Radiation from Poynting Jets and Collisionless Shocks

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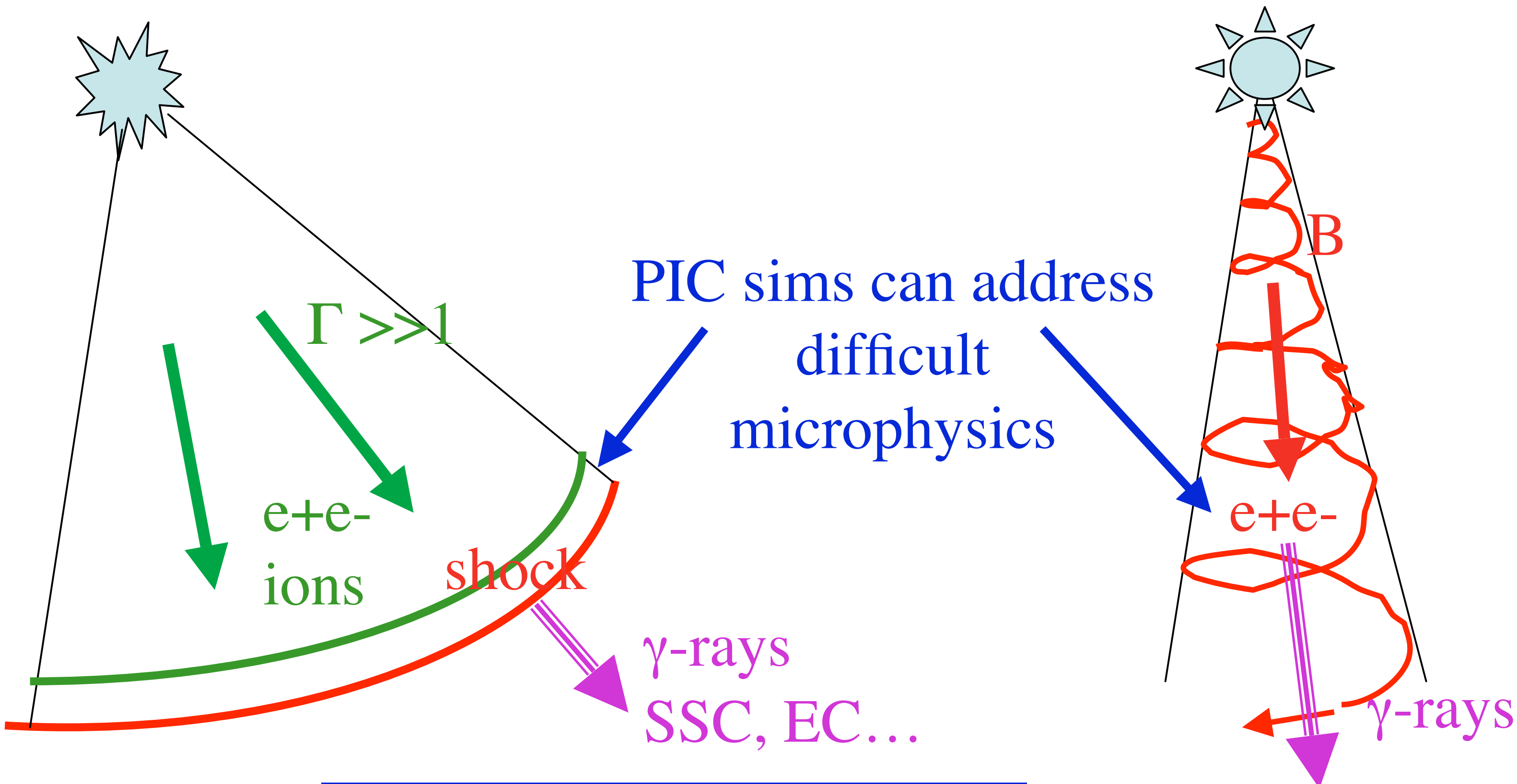
Acknowledgements: Scott Wilks, Bruce Langdon
Bruce Remington

Talk given at Glast Symposium 2007
(see http://spacibm.rice.edu/~liang/picsim
and spacibm.rice.edu/~knoguchi)

Popular Paradigms for the radiation of relativistic outflows in GRBs & Blazars



Internal shocks
Hydrodynamic
Outflow

What is energy source?
How are the e+e/ion accelerated?
How do they radiate?

