ON EMISSION BY FAST PARTICLES IN STOCHASTIC MEDIA

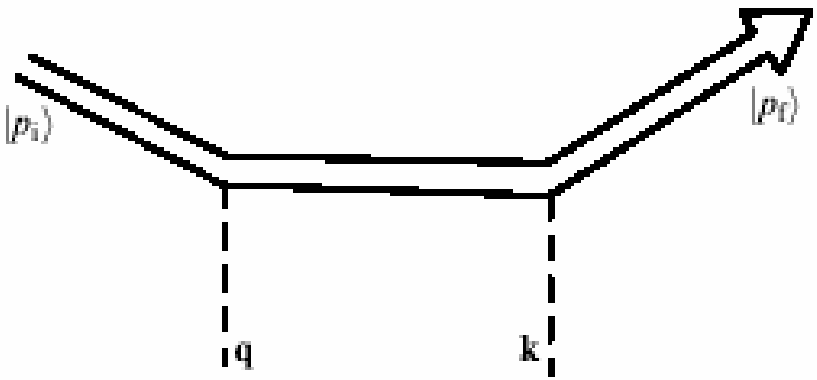
Gregory D.Fleishman

12 August 2004

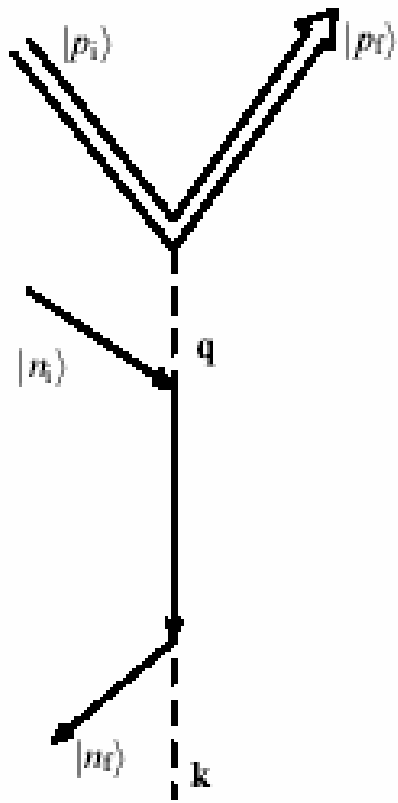
PPPL

Plan of the talk.

1. *Shake radiation*
2. *Transition radiation*
3. *Electron cyclotron maser emission*



а

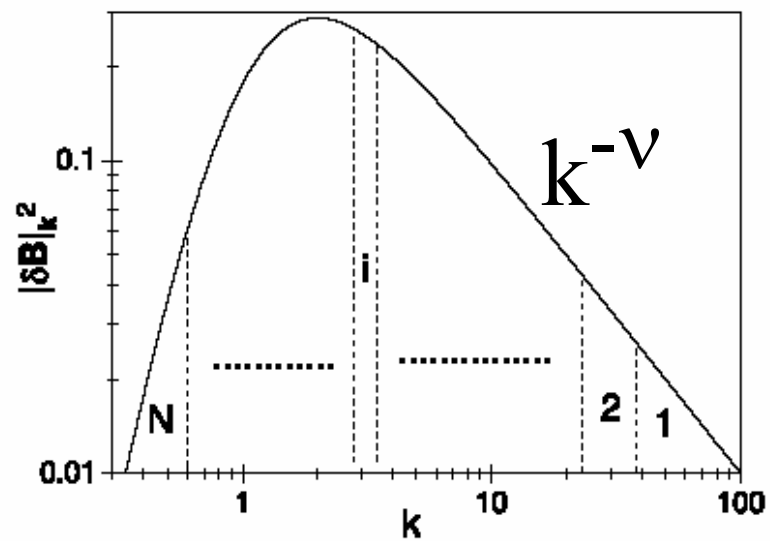


б

$$\mathbf{B}(\mathbf{r},t) = \mathbf{B}_0(\mathbf{r},t) + \mathbf{B}_{st}(\mathbf{r},t),$$

$$\mathbf{B}_0(\mathbf{r},t) =< \mathbf{B}(\mathbf{r},t) >,$$

$$< \mathbf{B}_{st}(\mathbf{r},t) >= 0,$$



$$K^{(2)}_{\alpha\beta}(\mathbf{r}_1,t_1,\mathbf{r}_2,t_2) =< B_{st,\alpha}(\mathbf{r}_1,t_1)B_{st,\beta}(\mathbf{r}_2,t_2) >$$

$$\mathcal{E}^{\sigma}_{\mathbf{n},\omega} = \frac{Q^2\omega^2 n_\sigma(\omega)}{4\pi^2 c^3} Re \int_{-T}^{T} dt \int_0^\infty d\tau e^{i\omega\tau} \left\langle e^{-i\mathbf{k}[\mathbf{r}(t+\tau)-\mathbf{r}(t)]}(\mathbf{e}^*_\sigma \cdot \mathbf{v}(t+\tau))(\mathbf{e}_\sigma \cdot \mathbf{v}(t))\right\rangle$$

$$\langle ... \rangle = \int d\mathbf{r} d\mathbf{p} d\mathbf{p}' (\mathbf{e}^*_\sigma \cdot \mathbf{v}')(\mathbf{e}_\sigma \cdot \mathbf{v}) F(\mathbf{r},\mathbf{p},t) W_{\mathbf{k}}(\mathbf{p},t;\mathbf{p}',\tau)$$

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

$$\mathbf{F}_L = \mathbf{F}_R + \mathbf{F}_{st}$$

$$f(\mathbf{r}, \mathbf{p}, t) = W(\mathbf{r}, \mathbf{p}, t) + \delta W(\mathbf{r}, \mathbf{p}, t)$$

$$\frac{\partial W}{\partial t} + \mathbf{v}\frac{\partial W}{\partial \mathbf{r}} + \mathbf{F}_R \frac{\partial W}{\partial \mathbf{p}} = -\left\langle \mathbf{F}_{st} \frac{\partial \delta W}{\partial \mathbf{p}} \right\rangle$$

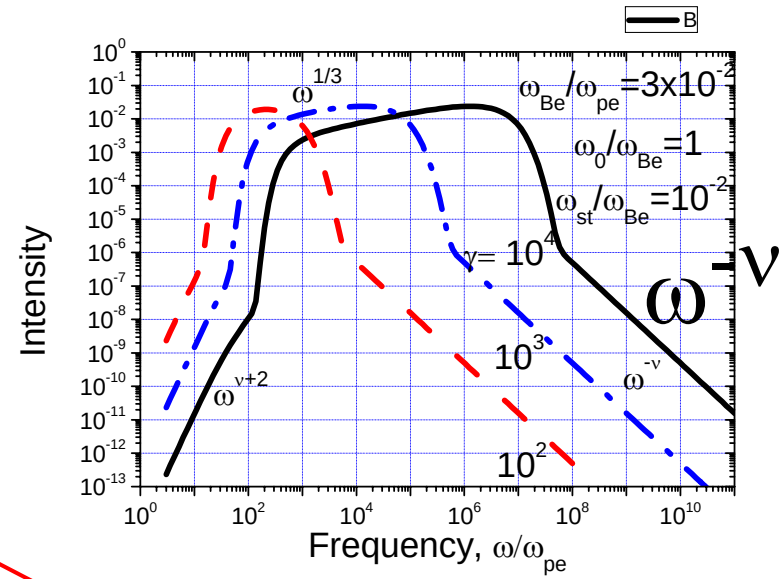
$$\frac{\partial W}{\partial t} + \mathbf{v}\frac{\partial W}{\partial \mathbf{r}} - (\mathbf{\Omega}\vec{\mathcal{O}})W =$$

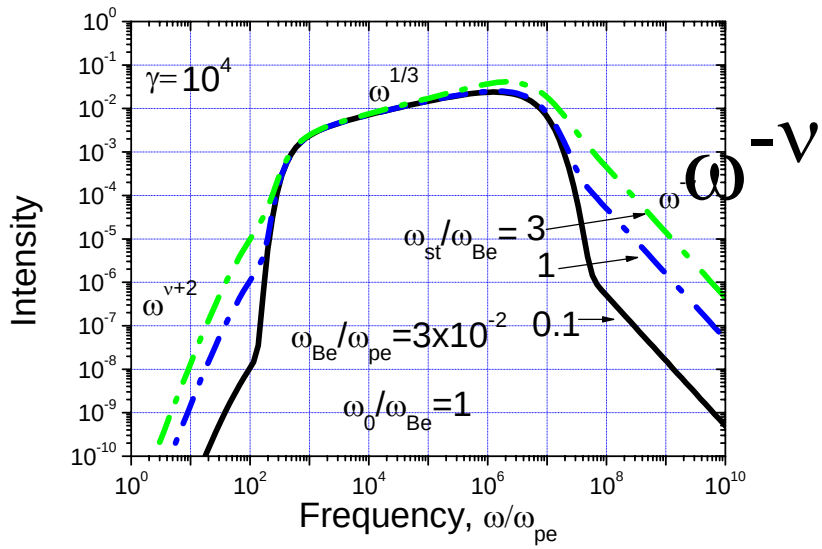
$$\vec{\mathcal{O}} = [\mathbf{v}\frac{\partial}{\partial \mathbf{v}}]$$

