Diffusive Synchrotron Radiation

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Perturbative one-wave/undulator approximation:

A.K.Gailitis, V.N.Tsytovich, 1964, Sov. Astron., 41, 452

V.N.Tsytovich, A.S.Chikhachev, 1969, Sov. Astron., 13, 385

G.G.Getmantsev, Yu.V.Tokarev, 1972, Astrophys. Lett., 12, 57

S. A.Kaplan, V.N.Tsytovich, 1972, Plasma Astrophysics.

M.V. Medvedev, 2000, ApJ, 540, 704

Perturbative multi-wave (random phase) approximation:

Iu.A.Nikolaev, V.N.Tsytovich, 1979, Phys. Scripta., 13, 385

Full non-perturbative theory:

I.N.Toptygin, G.D.Fleishman, 1987, Ap&SS, 132, 213

I.N.Toptygin et al., 1987, R&QE, 30, 334

I.N.Toptygin , G.D.Fleishman, 1987, R&QE, 30, 551

Recent developments and applications:

G.D.Fleishman, in 'Geospace Electromagnetic Waves and Radiation' (J.W.LaBelle & R.A.Treumann (Eds.), Lecturer Notes in Physics, Springer-Verlag, Berlin-Heidelberg-New York, V. lnp687, 2006, astro-ph/0510317

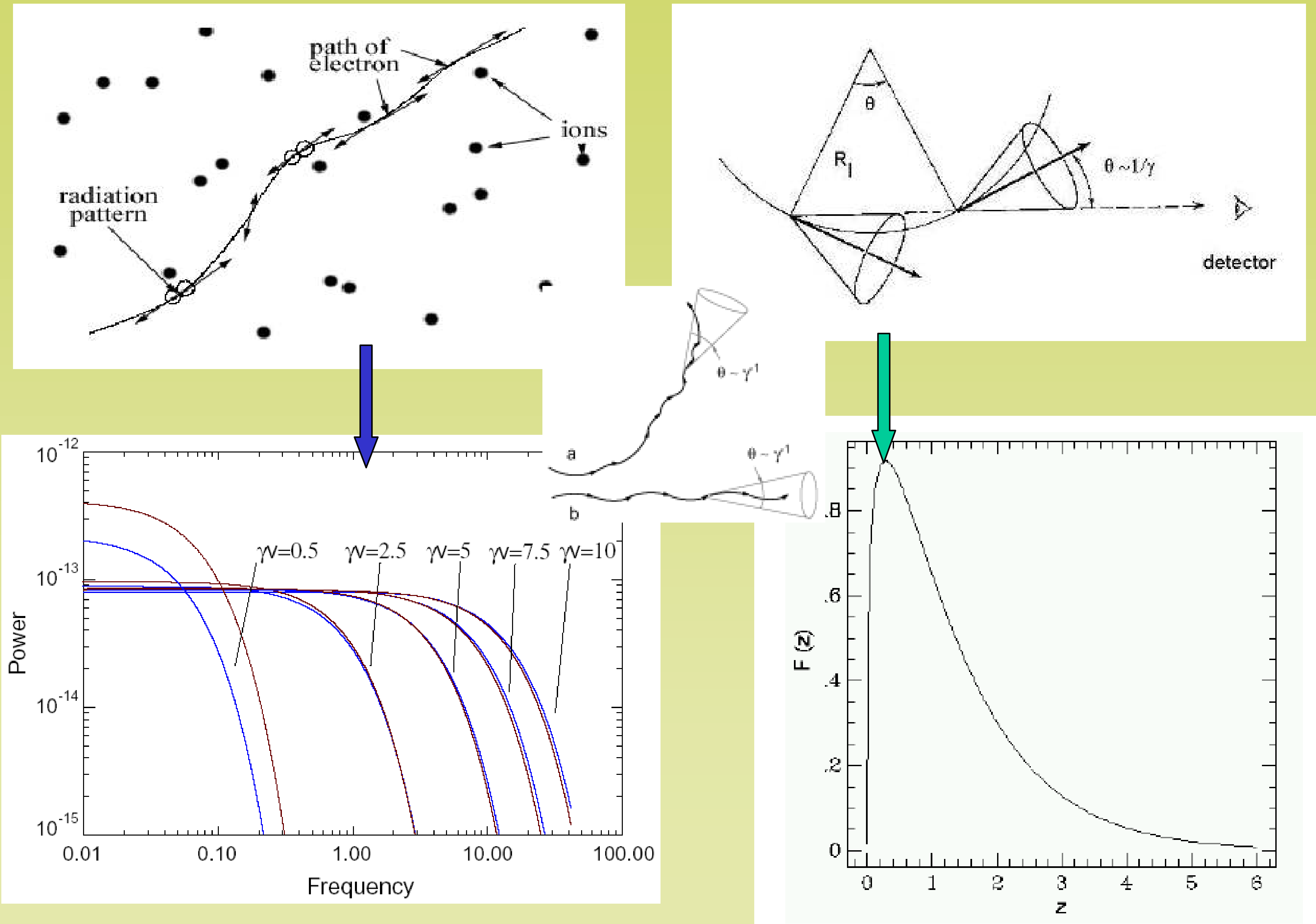
G.D.Fleishman, 2006, ApJ, v638n1, astro-ph/0502245

G.D.Fleishman, 2005, MNRAS Letters, in press, astro-ph/0511353

C.B.Hededal, Å.Nordlund, ApJL submitted, astro-ph/0511662

M.V. Medvedev, 2006, ApJ, in press

Bremsstrahlung vs Synchrotron Radiation



Prompt Gamma-Ray Burst Spectra

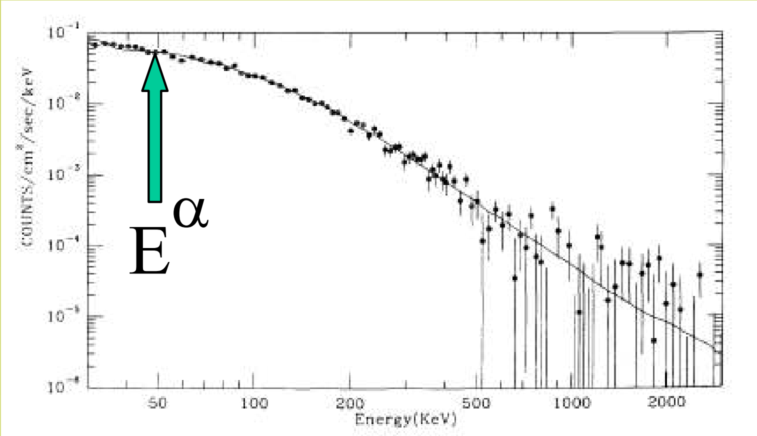


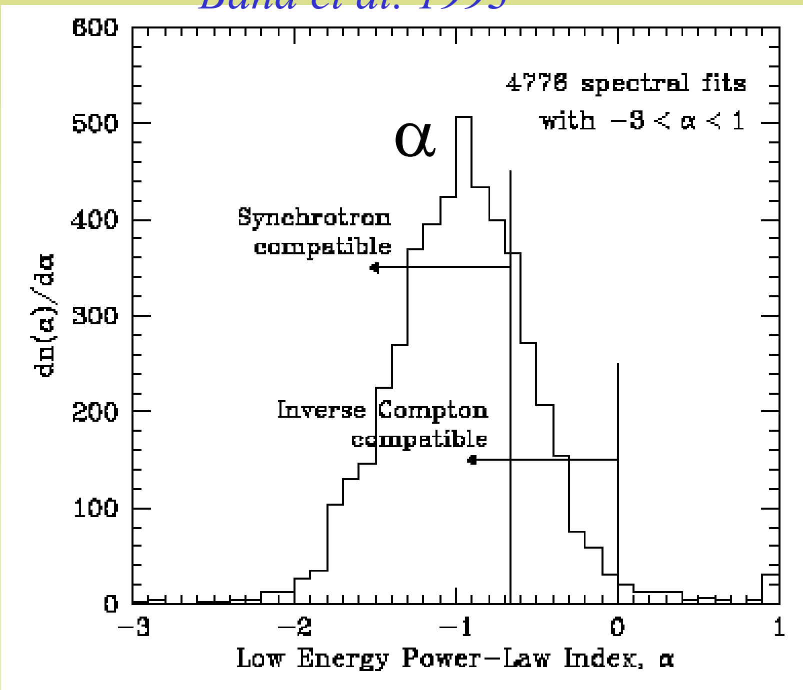
FIG. 1.—Example of a spectral fit. The GRB model (eq. [1]) was fitted to the average spectrum of 1B 911127. The low-energy spectral index is $\alpha = -0.968 \pm 0.022$, the high-energy spectral index $\beta = -2.427 \pm 0.07$, and the break energy $E_0 = 149.5 \pm 2.1$. With 100 degrees of freedom, $\chi^2 = 121.58$.