Poynting flux
Electro-magnetic
-dominated outflow

Highlight

We have developed a Particle-In-Cell code that simultaneously computes total radiation output from each superparticle.

We find that in-situ radiation output of highest energy electrons accelerated by Poynting Flux (and some Collisionless Shocks) are *much below* that predicted by the classical synchrotron formula.

This may solve the problem of too rapid synchrotron cooling in many internal shock models of GRBs.

Question: *How do particles radiate while they are being accelerated to high energies?*

We compute the power radiated simultaneously from the force terms used in the particle movers of the PIC code:

$$P_{rad} = 2e^2(F_{||}{}^2 + \gamma^2 F_+{}^2) / 3m^3c$$

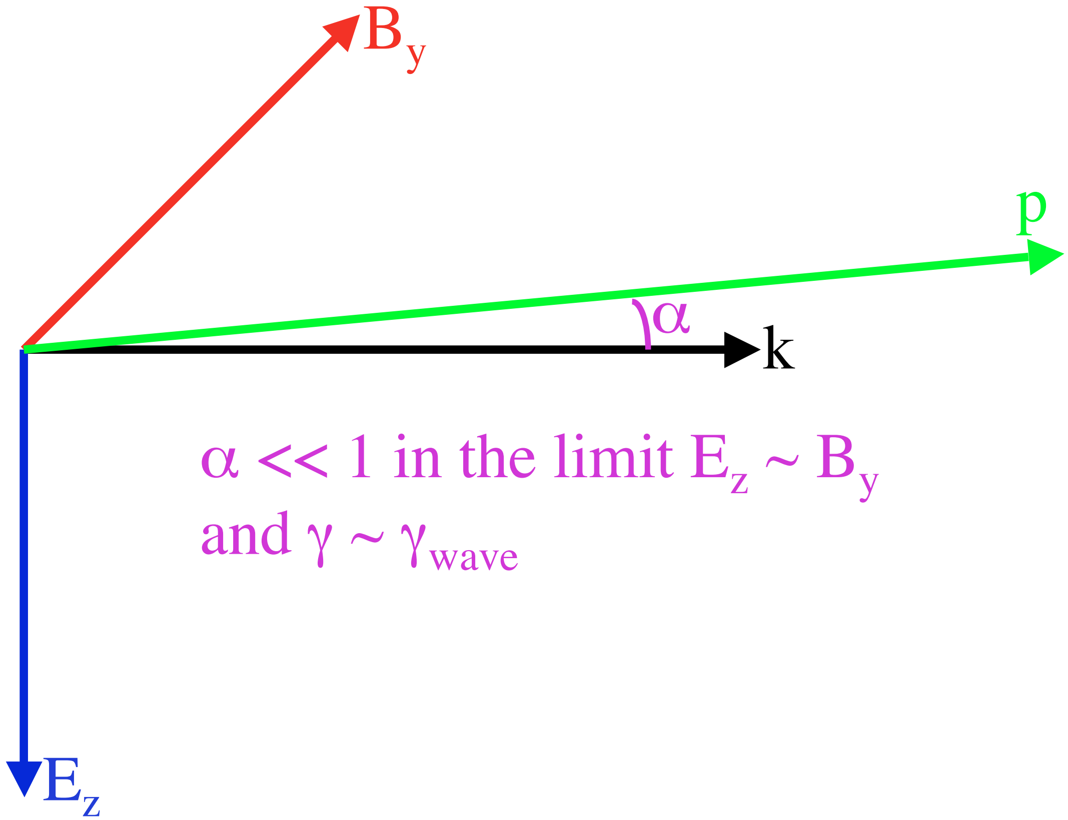
where $F_{||}$ is force along v
and F_+ is force orthogonal to v

(we have carefully calibrated our procedure against analytic results)

In Poynting flux acceleration, most energetic particles ~ comoving with local EM field