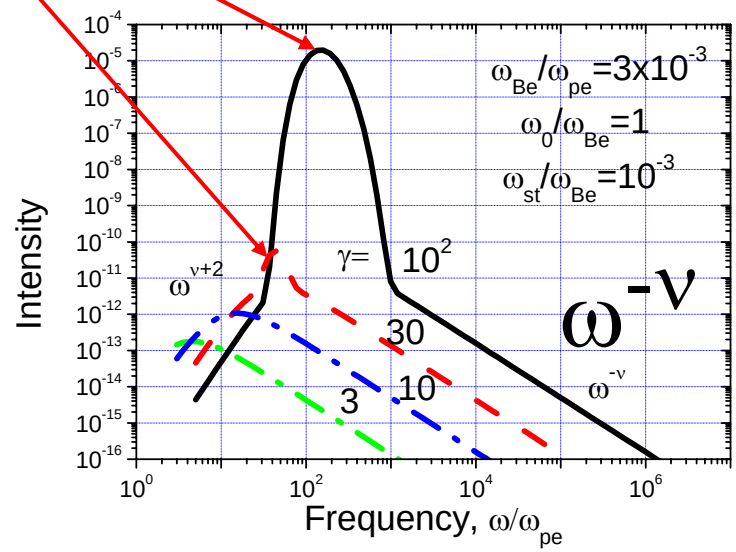
$$\frac{< B_{st}^2 >}{3}\left(\frac{Qc}{\mathcal{E}}\right)^2 \mathcal{O}^2 \int_0^\infty d\tau \psi(v\tau) W(\mathbf{r} - \mathbf{v}\tau, \mathbf{p}, t - \tau)$$

Radiation by a single electron in a dense plasma

$$I_\omega \approx \frac{3^{1/4}Q^2}{2\sqrt{\pi}c}\left(\frac{\omega_{pe}\omega_{B\perp}}{\gamma}\right)^{1/2}\exp\left(-\frac{\sqrt{3}\omega_{pe}}{\omega_{B\perp}\gamma}\right)$$



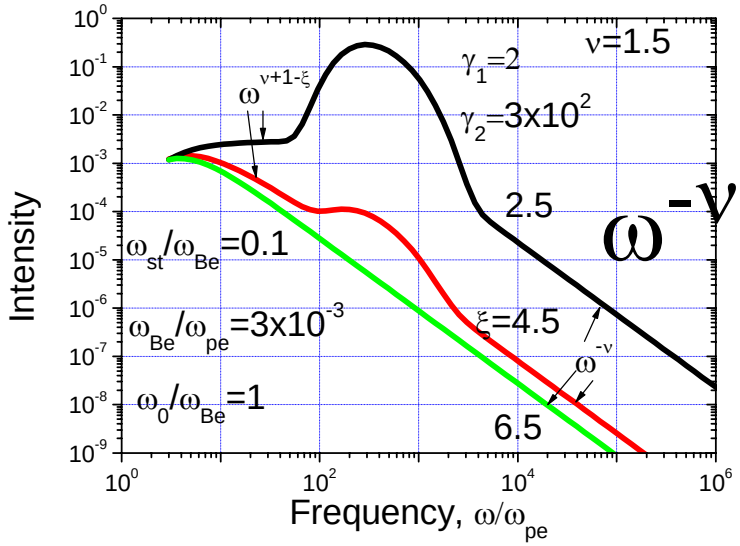


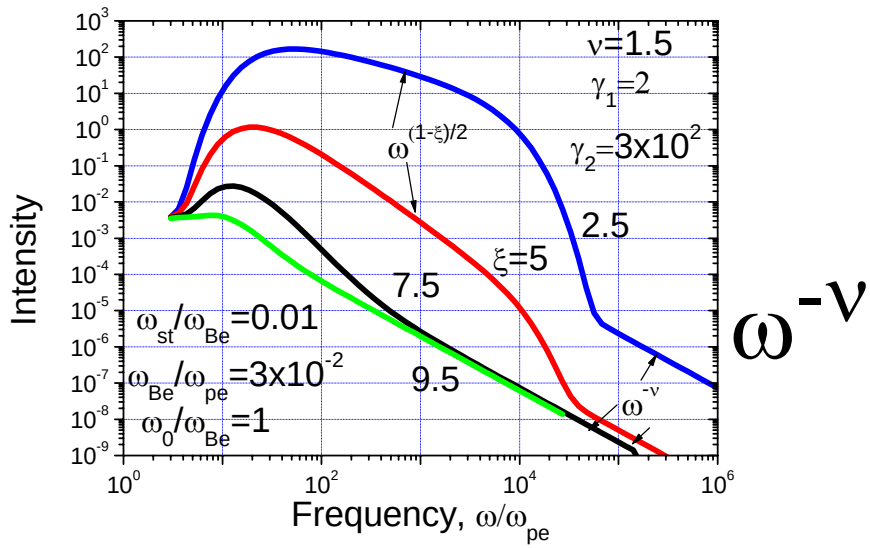


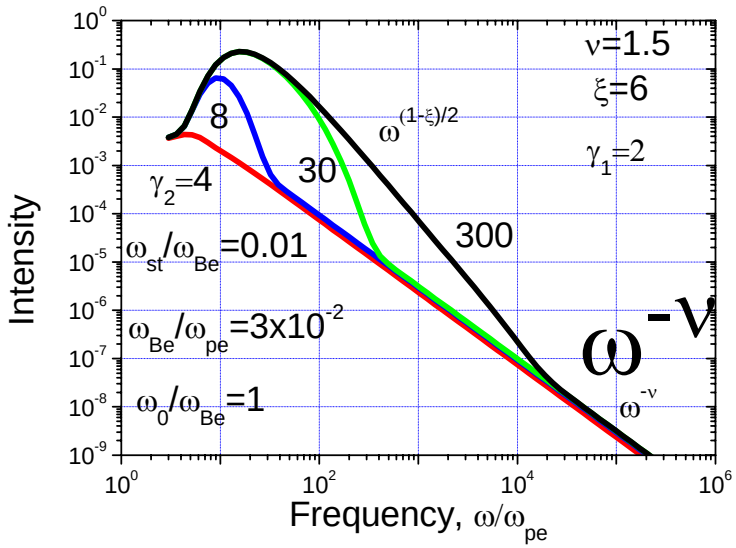
Radiation by an ensemble of electrons with a power-law spectrum

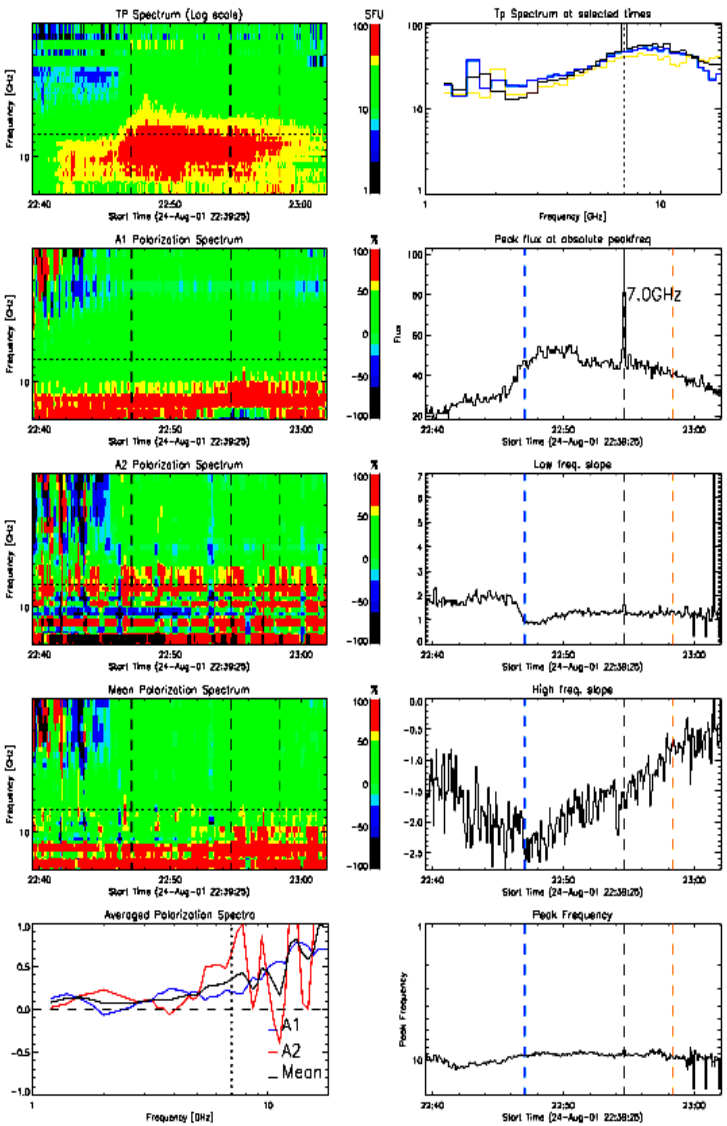
$$dN \sim E^{-\xi} dE, \quad E_1 < E < E_2$$