Band et al. 1993

Problem: *soft index distribution incompatible with synchrotron spectrum.*

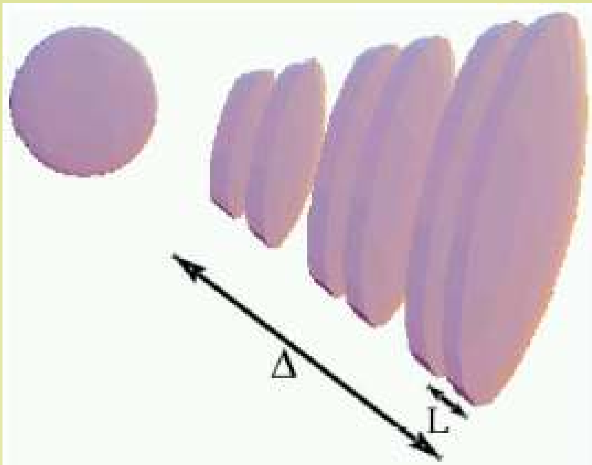
Current model: *interacting internal shocks produced by a central engine.*

This interaction gives rise to efficient generation of the extremely small-scale magnetic/electric fields due to two-stream (e.g.,Weibel) instability.



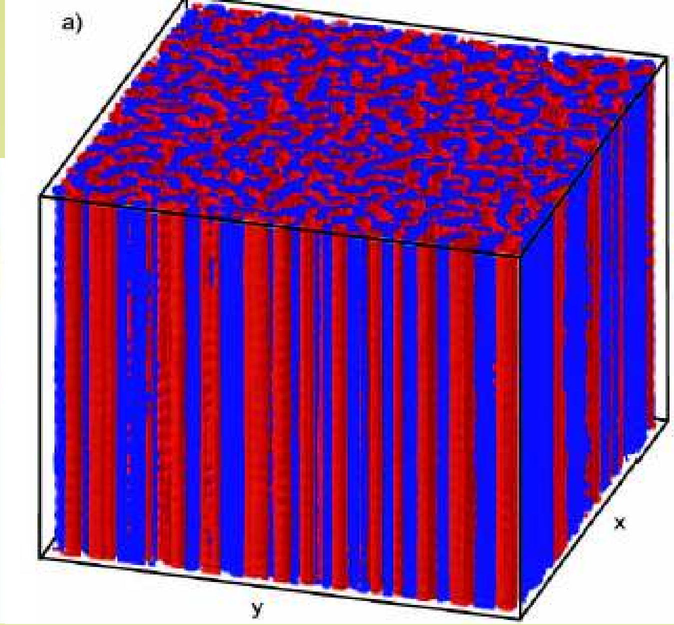
Baring & Braby 2004

Internal shocks



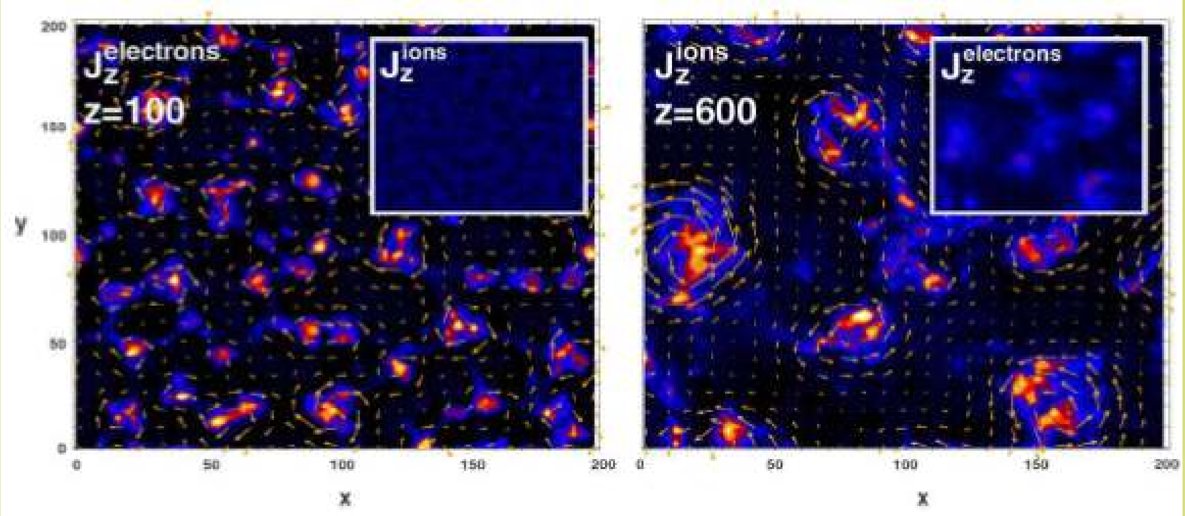
Piran 2005

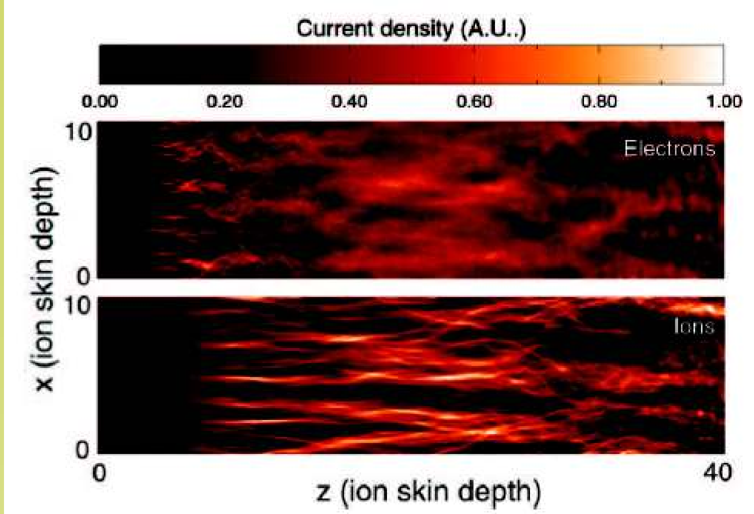
Current filaments



Jaroshek et al. 2005

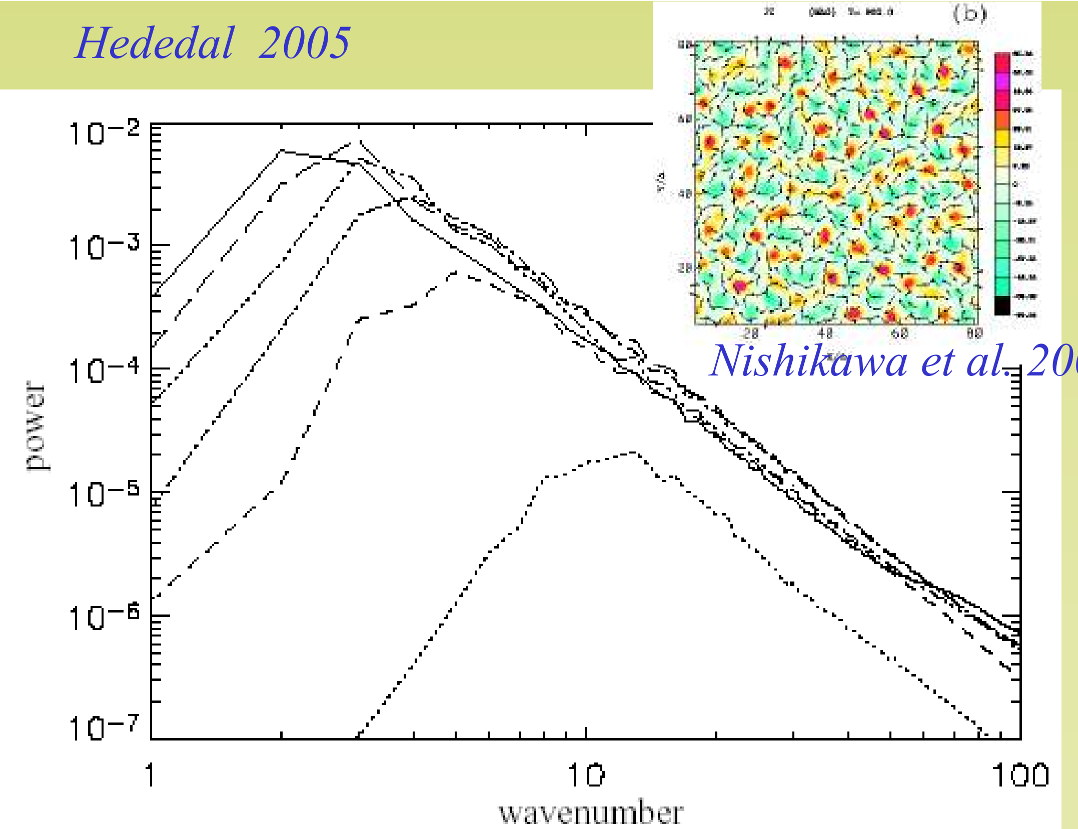
Bulk current density and magnetic field structure in relativistic shocks