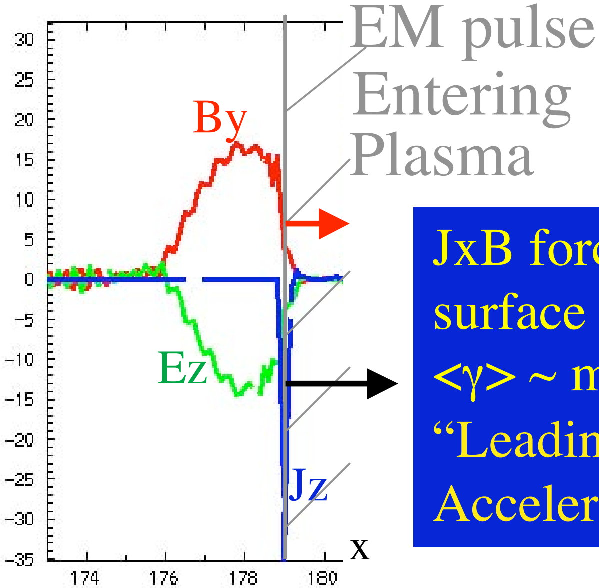
$P_{rad} \sim \Omega_e^2\gamma^2\sin^4\alpha << P_{syn} \sim \Omega_e^2\gamma^2$

where α is angle between v and Poynting vector k.

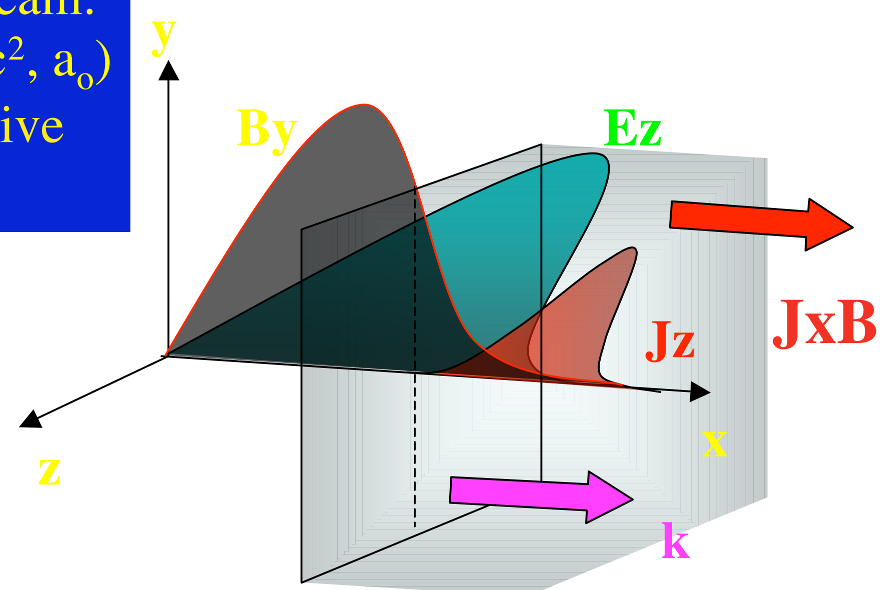


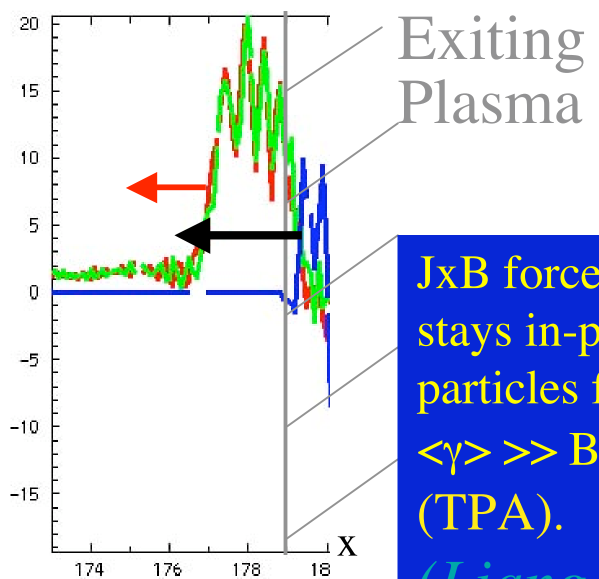
critical frequency $\omega_{cr} \sim \Omega_e\gamma^2\sin^2\alpha << \omega_{crsyn} \sim \Omega_e\gamma^2$