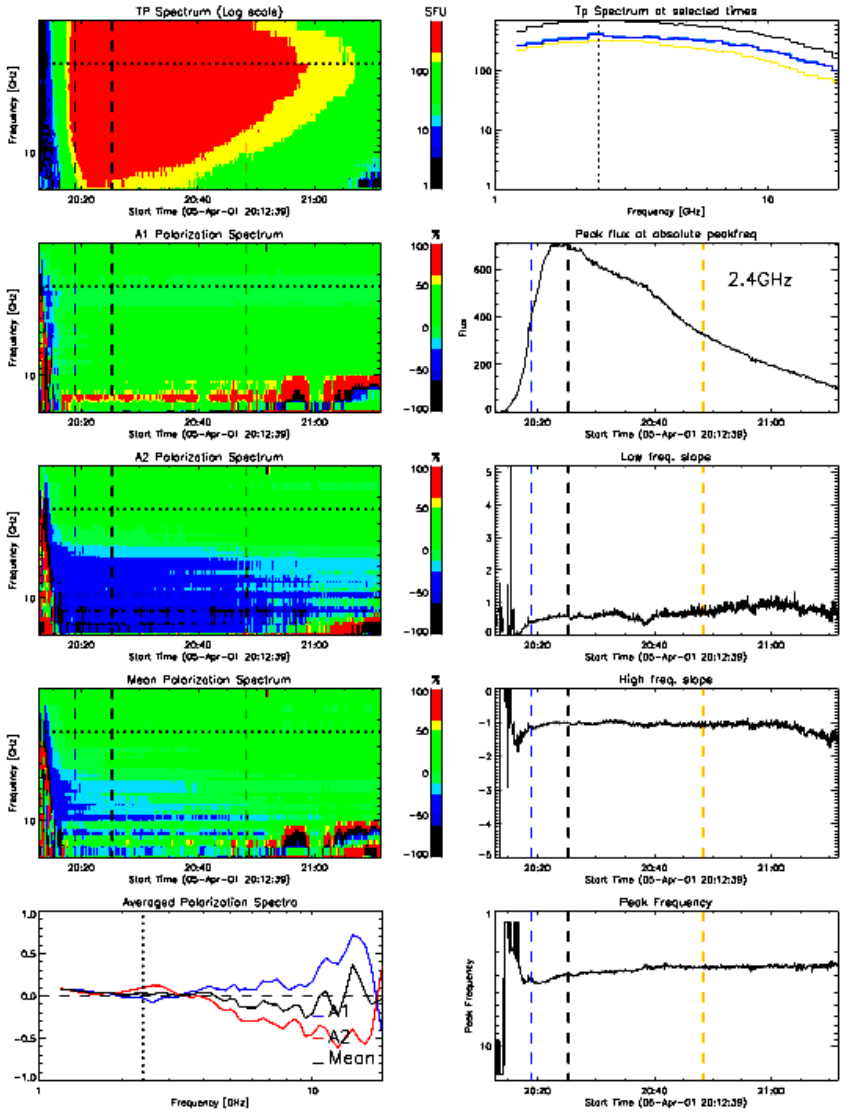
in a dense plasma








TP Spectrum (Log scale)
SFU
Tp Spectrum at selected times
Frequency [GHz]
Start Time (24-Aug-01 22:39:29)
A1 Polarization Spectrum
Peak flux at absolute peakfreq
7.0GHz
Flux
Start Time (24-Aug-01 22:38:26)
A2 Polarization Spectrum
Low freq. slope
Mean Polarization Spectrum
High freq. slope
Averaged Polarization Spectra
A1
A2
Mean
Peak Frequency


TP Spectrum (Log scale)
SFU
Tp Spectrum at selected times
Frequency [GHz]
Start Time (05-Apr-01 20:12:39)
A1 Polarization Spectrum
Peak flux at absolute peakfreq
2.4GHz
Flux
A2 Polarization Spectrum
Low freq. slope
Mean Polarization Spectrum
High freq. slope
Averaged Polarization Spectra
A1
A2
Mean
Peak Frequency

Transition Radiation

$$\mathbf{j}^m_{\omega,\mathbf{k}} = \frac{ie^2}{m\omega}\int d\mathbf{k}'\mathbf{E}^Q_{\omega,\mathbf{k}-\mathbf{k}'}\delta N_{\mathbf{k}'}$$

$$\mathcal{E}_{\mathbf{n},\omega} = (2\pi)^6\frac{\omega^2}{c^3}\varepsilon^{1/2}\left\langle \mid [\mathbf{n}\mathbf{j}^m_{\omega,\mathbf{k}}] \mid^2 \right\rangle$$

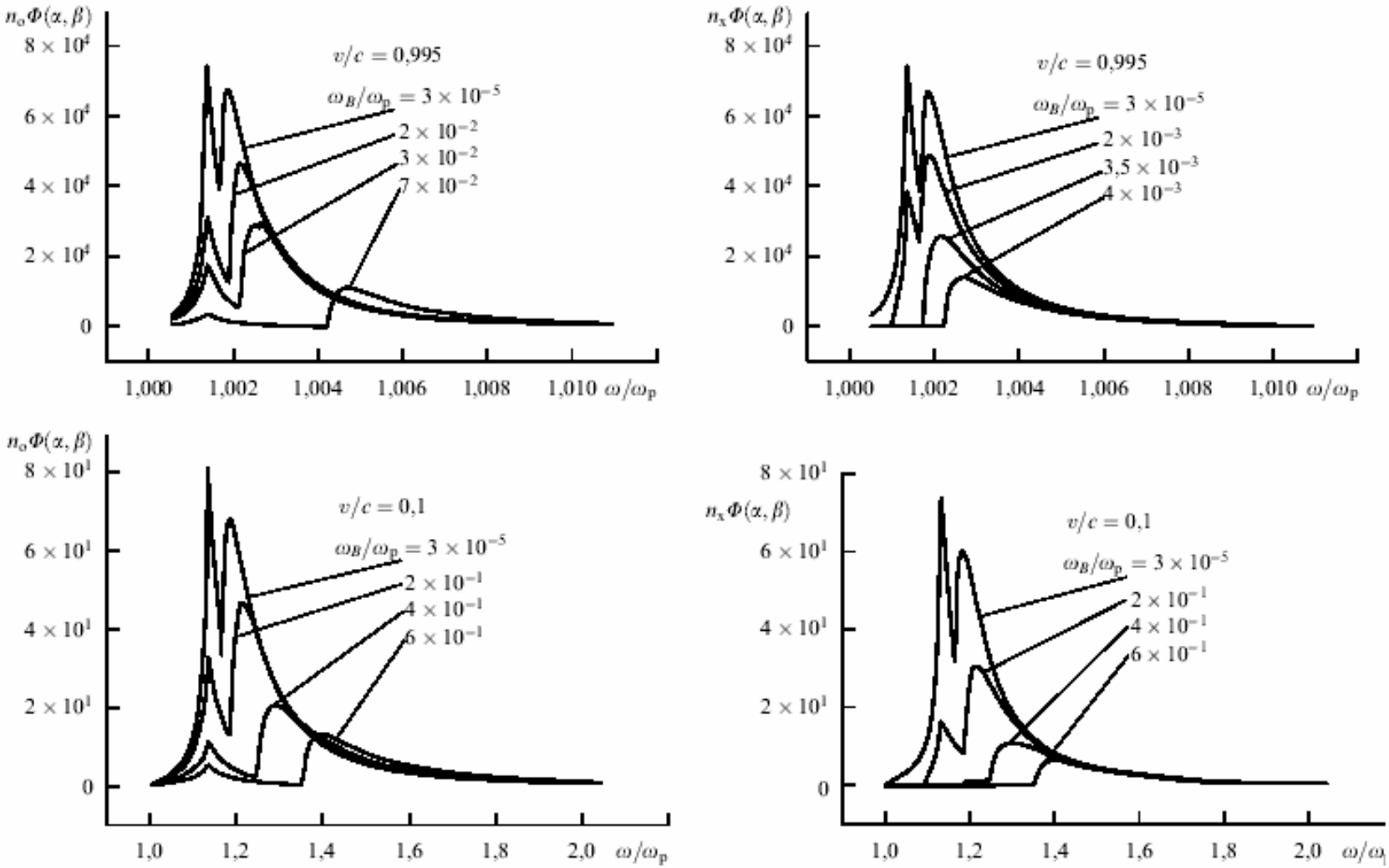
$$\mid \delta N \mid^2_{\mathbf{k}_1} = \frac{\nu-1}{4\pi}\frac{k_0^{\nu-1}\left\langle \Delta N^2 \right\rangle}{k_1^{\nu+2}}$$

$$I_{\mathbf{n},\omega} = \frac{8\pi e^4 Q^2}{m^2 c^3 \omega^2 \varepsilon^{3/2}} \int d\mathbf{k}' \mid \delta N \mid^2_{\mathbf{k}'} \frac{\left([\mathbf{nv}] + [\mathbf{nk}']\omega/k^2\right)^2}{[(\mathbf{k}-\mathbf{k}')^2/k^2 - 1]^2} \delta[\omega - (\mathbf{k}-\mathbf{k}')\mathbf{v}]$$

$$I^R_{\mathbf{n},\omega} = \frac{8\pi e^4 Q^2 \varepsilon^{1/2}}{m^2 c^3} \int k'^2 dk' \frac{[\mathbf{nk}']^2 \delta[\omega - (\mathbf{k}-\mathbf{k}')\mathbf{v}] \mid \delta N \mid^2_{\mathbf{k}'} d\varphi \mathrm{d}\cos\vartheta}{(\mathbf{k}-\mathbf{k}')^4 [(\varepsilon(\omega) - 3(\mathbf{k}-\mathbf{k}')^2 d^2)^2 + \varepsilon''^2]}$$

$$I^{R,\sigma}_{\mathbf{n},\omega} = \frac{4\pi e^4 Q^2 n_\sigma}{m^2 c^3} \int d^3 k' \frac{[\mathbf{nk}']^2 \delta[\omega - (\mathbf{k}-\mathbf{k}')\mathbf{v}] \mid \delta N \mid^2_{\mathbf{k}'}}{(\mathbf{k}-\mathbf{k}')^4 [(\varepsilon(\omega) - 3(\mathbf{k}-\mathbf{k}')^2 d^2 - \frac{\omega^2_{pe}\omega^2_{Be}}{\omega^4}\sin^2\theta)^2 + \varepsilon''^2]}$$