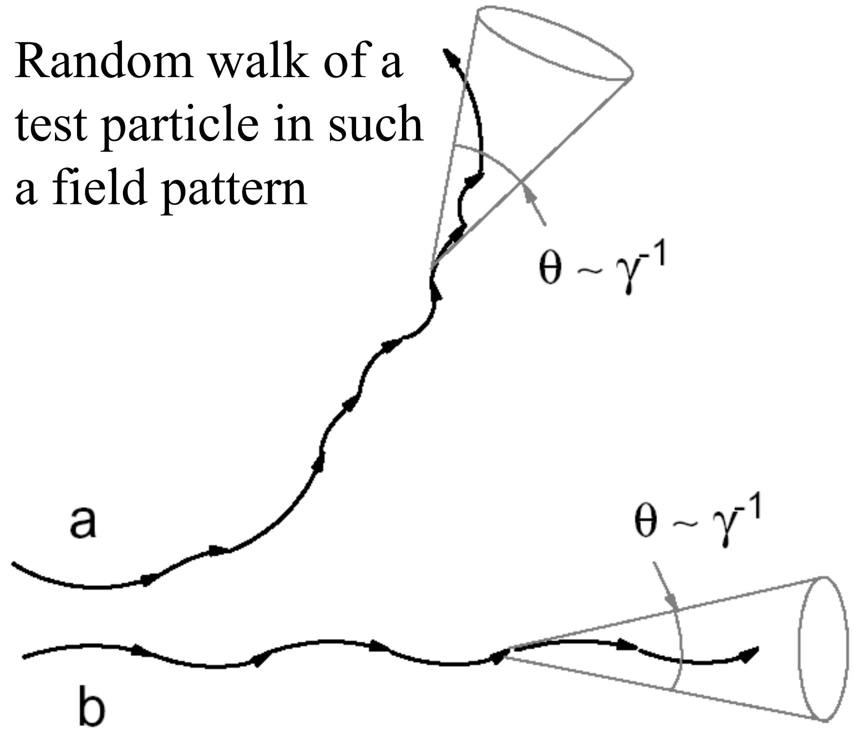


Hededal 2005

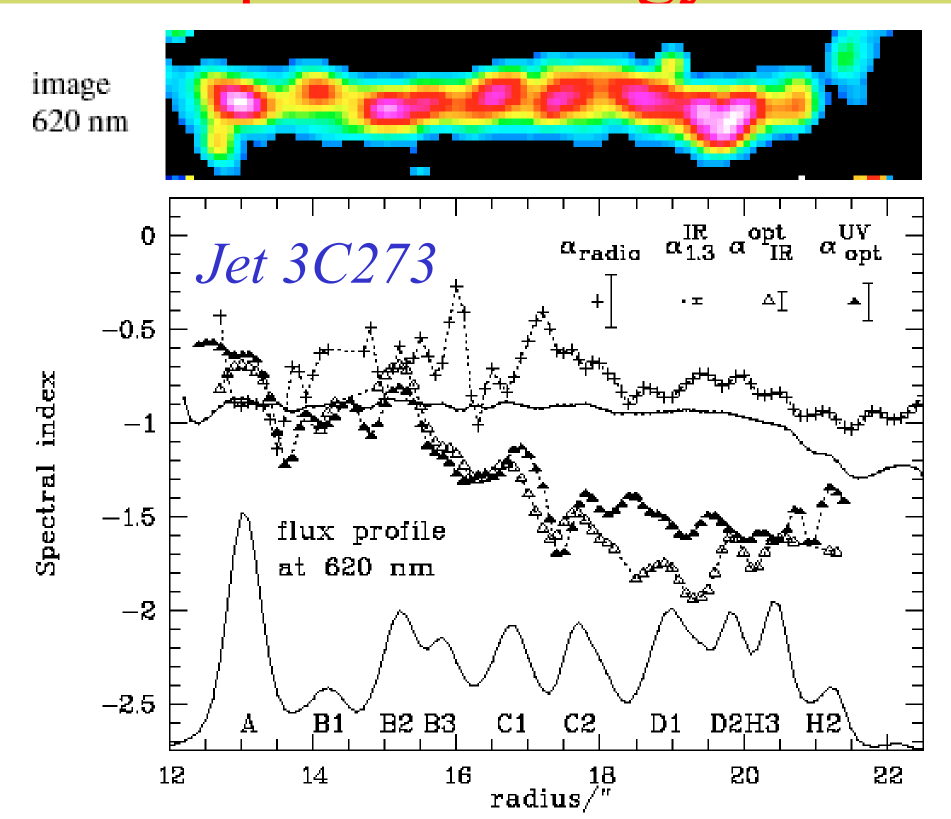
Nishikawa et al. 2005



Random walk of a test particle in such a field pattern

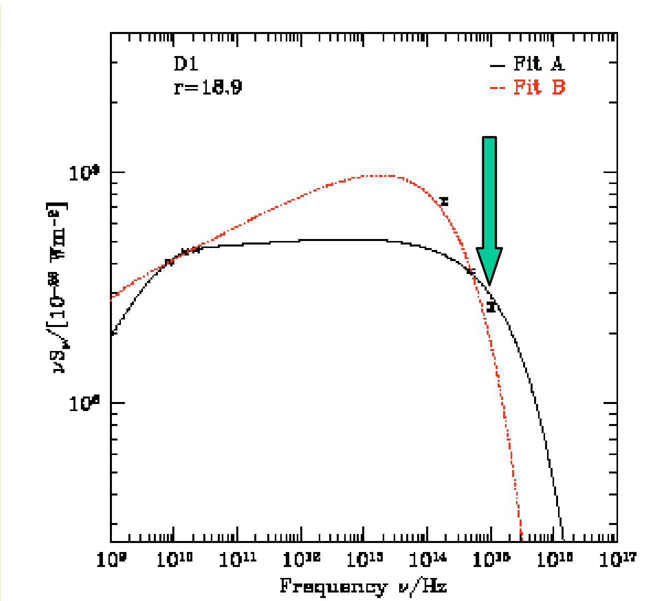


Spectral Energy Distribution in Extragalactic Jets



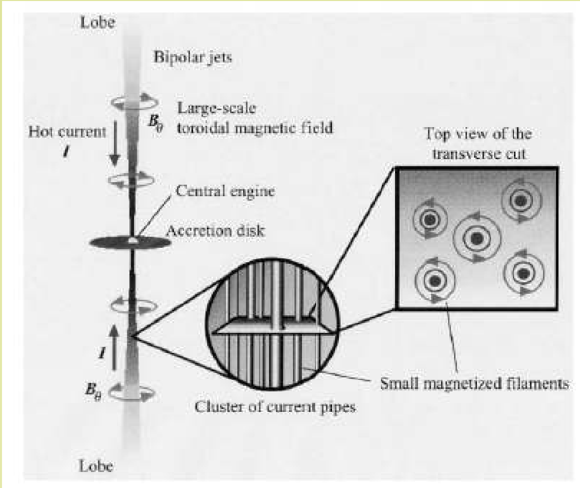
Problem: *UV – X-ray flattenings inconsistent with synchrotron emission from a single electron population.*

Current model: *filamentation of the jet current as well as interaction of the flow with ambient plasma gives rise to efficient generation of the extremely small-scale magnetic fields transverse to the jet speed..*



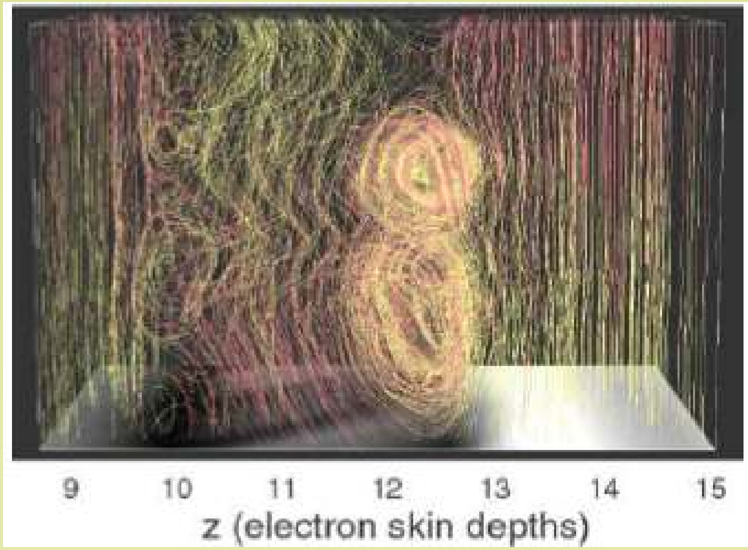
Jester et al. 2005

Jet filamentation



Honda & Honda 2004

Magnetic field lines



Hededal & Nishikawa 2005

Implication for the e/m emission theory

Radiated energy can be expressed via electric current in the source

$$\mathcal{E}^{\sigma}_{\boldsymbol{n},\omega} = (2\pi)^6 \frac{\omega^2 n_\sigma(\omega)}{c^3} |(\boldsymbol{e}_\sigma \cdot \boldsymbol{j}_{\omega,\boldsymbol{k}})|^2$$

In uniform plasma and regular magnetic field the current is the regular function expressed via fast particle trajectory and velocity:

$$\boldsymbol{j}_{\omega,\boldsymbol{k}} = Q \int_{-\infty}^{\infty} \boldsymbol{v}(t) \exp(i\omega t - i\boldsymbol{k}\boldsymbol{r}(t)) \frac{dt}{(2\pi)^4}$$

Random inhomogeneities of the magnetic and electric fields as well as number density of the background plasma give rise to *important change* in the ***microphysics of the radiative processes***

Total current

Plasma response current ← Total current → Intrinsic random current

$\langle B_{st}^2 \rangle$, $\langle E_{st}^2 \rangle$, $\langle \Delta N^2 \rangle$

Transition radiation due to coherent plasma response on the external perturbations provided by fast particles

Diffusive synchrotron radiation produced by the random walk of the fast particles in addition to normal synchrotron emission

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

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

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

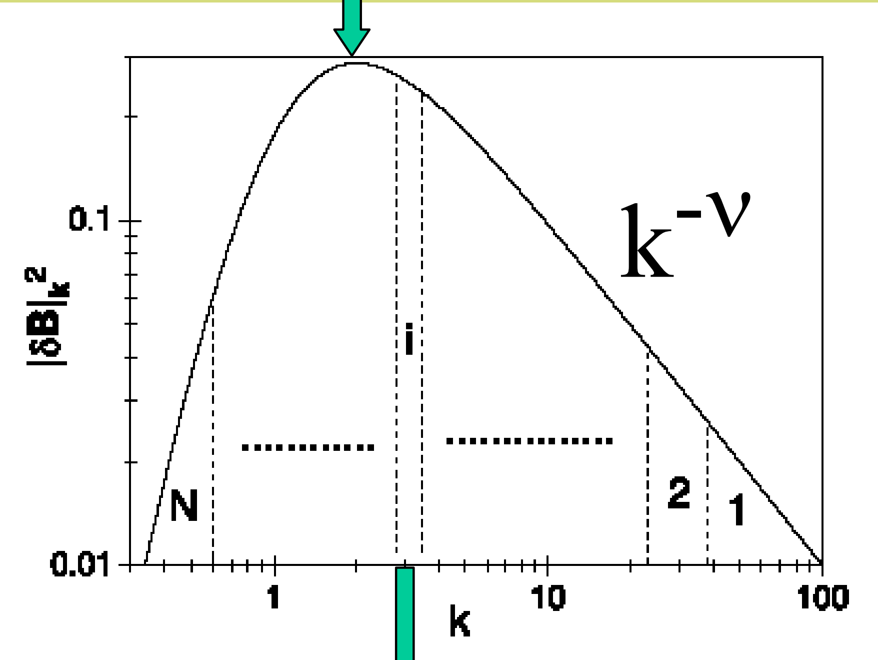
Random Magnetic Field. Definitions.

$$\omega_B = \frac{QB_0}{Mc}$$

Stochastic gyrofrequency:

$$\omega_{st} = \frac{Q \langle B_{st}^2 \rangle^{1/2}}{Mc}$$

$$k_{min} = \omega_0 / c$$



$$\delta\mathcal{E}_{st} \sim K(\boldsymbol{k})k^2\Delta k$$

$$\delta\omega_{st} \sim Q\sqrt{\delta\mathcal{E}_{st}}/(Mc)$$

Weak (small-scale) random magnetic field

$$\omega_0 \gg \omega_{st}$$

Strong (large-scale) random magnetic field

$$\omega_{st} \gg \omega_0$$

Calculation of e/m emission. Scheme.

$$\mathcal{E}^{\sigma}_{\boldsymbol{n},\omega} = (2\pi)^6 \frac{\omega^2 n_\sigma(\omega)}{c^3} \left|(\boldsymbol{e}_\sigma \cdot \boldsymbol{j}_{\omega,\boldsymbol{k}})\right|^2$$

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

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

Treatment of Random Particle Motion

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

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

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

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

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

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

$$\frac{\langle B_{st}^2 \rangle}{6} \left(\frac{Qc}{\mathcal{E}} \right)^2 \mathcal{O}^2 \int_{-\infty}^{\infty} d\tau \psi(v\tau) W(\mathbf{r} - \mathbf{v}\tau, \mathbf{p}, t - \tau)$$

Spectrum of e/m emission.