Relativistic Poynting Flux Acceleration via induced j x B(ponderomotive) force



JxB force pushes all surface particles upstream: $\langle\gamma\rangle \sim \max(B^2/4\pi n m_e c^2, a_o)$ "Leading Ponderomotive Accelerator" (LPA)

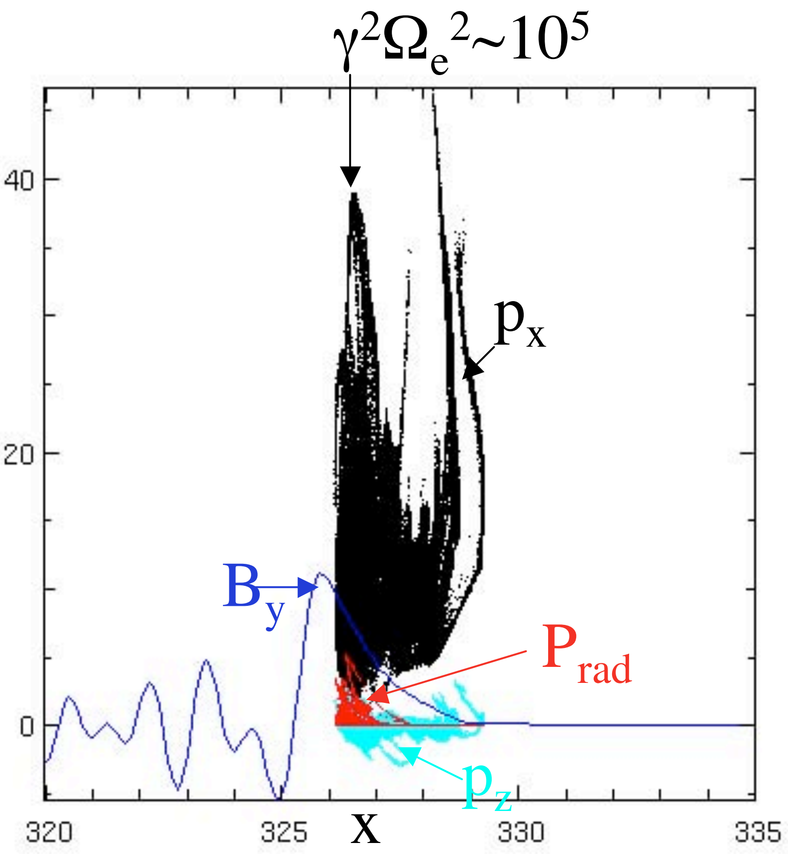


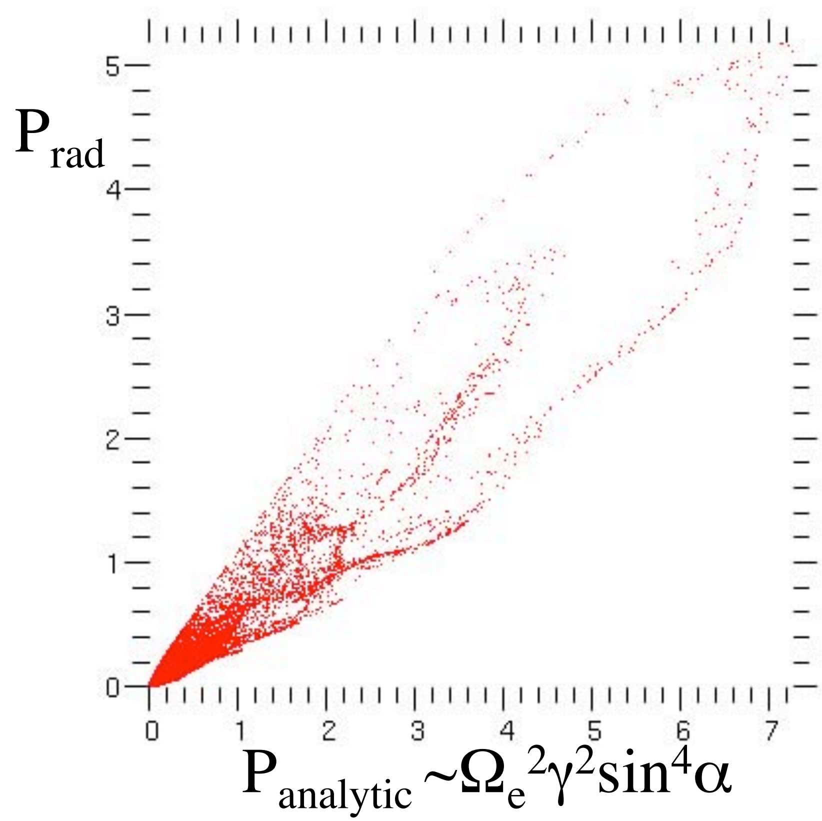