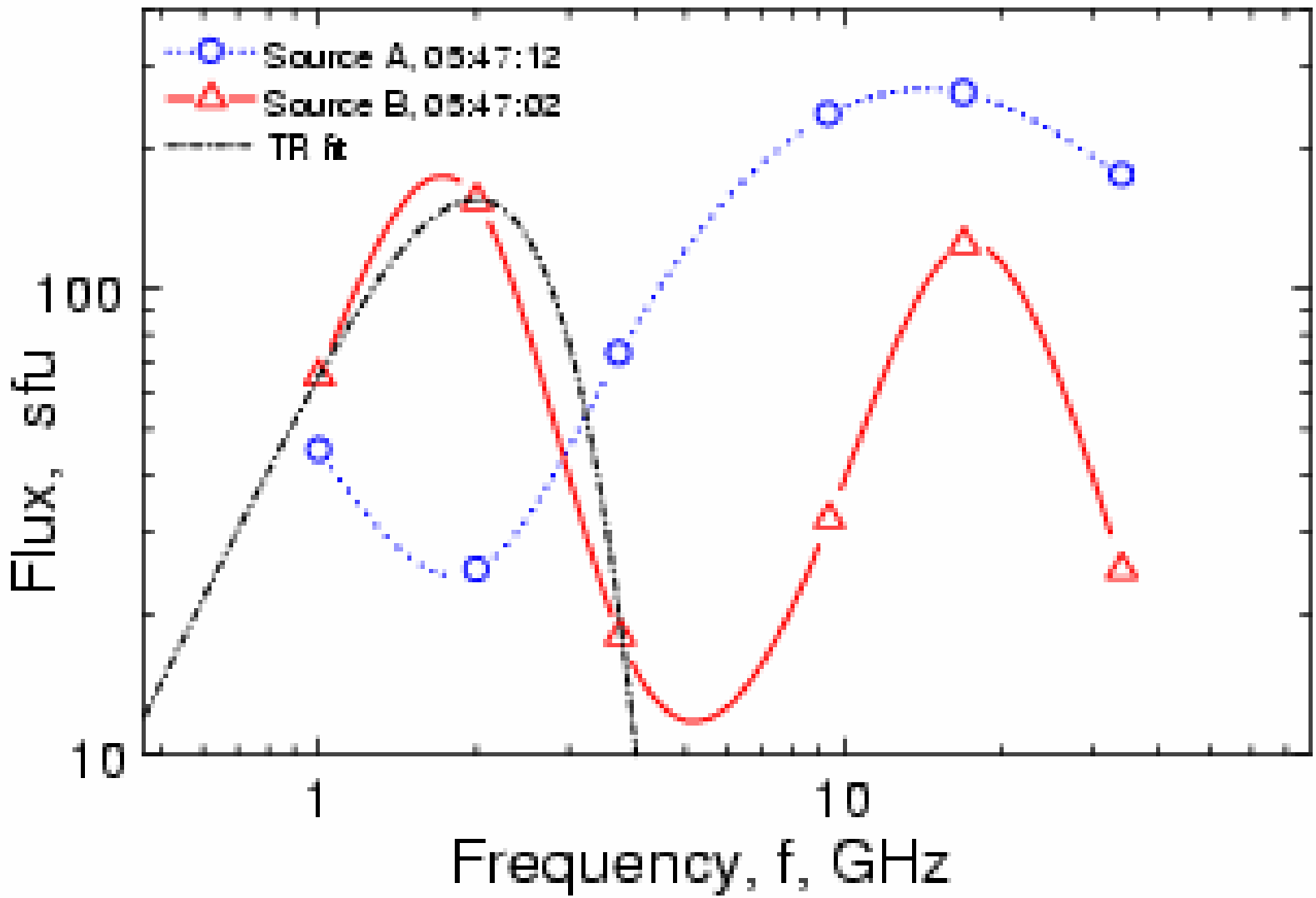
$$I^{R,\sigma}_{\mathbf{n},\omega} = \frac{\pi e^4 Q^2 n_\sigma}{3 v m^2 c^3} \left\langle \Delta N^2 \right\rangle k_o \left(\frac{v}{\omega}\right)^4 \Phi$$

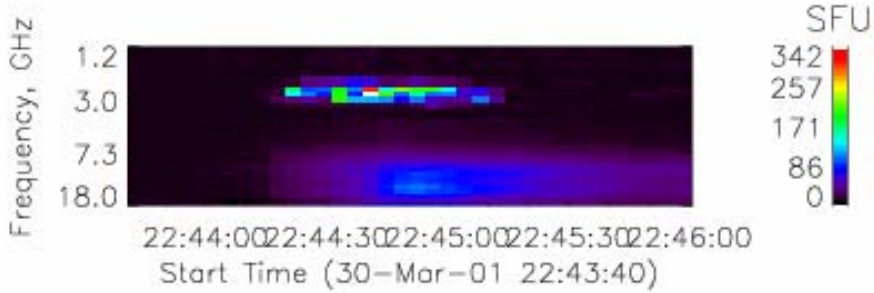

$n_o\Phi(\alpha,\beta)$
8×10^4
6×10^4
4×10^4
2×10^4
0
$v/c = 0{,}995$
$\omega_B/\omega_p = 3\times10^{-5}$
2×10^{-2}
3×10^{-2}
7×10^{-2}
1,000 1,002 1,004 1,006 1,008 1,010 ω/ω_p
$n_x\Phi(\alpha,\beta)$
8×10^4
6×10^4
4×10^4
2×10^4
0
$v/c = 0{,}995$
$\omega_B/\omega_p = 3\times10^{-5}$
2×10^{-3}
$3{,}5\times10^{-3}$
4×10^{-3}
1,000 1,002 1,004 1,006 1,008 1,010 ω/ω_p
$n_o\Phi(\alpha,\beta)$
8×10^1
6×10^1
4×10^1
2×10^1
0
$v/c = 0{,}1$
$\omega_B/\omega_p = 3\times10^{-5}$
2×10^{-1}
4×10^{-1}
6×10^{-1}
1,0 1,2 1,4 1,6 1,8 2,0 ω/ω_p
8×10^1
$n_x\Phi(\alpha,\beta)$
6×10^1
4×10^1
2×10^1
0
$v/c = 0{,}1$
$\omega_B/\omega_p = 3\times10^{-5}$
2×10^{-1}
4×10^{-1}
6×10^{-1}
1,0 1,2 1,4 1,6 1,8 2,0 ω/ω

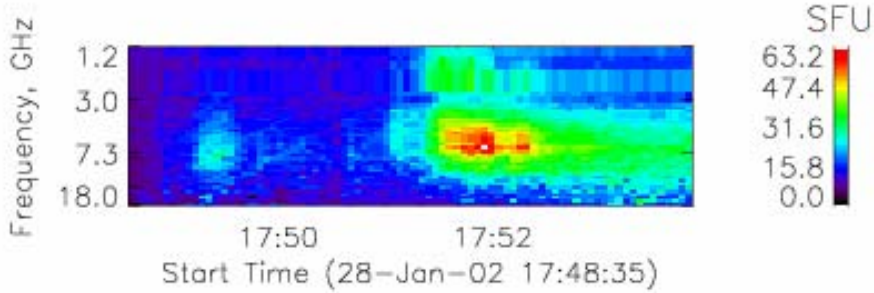
RTR PROPERTIES

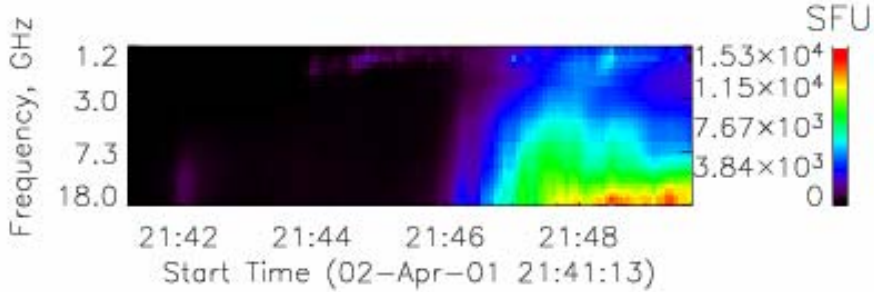
(Platonov & Fleishman, Physics – Uspekhi, 2002)

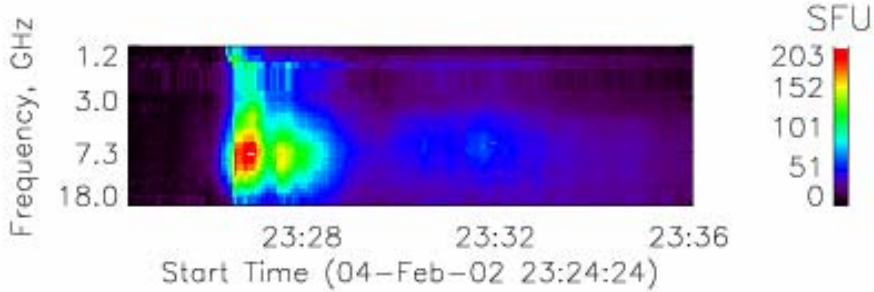
- Originates in a dense plasma, $f_{pe} >> f_{Be}$.
- O-polarization, possibly – strong.
- High-frequency slope does not depend on the fast electron spectral index.
- Originates at lower frequencies than GSE.
- Intensity is proportional to the total number of fast electrons in the range E ~ 10-100 keV.

