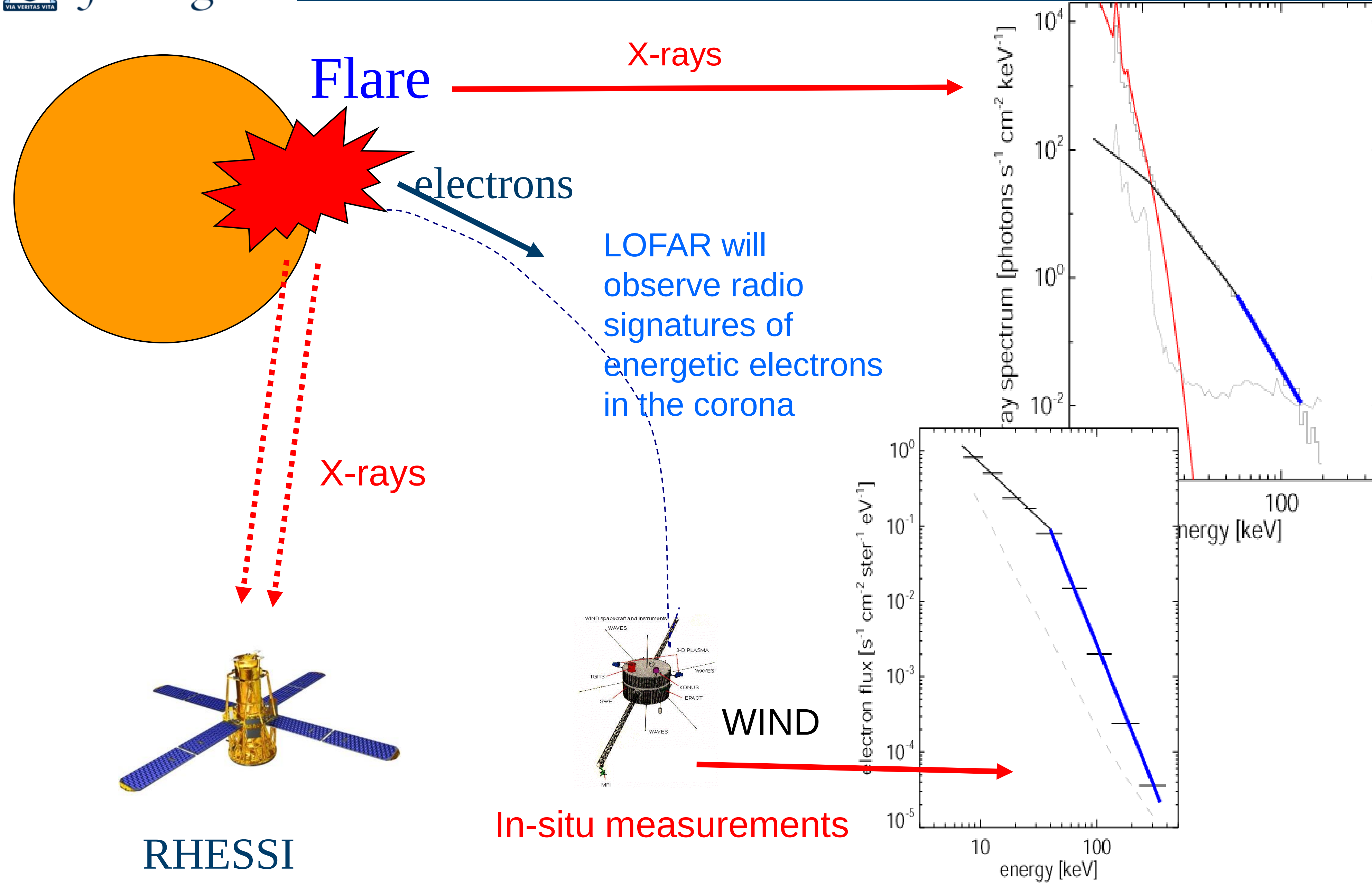
Battaglia and Benz, 2009



Note displacement from the flaring site

What is the nature of radio spikes and their relation to solar energetic particles?

Electrons from the Sun



The Sun and solar radio observations

Radio gives a unique insight into key questions in Solar and Solar-Terrestrial Physics:

- **solar atmosphere diagnostics (Temperature, density and magnetic field)**
- **particle acceleration and energy release during solar flares**
- **production and effects of CMEs, MHD waves, and shocks**
- **coronal heating**
- **‘Space Weather’ (the influence of the Sun on the heliosphere)**
- **and there are many radio observations we do not understand!**