$$I_\omega = \frac{8Q^2 q(\omega)}{3\pi c}\gamma^2\left(1+\frac{\omega_{pe}^2\gamma^2}{\omega^2}\right)^{-1}\Phi_1(s,r) + \frac{Q^2\omega}{4\pi c\gamma^2}\left(1+\frac{\omega_{pe}^2\gamma^2}{\omega^2}\right)\Phi_2(s,r)$$

$$\Phi_1(s,r) = 24s^2 Im\int_0^\infty dt\,\exp(-2s_0 t)\left[\mathrm{cth}\,t\,\exp\left(-2rs_0^3(\mathrm{cth}\,t - \mathrm{sh}^{-1}\,t - t/2)\right) - \frac{1}{t}\right]$$

$$\Phi_2(s,r) = 4rs^2 Re\int_0^\infty dt\frac{\mathrm{ch}\,t - 1}{\mathrm{sh}\,t}\exp\left(-2s_0 t - 2rs_0^3(\mathrm{cth}\,t - \mathrm{sh}^{-1}\,t - t/2)\right)$$

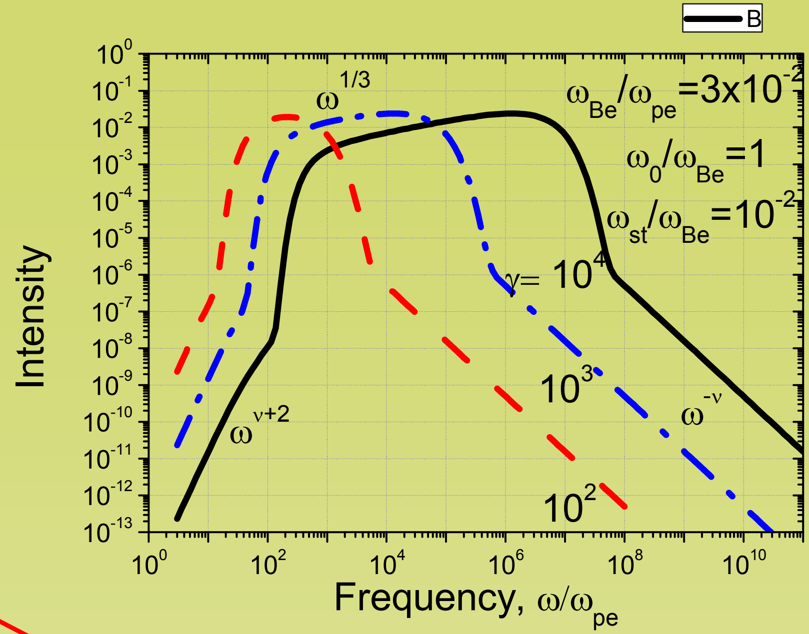
$$s_0 = (1-i)s = \frac{1-i}{8\gamma^2}\left(\frac{\omega}{q(\omega)}\right)^{1/2}\left(1+\frac{\omega_{pe}^2\gamma^2}{\omega^2}\right)$$

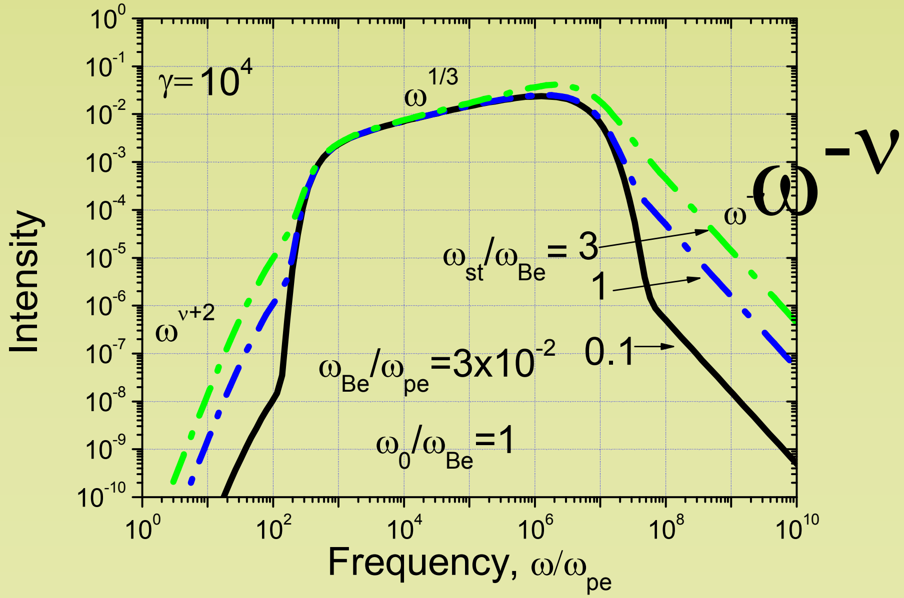
$$r = 32\gamma^6\left(\frac{\Omega_\perp}{\omega}\right)^2\left(1+\frac{\omega_{pe}^2\gamma^2}{\omega^2}\right)^{-3}$$

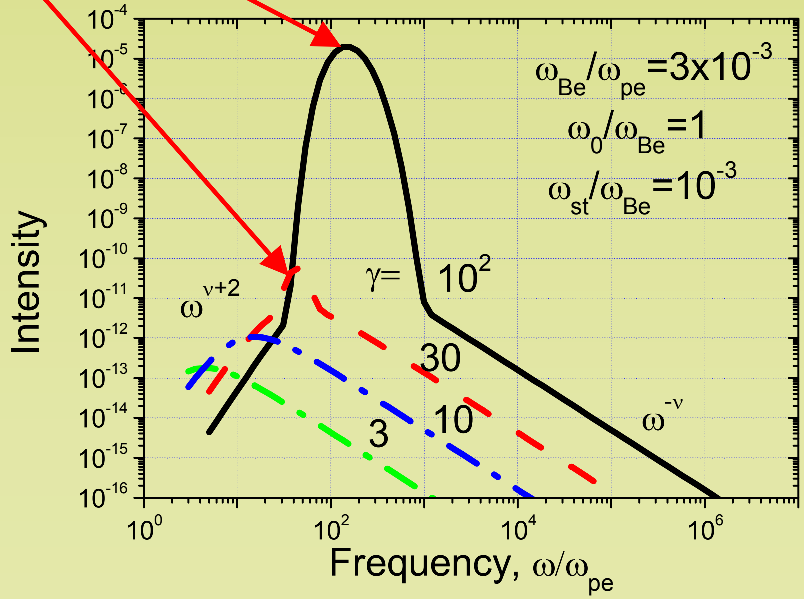
$$q(\omega) = \frac{\sqrt{\pi}\Gamma(\nu/2)\omega_{st}^2\omega_0^{\nu-1}}{3\Gamma(\nu/2-1/2)\gamma^2\left[(a\omega/2)^2\left(\gamma^{-2}+\omega_{pe}^2/\omega^2\right)^2+\omega_0^2\right]^{\nu/2}}$$

Radiation by a single electron in a dense plasma. Uniform field plus random field.