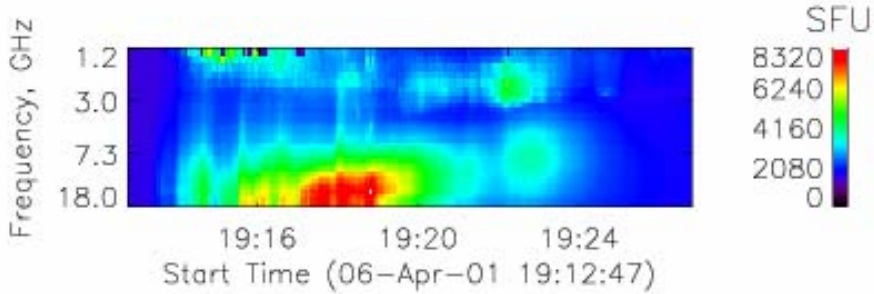

Source A, 05:47:12
Source B, 05:47:02
TR fit
100
10
Flux, sfu
1
10
Frequency, f, GHz

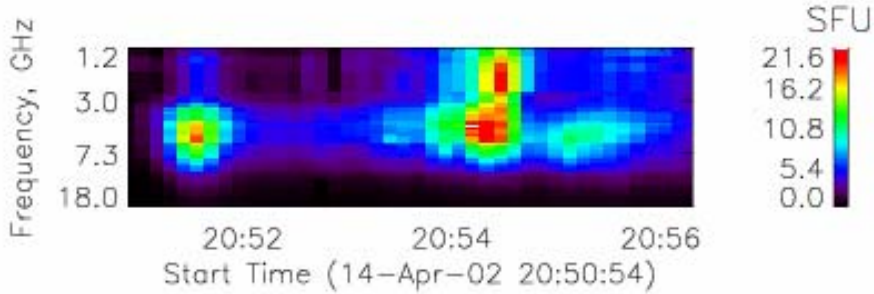

SFU
342
257
171
86
0
Frequency, GHz
1.2
3.0
7.3
18.0
22:44:00 22:44:30 22:45:00 22:45:30 22:46:00
Start Time (30−Mar−01 22:43:40)

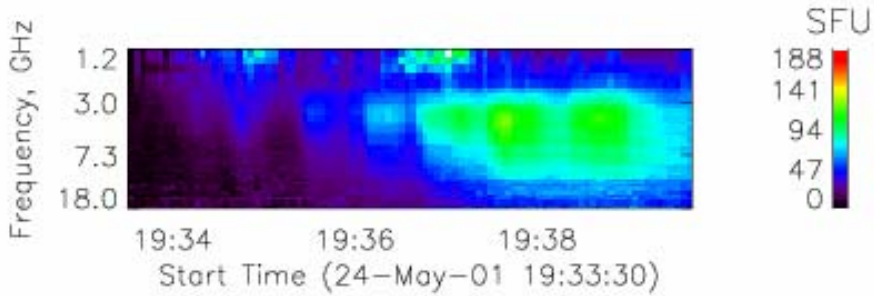

SFU
63.2
47.4
31.6
15.8
0.0
Frequency, GHz
1.2
3.0
7.3
18.0
17:50 17:52
Start Time (28−Jan−02 17:48:35)

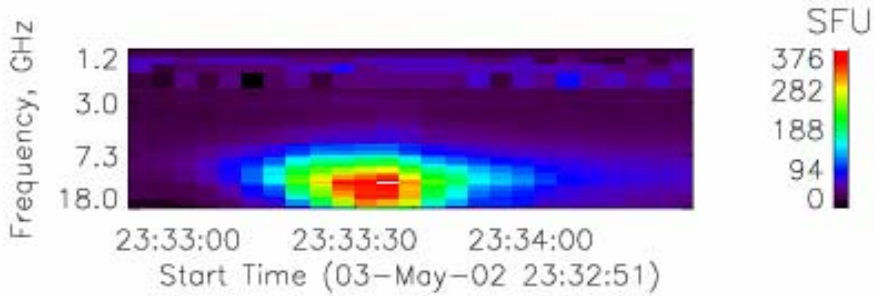

SFU
1.53×10⁴
1.15×10⁴
7.67×10³
3.84×10³
0
Frequency, GHz
1.2
3.0
7.3
18.0
21:42 21:44 21:46 21:48
Start Time (02−Apr−01 21:41:13)


SFU
203
152
101
51
0
Frequency, GHz
1.2
3.0
7.3
18.0
23:28 23:32 23:36
Start Time (04−Feb−02 23:24:24)


SFU
8320
6240
4160
2080
0
Frequency, GHz
1.2
3.0
7.3
18.0
19:16 19:20 19:24
Start Time (06−Apr−01 19:12:47)


SFU
21.6
16.2
10.8
5.4
0.0
Frequency, GHz
1.2
3.0
7.3
18.0
20:52 20:54 20:56
Start Time (14−Apr−02 20:50:54)


SFU
188
141
94
47
0
Frequency, GHz
1.2
3.0
7.3
18.0
19:34 19:36 19:38
Start Time (24−May−01 19:33:30)


SFU
376
282
188
94
0
Frequency, GHz
1.2
3.0
7.3
18.0
23:33:00 23:33:30 23:34:00
Start Time (03−May−02 23:32:51)

Observed Properties of dm Continuum Bursts

(Nita, this workshop)

1. The decimetric emission has a relatively smooth dynamic spectrum, comparable with its centimetric counterpart.

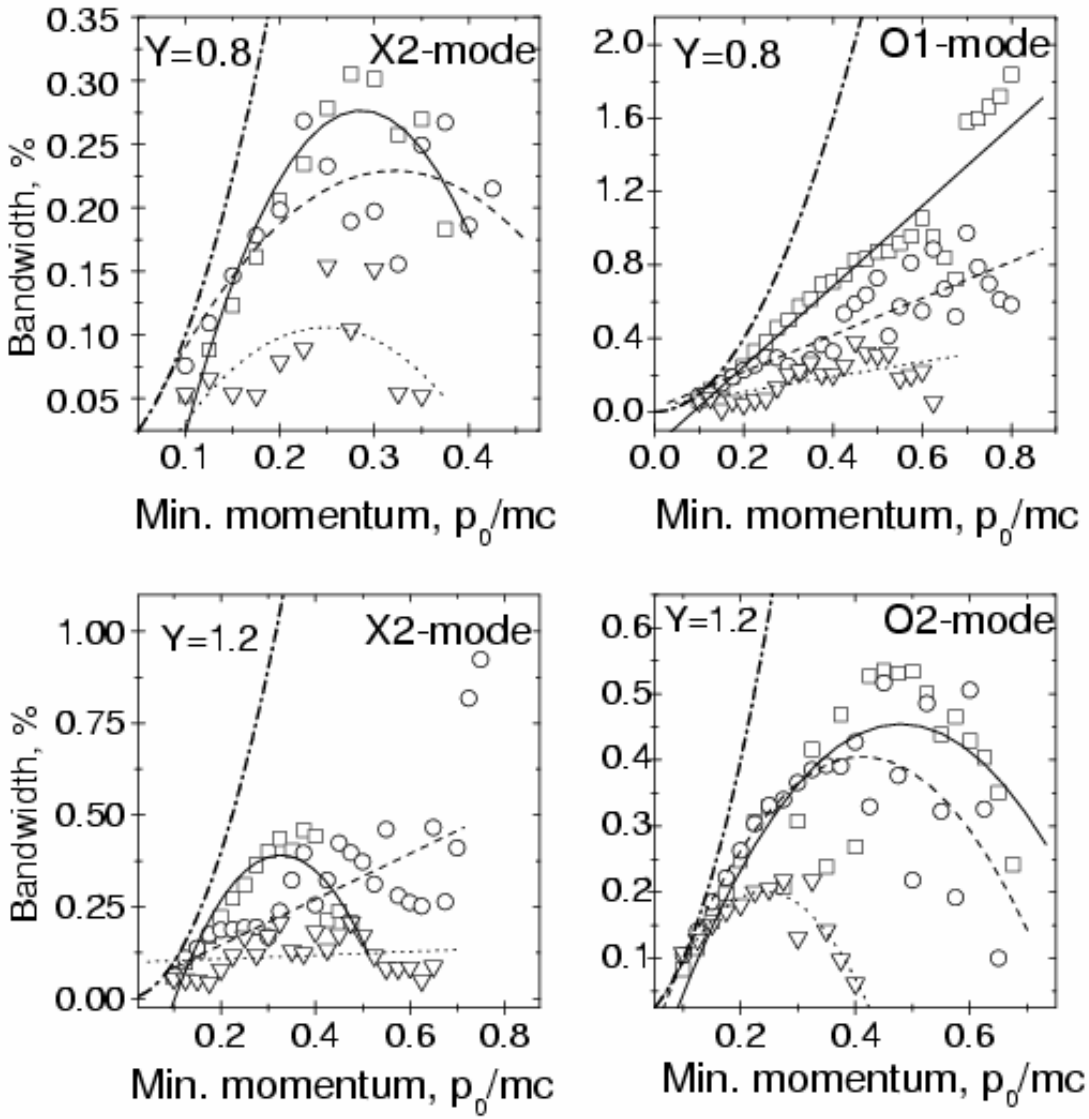
2. The decimetric components generally display a *high degree of circular polarization*, sometimes as high as 100%, which we infer to be of *o-mode*.

3. A high plasma density, of about 10^{10} -$10^{11} cm^{-3}$, at least at the GS source site, which implies a *high plasma to gyro frequency ratio*.

4. The decimetric and centimetric radio fluxes depend linearly on the number of accelerated electrons belonging to the same population, *provided that both radiations are* ***produced by incoherent emission processes***.

5. The *dm emission is proportional with the number of low-energy electrons*, while the cm emission is proportional with the number of the high-energy ones.

Natural bandwidth of the emission peak.