JxB force pulls out surface particles. Loaded EM pulse (speed < c) stays in-phase with the fastest particles, but gets "lighter" as slower particles fall behind. It accelerates indefinitely over time: $\langle\gamma\rangle >> B^2/4\pi n m_e c^2$, a_o "Trailing Ponderomotive Accelerator" (TPA).

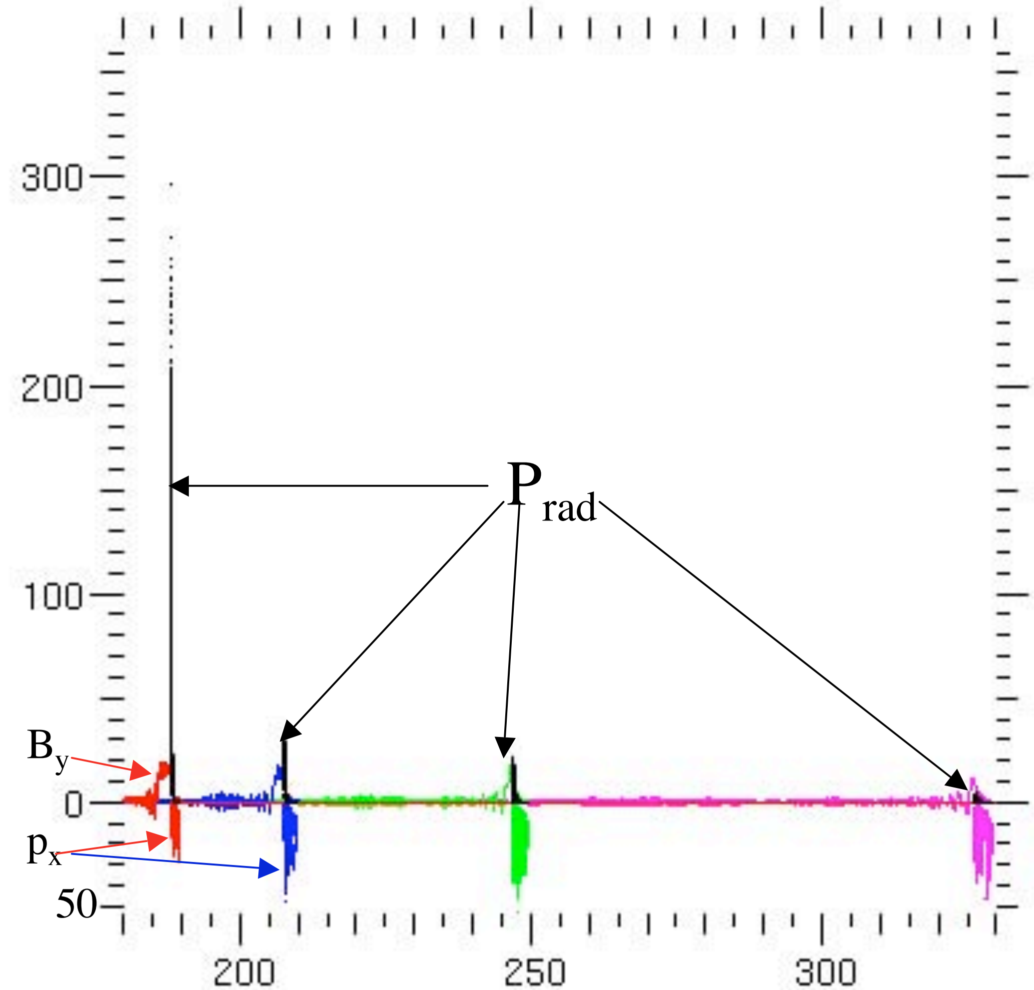
(Liang et al. PRL 90, 085001, 2003)