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



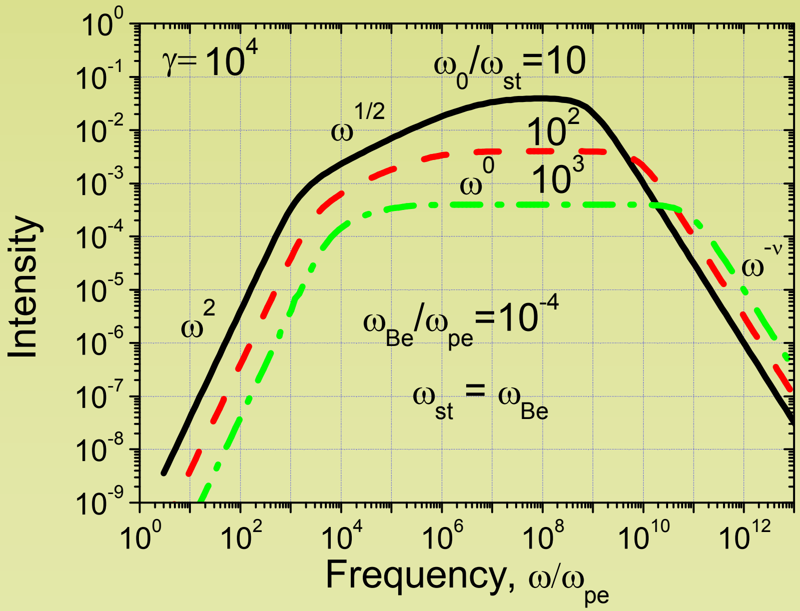


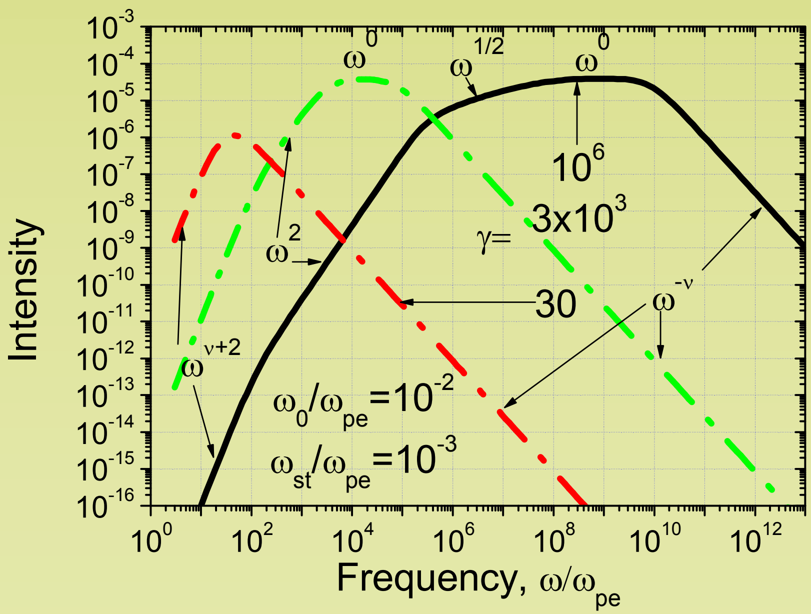


Radiation by a single electron. Random field only.

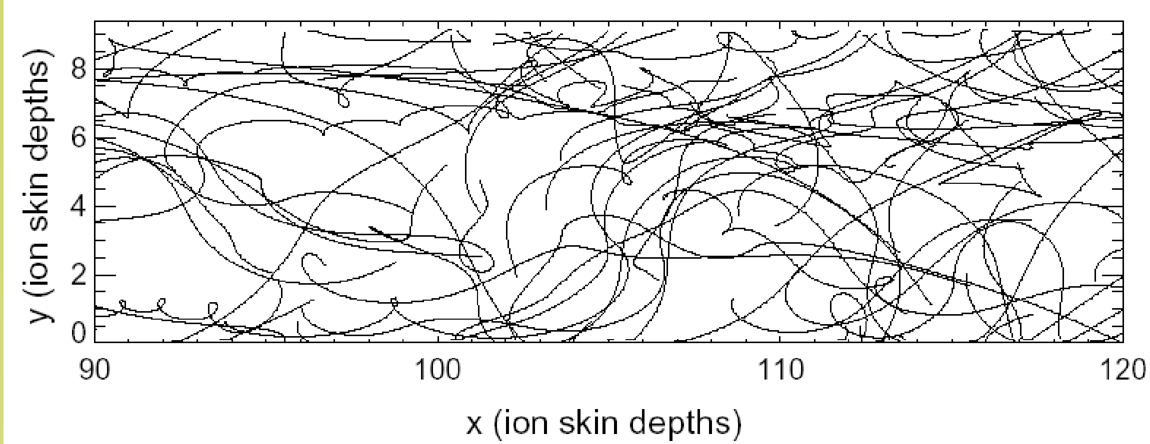
Small-scale random field.