$0.1(p_0/mc)^2$

$\theta_c = 45^o, 60^o, 75^o$

Broadening of the peak due to random inhomogeneities

(Fleishman, ApJ 2004)

$$I = I_0 \left\langle \int d\mathbf{r}_\perp \exp\left(\int dz \varkappa_\sigma(\mathbf{r}) \right) \right\rangle$$

$$\varkappa_\sigma = \varkappa_\sigma^m(0) \left\{ A_0 + A_1 \frac{\delta B}{B} + A_2 \left(\frac{\delta B}{B} \right)^2 \right\}$$

$$A_0 = (1 - \alpha(s - s_0)^2)$$

$$A_1 = \lambda + 2\alpha s_0 (1 + \epsilon)(s - s_0) + 2\alpha(2 - \lambda)(s - s_0)^2$$

$$A_2 = -\alpha s_0^2 (1 + \epsilon)^2 + \alpha s_0 (1 + \epsilon)(\epsilon - 2(2 - \lambda))(s - s_0)$$

$$\langle \exp(AX) \rangle = \exp\left(A^2 \langle X^2 \rangle / 2 \right)$$

Broadening of the peak due to random inhomogeneities

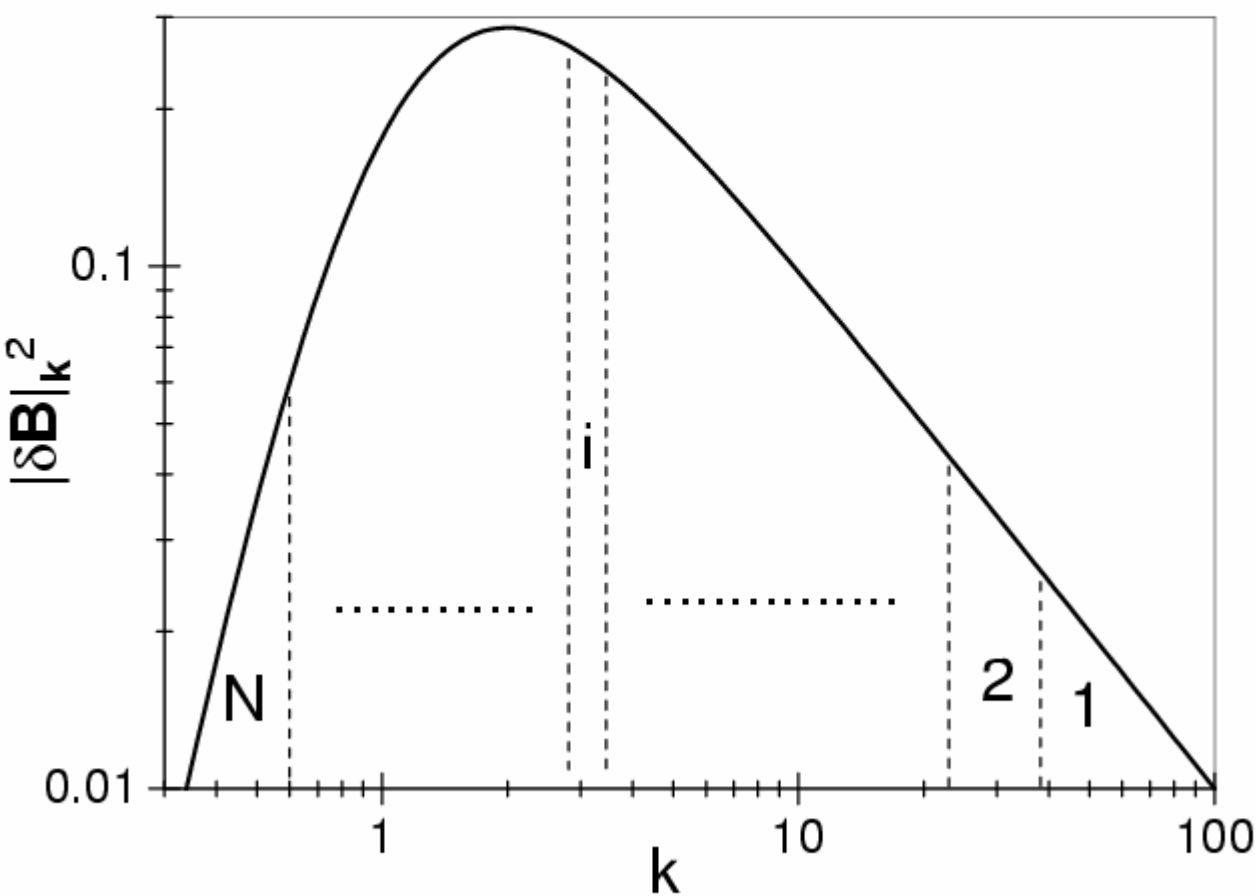
$$I = I_m \exp\left\{-(1-\Delta_{st})\frac{(s-s_0-\Delta s_0)^2}{2\Gamma_0^2}\right\}$$

$$\Delta_{st} = 2(1+\epsilon)^2 s_0^2 \alpha \tau_0 \frac{\langle \delta B^2 \rangle}{B^2}$$

$$\int_{k_i}^{k_{i+1}} |\delta B|_{\mathbf{k}}^2 d\mathbf{k} = \delta B_i^2$$

$$\sum_{i=1}^{N} \delta B_i^2 = \delta B^2, \quad \delta B_i^2 \ll \delta B^2 \text{ if } N \gg 1$$

Broadening of the peak due to random inhomogeneities



Broadening of the peak due to random inhomogeneities

$$I = I_m \exp\left\{ -\frac{(s - s_0 - \Delta s_p)^2}{2\Gamma_0^2} \prod_{i=1}^{N} (1 - \Delta_{st,i}) \right\}$$

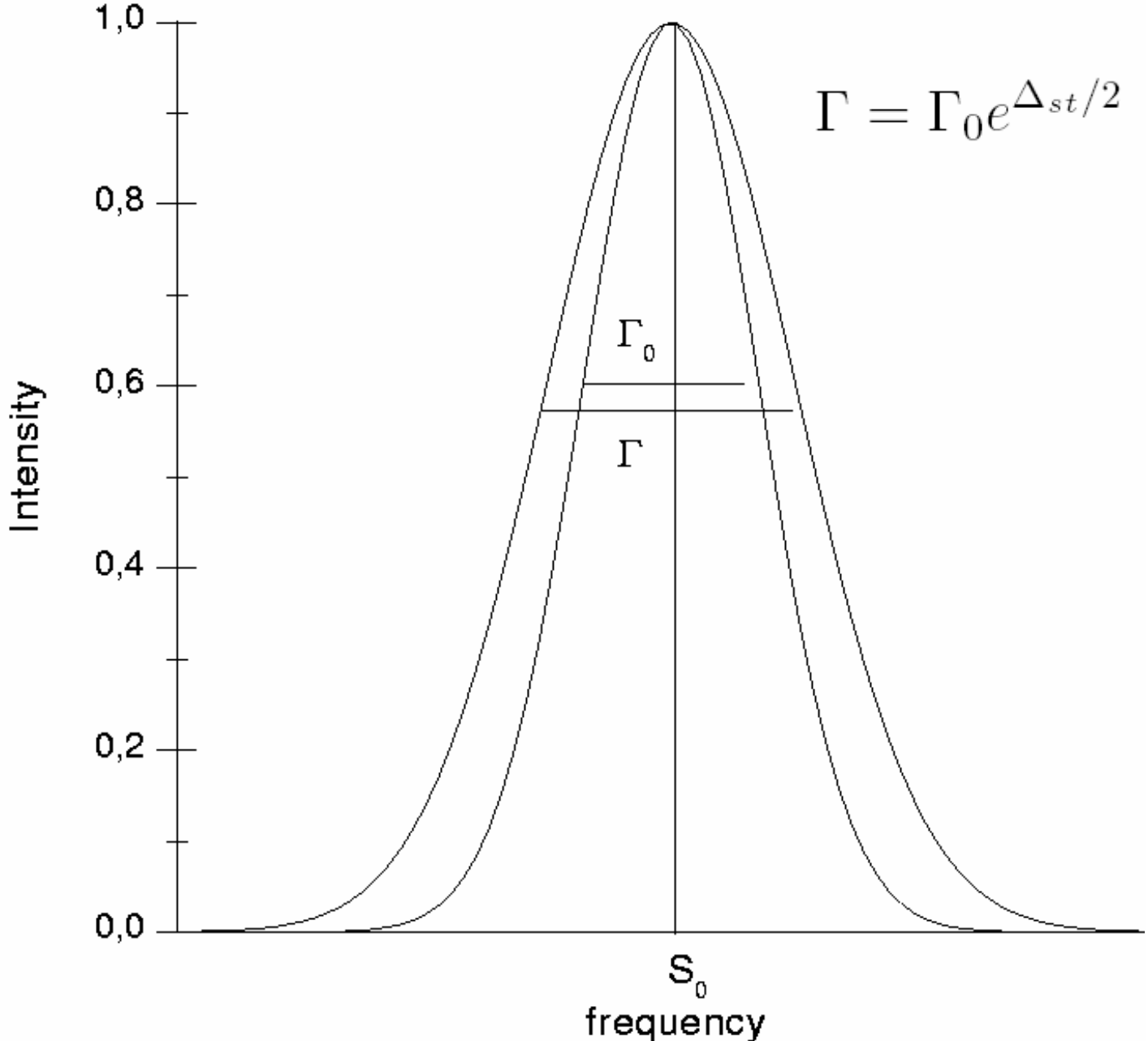
$$\Delta_{st,i} = \frac{\Delta_{st}}{N}$$