Electrons accelerated by LPA radiate at a level ~ 10^{-4} of classical synchrotron formula, due to $\sin\alpha \sim p_z/p_x \leq 0.1$

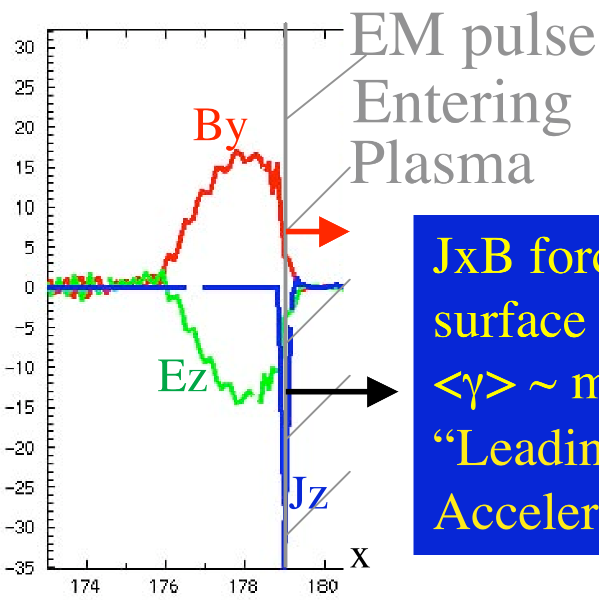




Evolution of e+e- plasma accelerated by Poynting flux (LPA) shows decline of radiative power output P_{rad} despite increase of γ



Relativistic Poynting Flux Acceleration via induced j x B(ponderomotive) force



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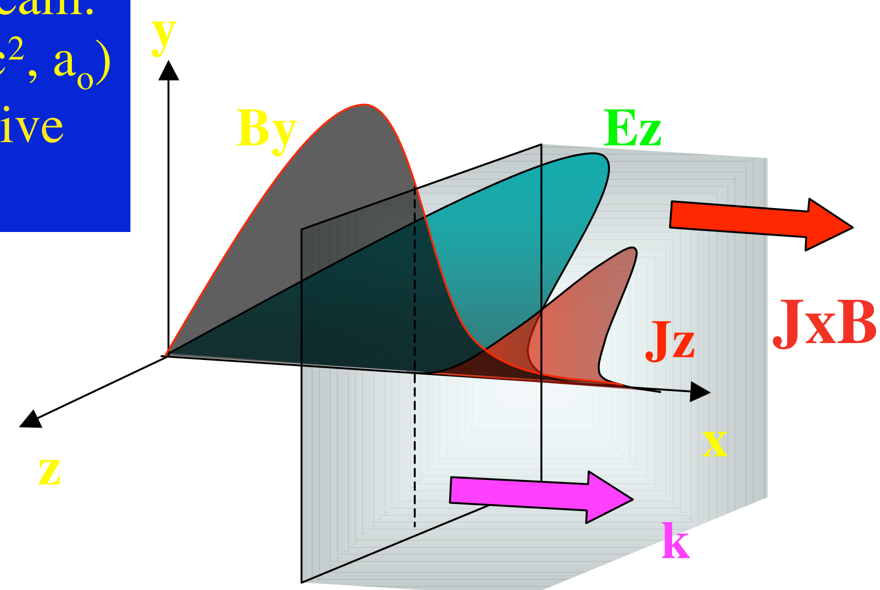