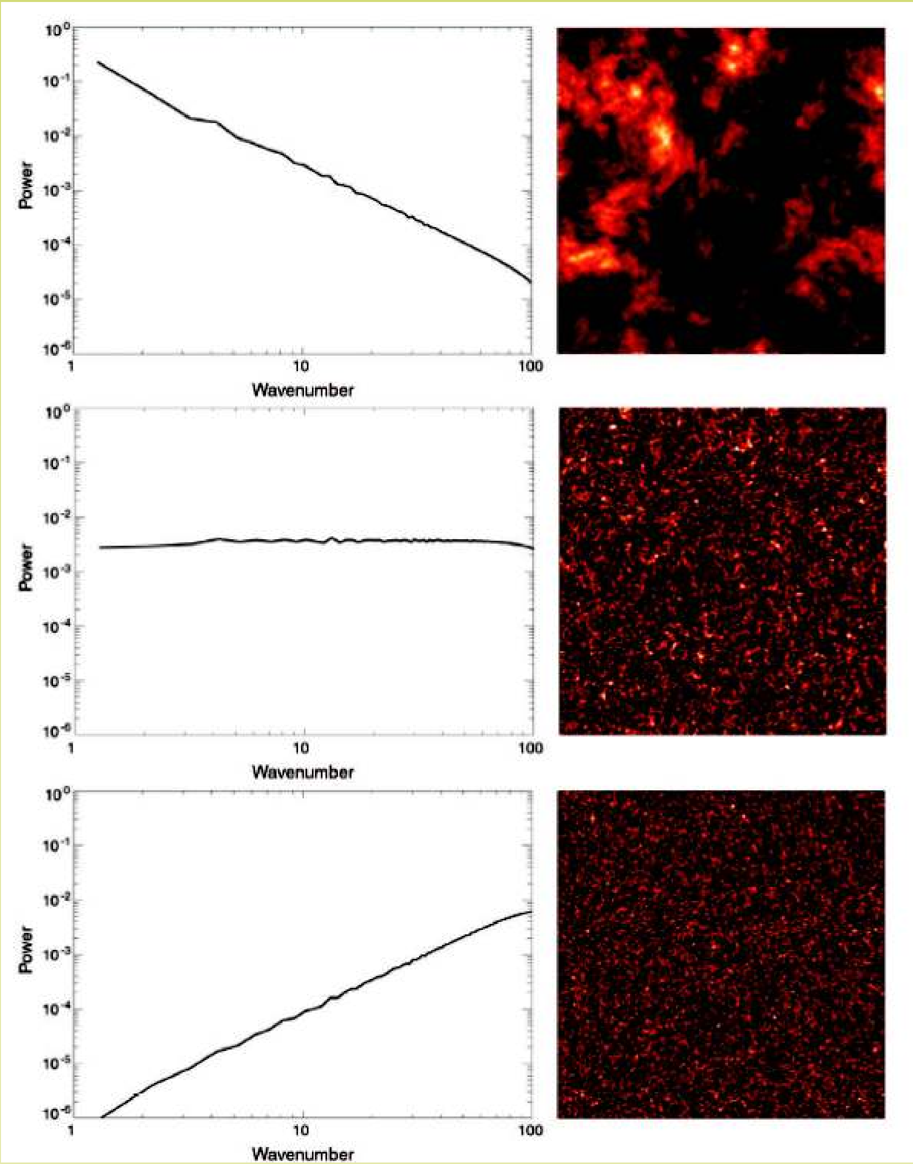
$$\omega_0 \gg \omega_{st}$$

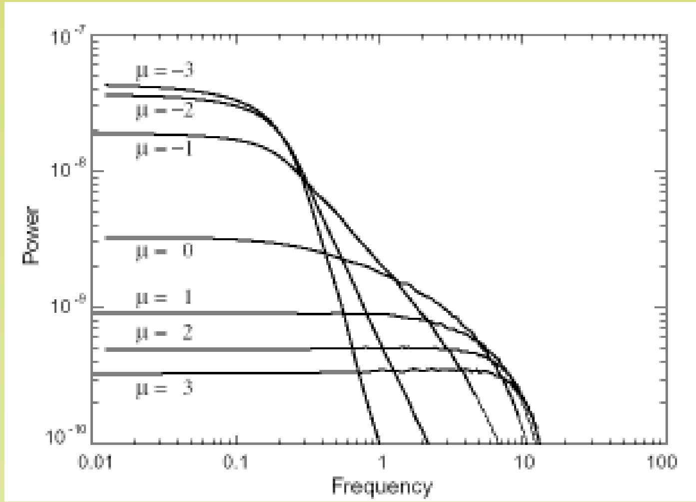


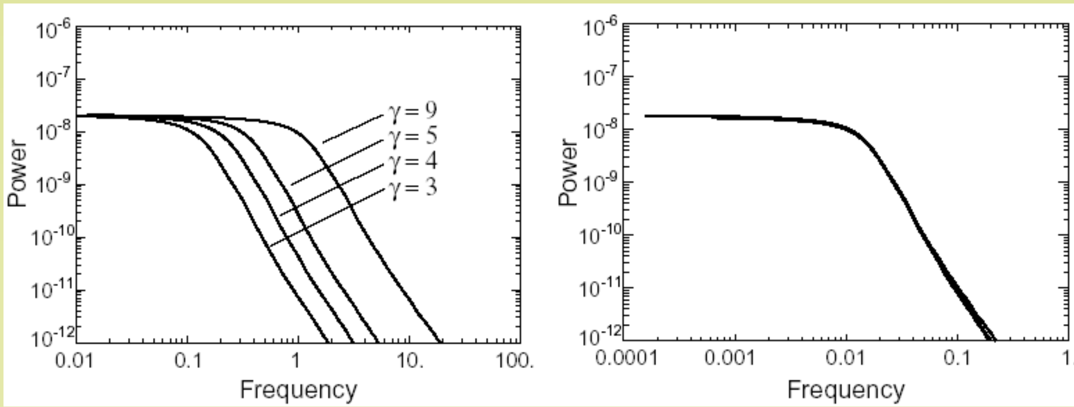


Radiation from PIC simulations. Random field only.(Hededal, 2005)