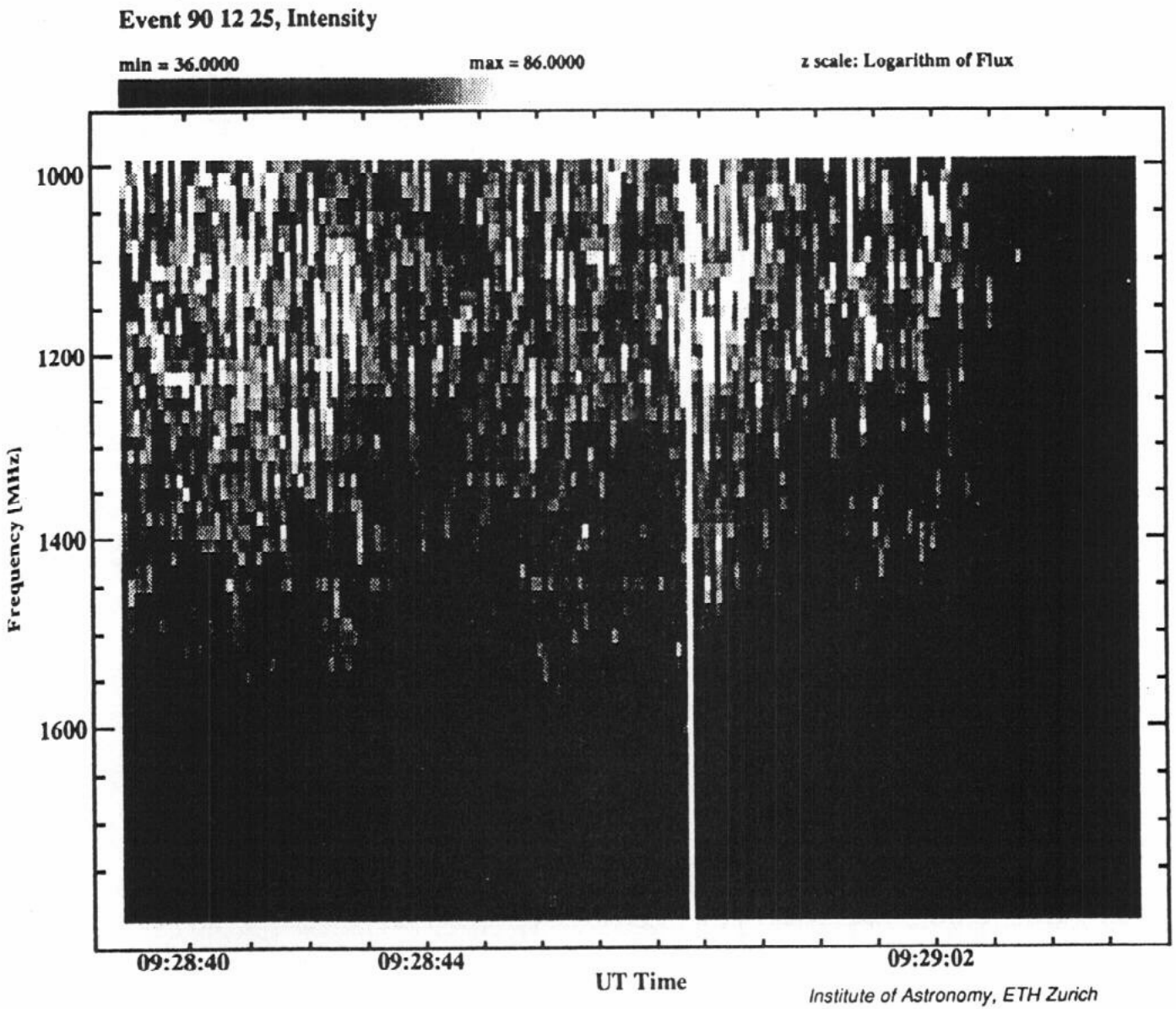
$$\lim_{N\to\infty} \prod_{i=1}^{N} (1 - \Delta_{st}/N) = \lim_{N\to\infty} \left(1 - \frac{\Delta_{st}}{N}\right)^N = \exp(-\Delta_{st})$$

$$I = I_m \exp\left\{ -e^{-\Delta_{st}} \frac{(s - s_0 - \Delta s_p)^2}{2\Gamma_0^2} \right\}$$

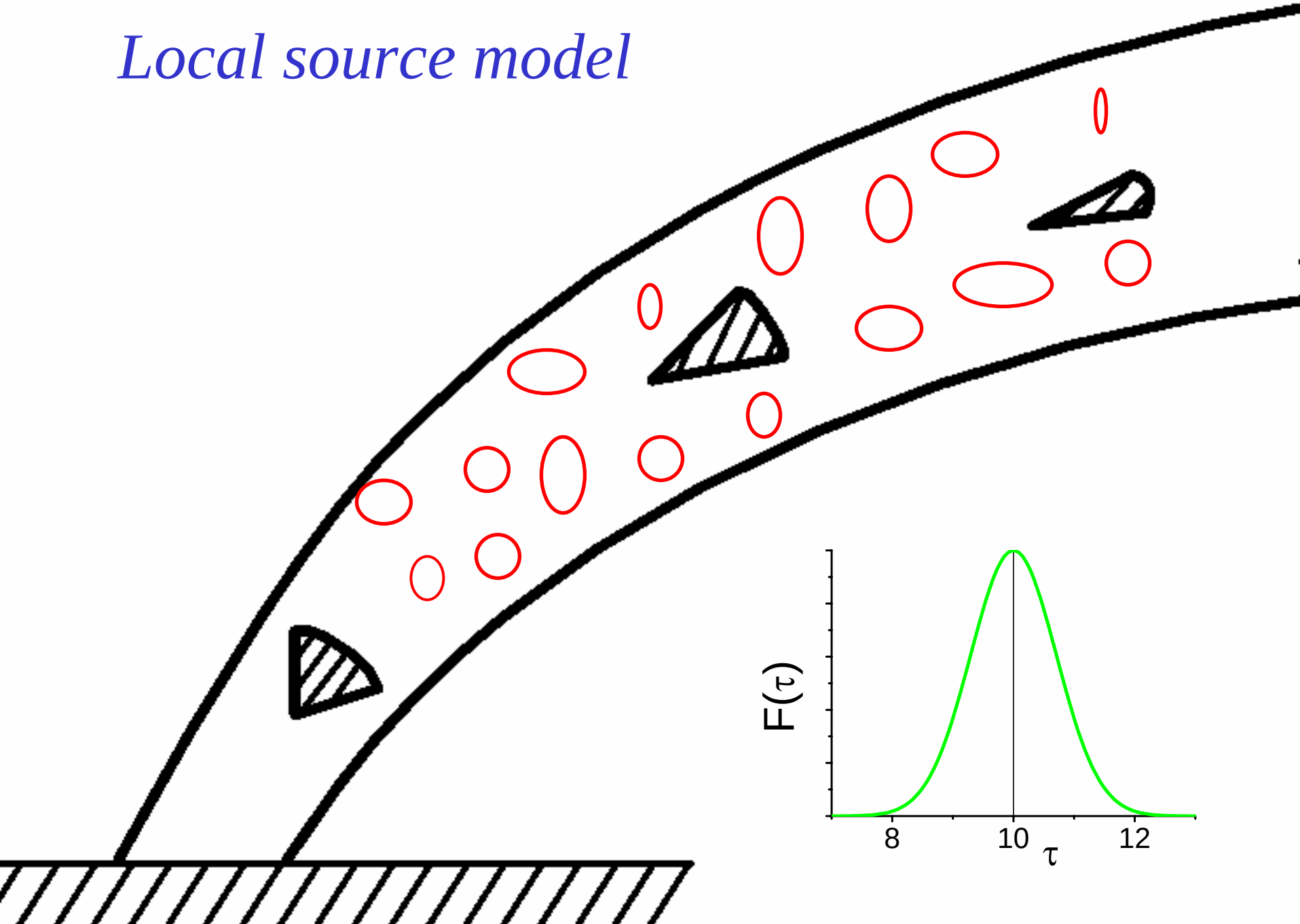
$$\Gamma = \Gamma_0 e^{\Delta_{st}/2}$$

Broadening of the peak due to random inhomogeneities

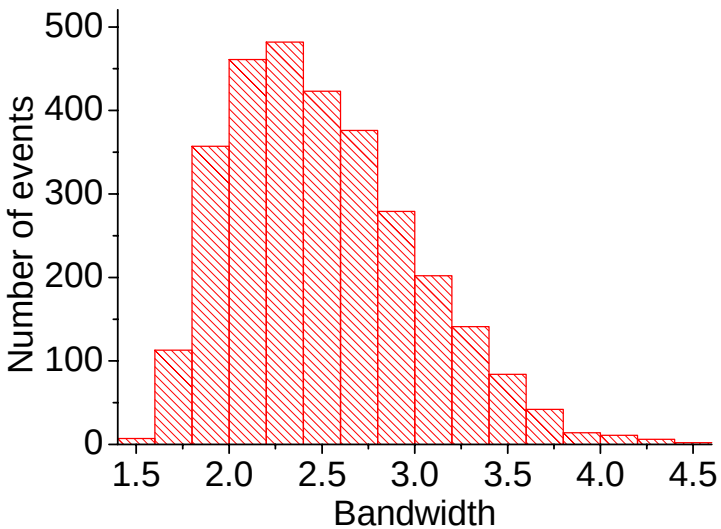


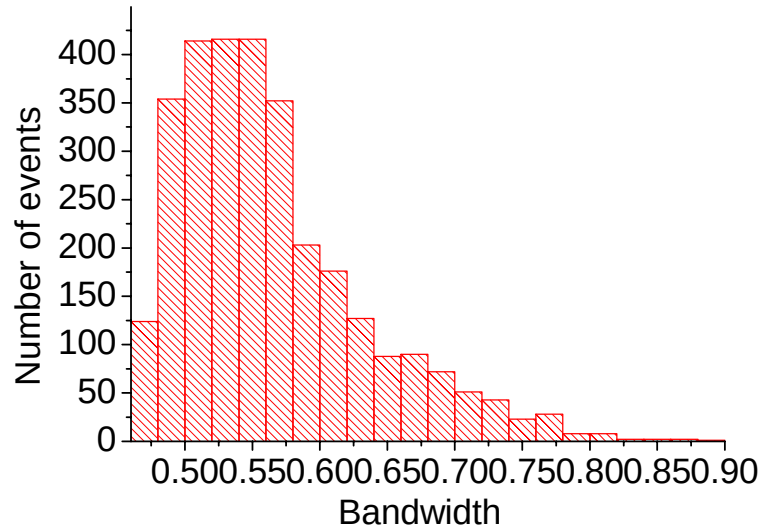

Event 90 12 25, Intensity
min = 36.0000
max = 86.0000
z scale: Logarithm of Flux
1000
1200
1400
1600
Frequency [MHz]
09:28:40
09:28:44
09:29:02
UT Time
Institute of Astronomy, ETH Zurich