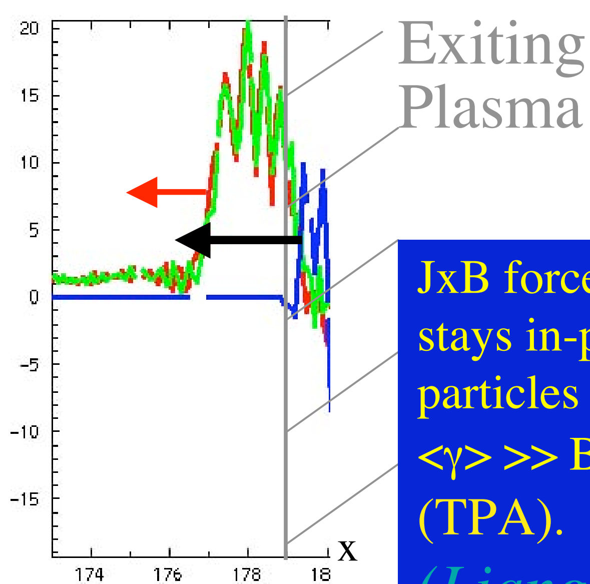

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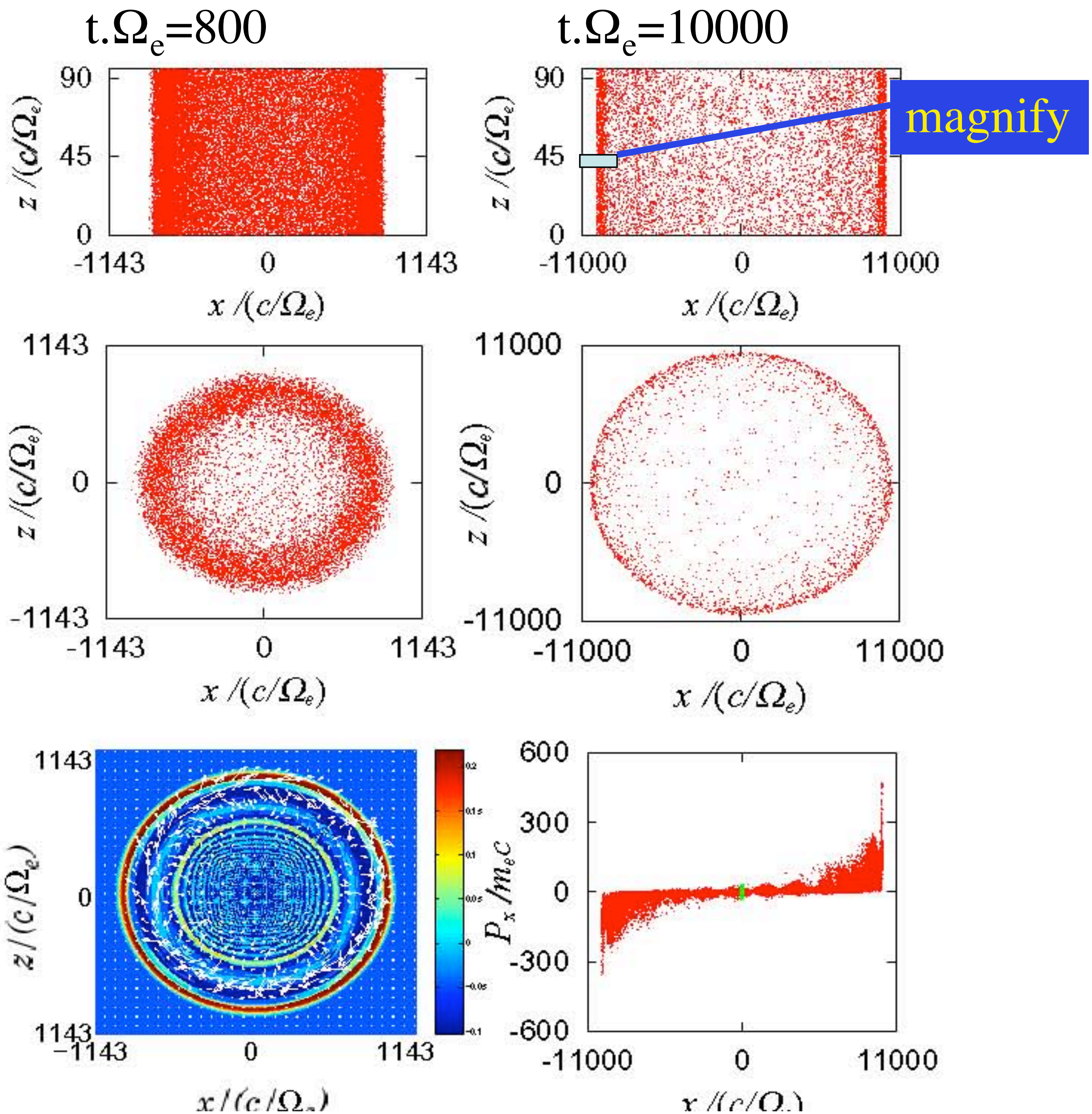