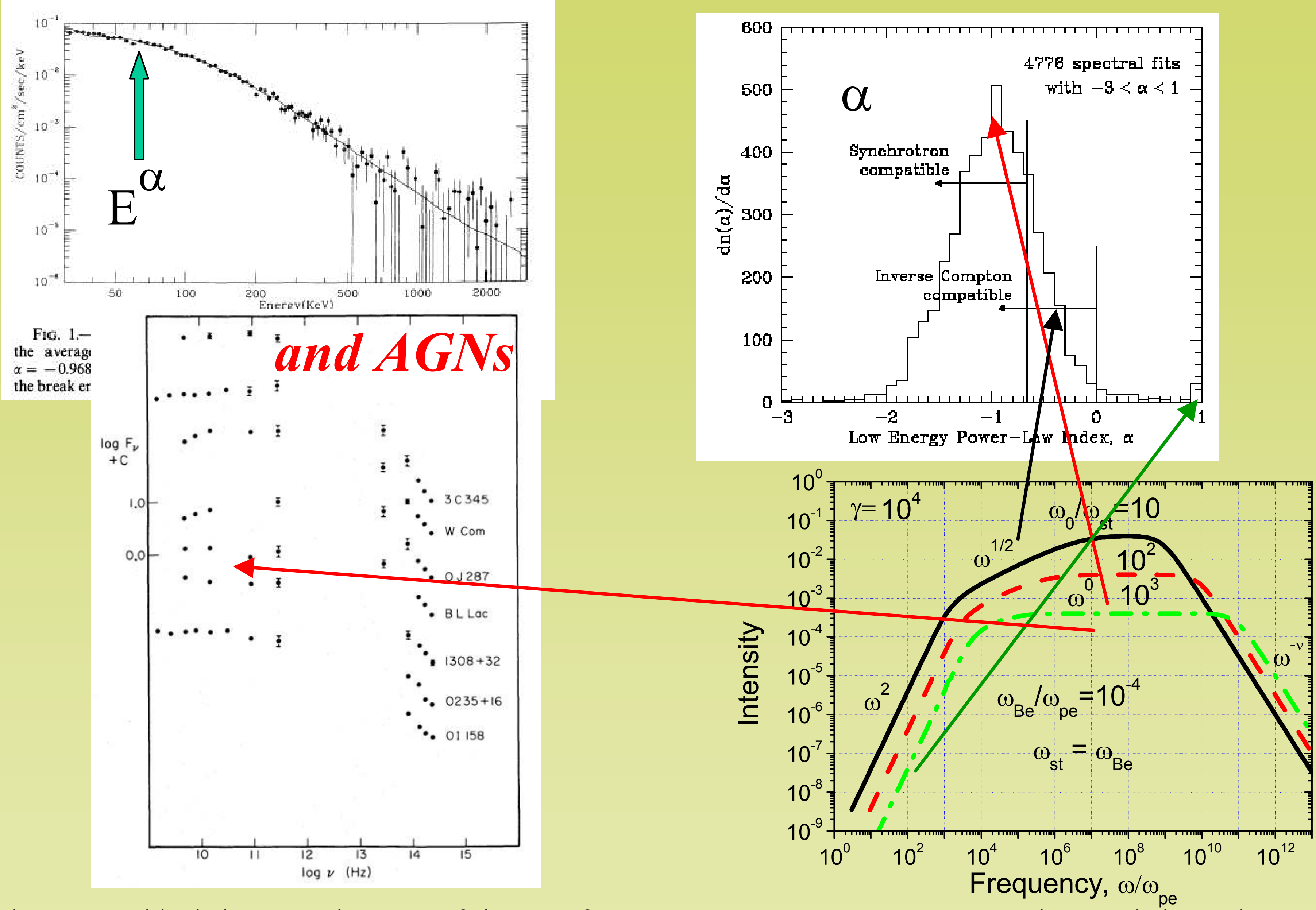








Diffusive synchrotron radiation in the Gamma-Ray Burst Sources

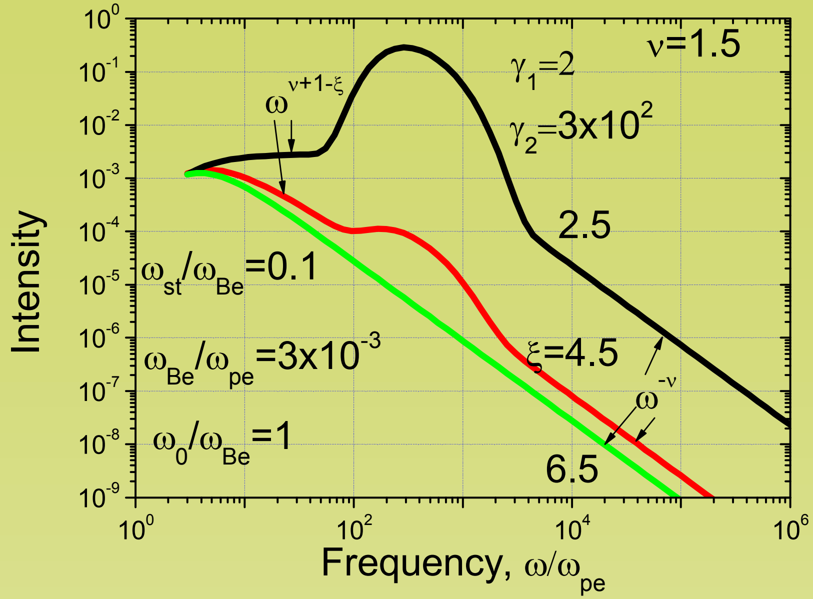


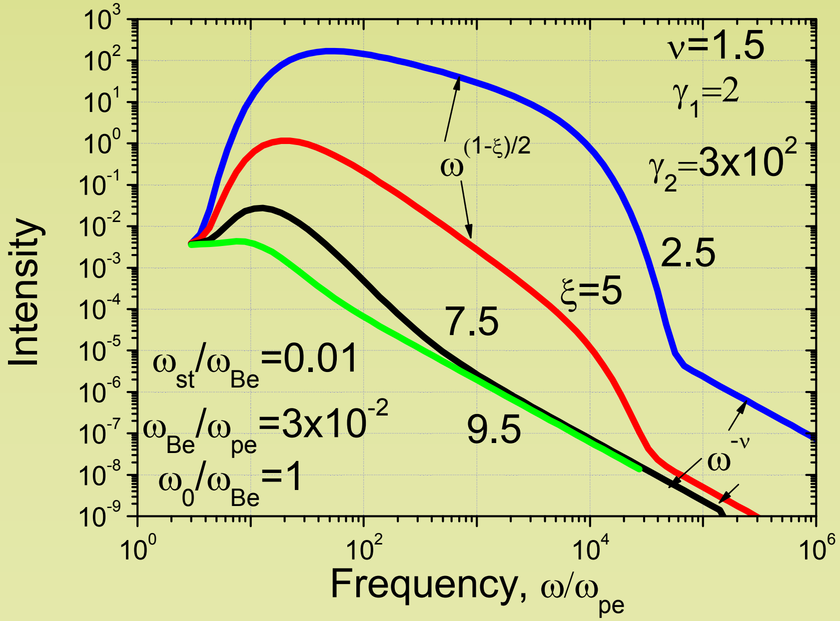
The available variety of low-frequency asymptotes is evidently compatible with GRB soft spectral index distribution.

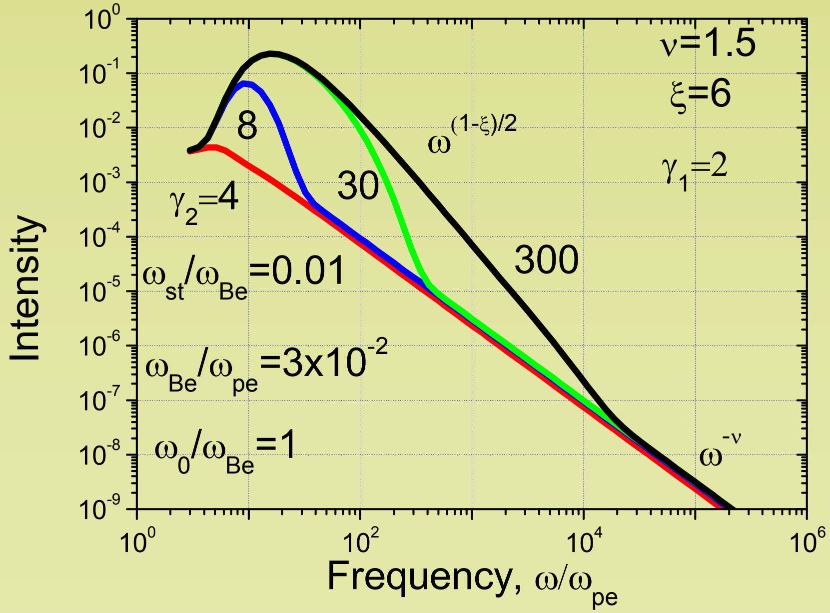
Radiation by an ensemble of electrons with a power-law spectrum

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

in a dense plasma

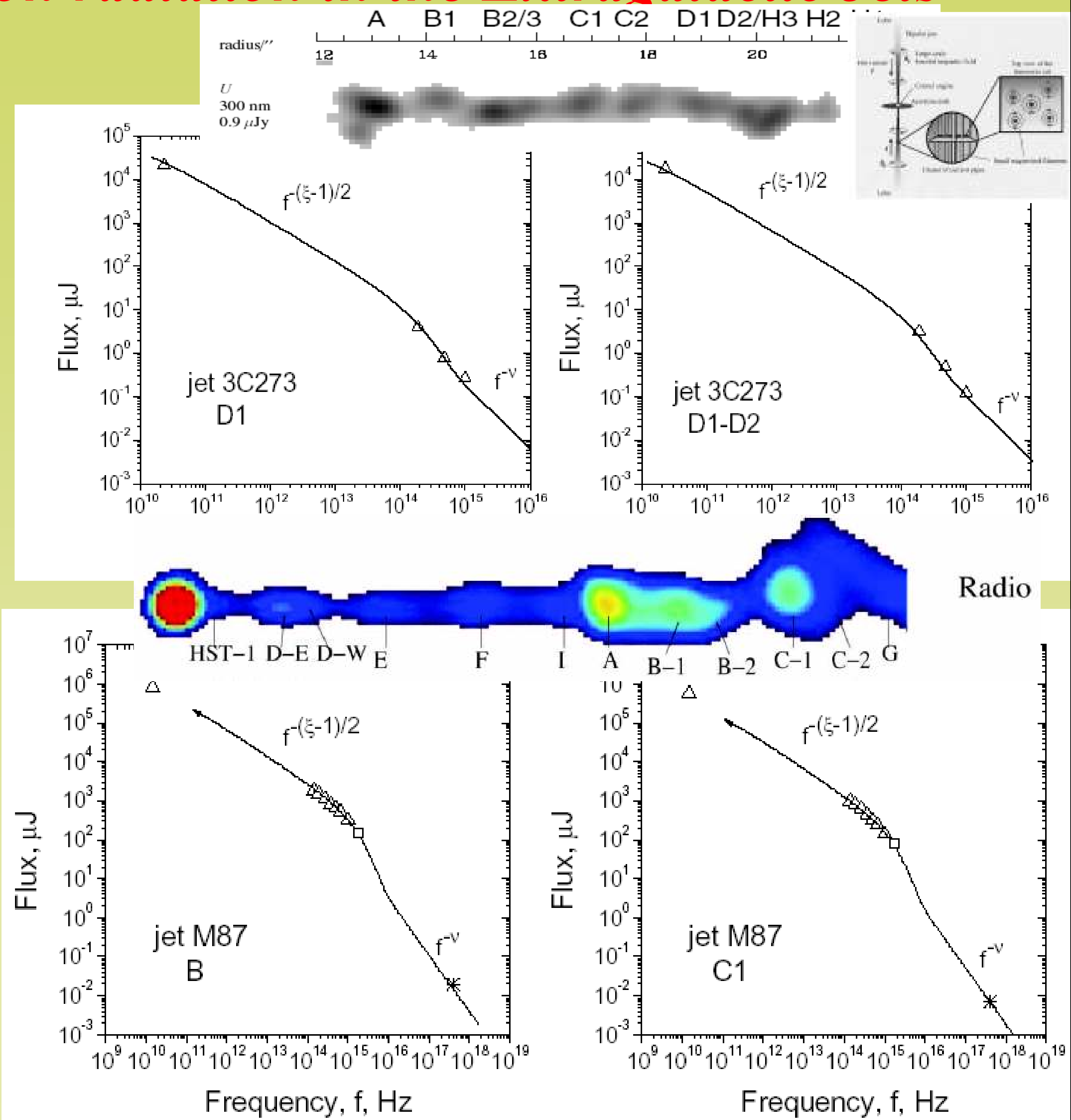






Diffusive synchrotron radiation in the Extragalactic Jets

Model spectra of the ***diffusive synchrotron radiation*** in a small-scale random magnetic field superimposed on a comparable regular magnetic field. The spectral flattening observed in UV – X-ray range does not require the presence of a secondary population of the relativistic electrons.



CONCLUSIONS

1.The basic theory of ***diffusive synchrotron radiation*** applicable for a broad range of random magnetic field models including ***anisotropic and isotropic*** spectral functions, and absence/presence of the regular magnetic field is presented.

2.The use of the theory of ***diffusive synchrotron radiation*** combined with the current models of the microphysics of the astrophysical sources for calculating the e/m emission produced offers a straightforward way of solving many puzzling and poorly understood observations.

3.In particular, various specific regimes of the ***diffusive synchrotron radiation*** are shown to agree well with low-energy spectral index distribution of the gamma-ray bursts and with broad band spatially resolved spectra of the extragalactic jets.