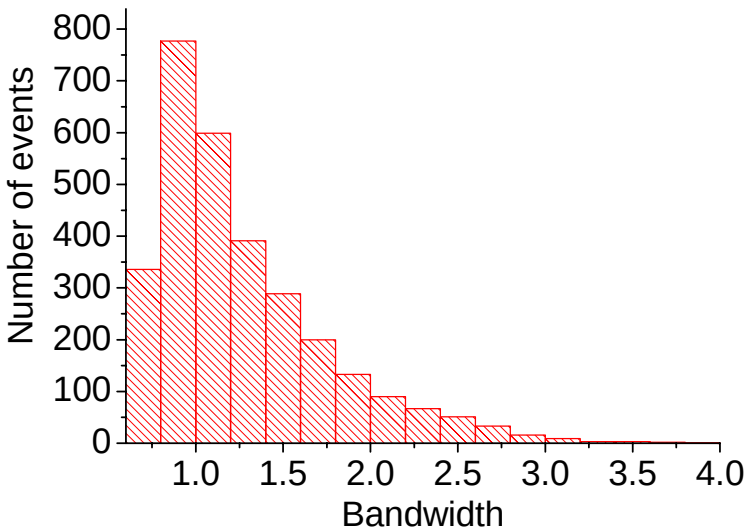
Local source model

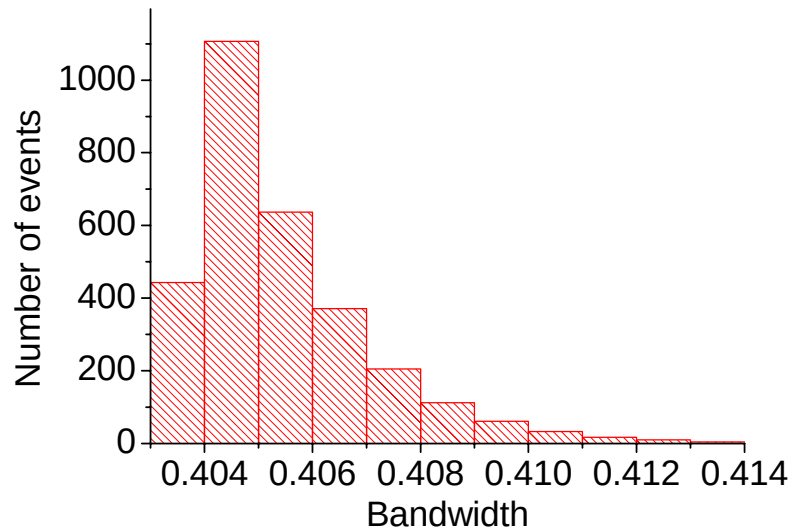


Applications
(Avdeeva & Fleishman, 2004)

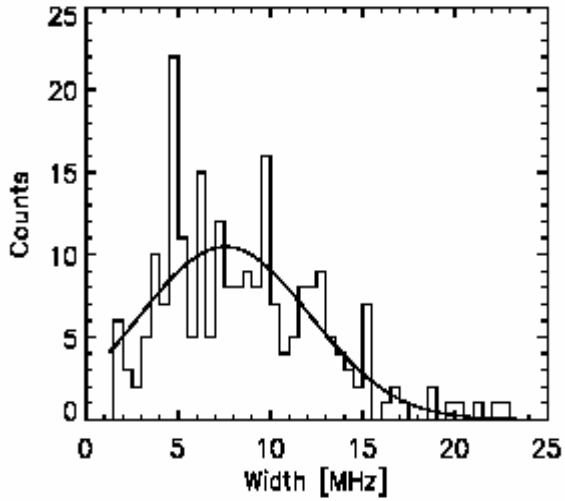


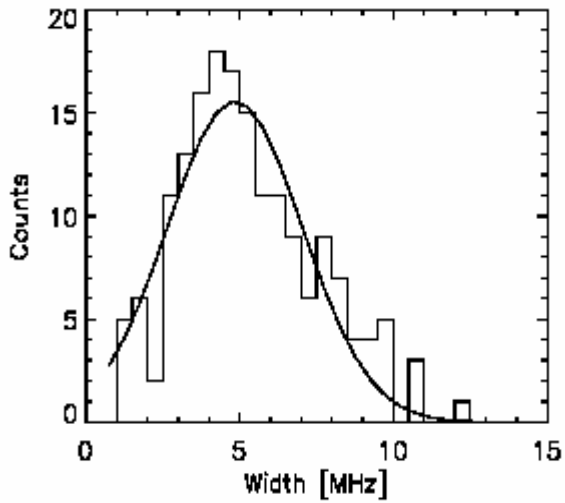


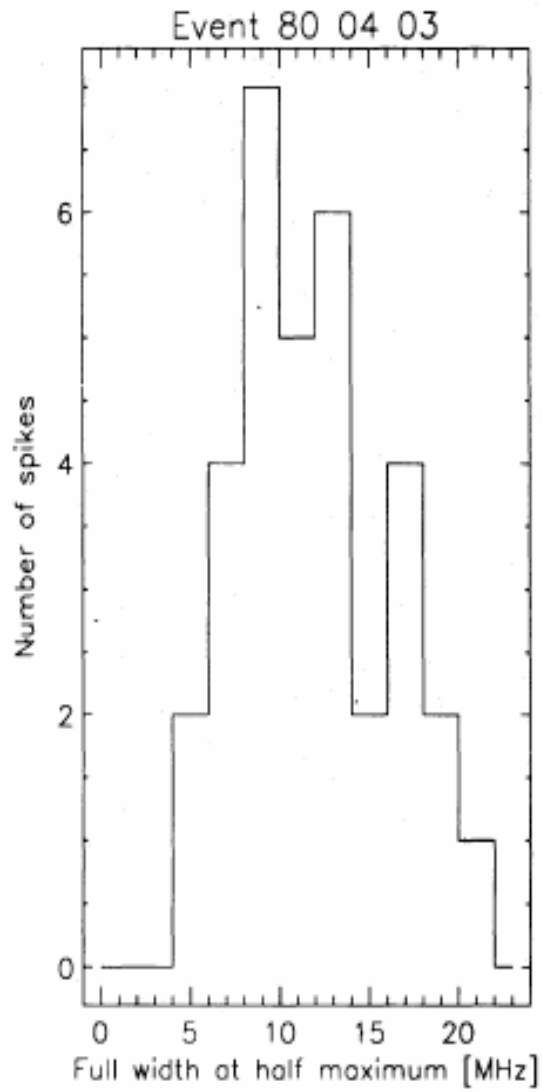


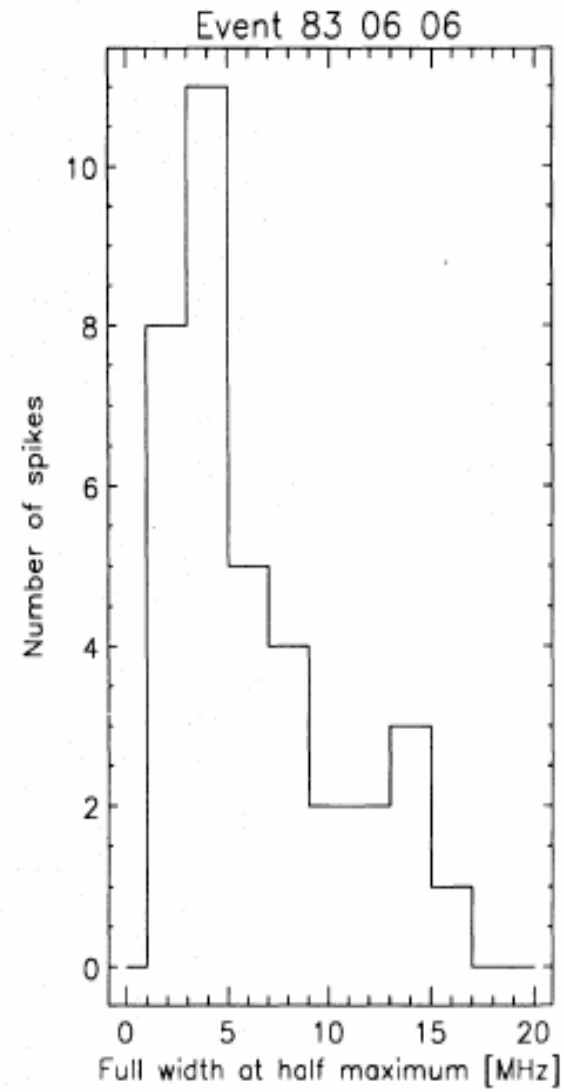


Applications









Conclusions.

1. Random Inhomogeneities of Plasma Parameters (n, B) have Huge Effect on the Generation of Radio Emission.

2. There are Many Possibilities to Improve the Diagnostics of Plasma Using the Considered Emission Processes.