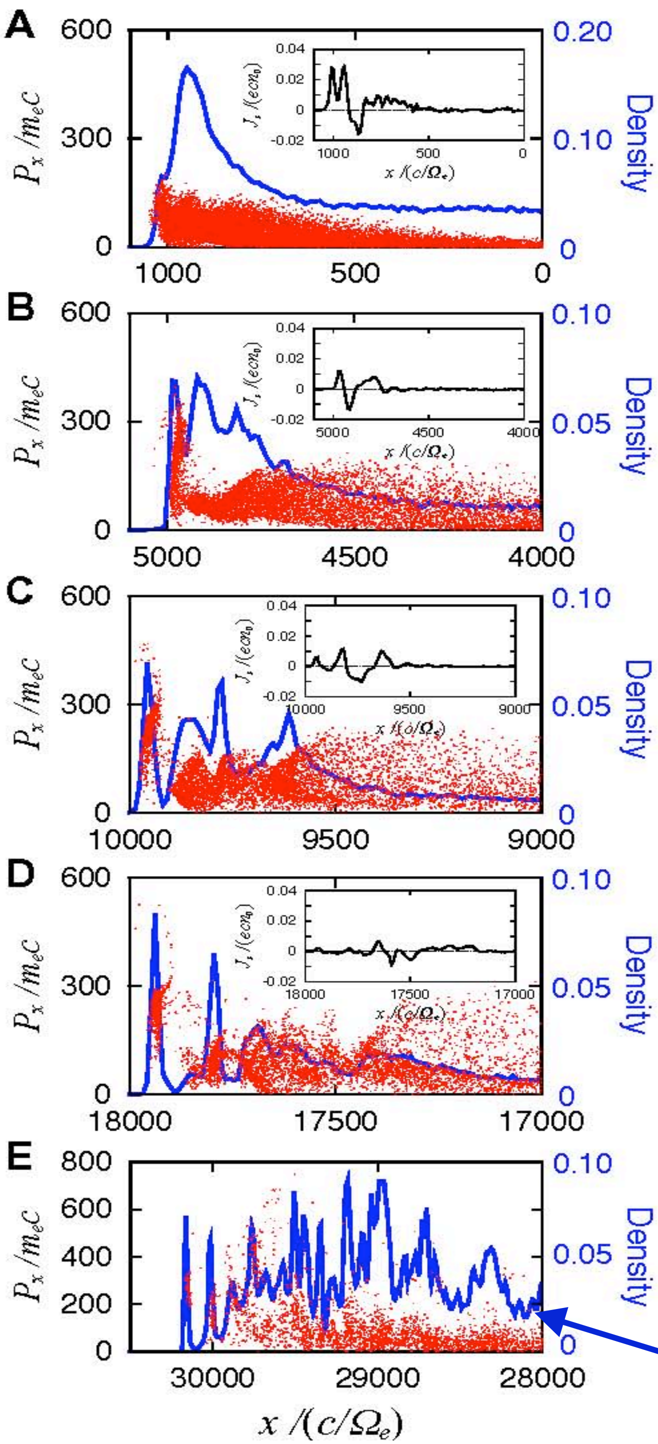
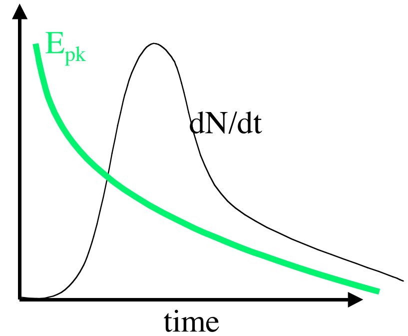
(Liang et al. PRL 90, 085001, 2003)

TPA Occurs whenever EM-dominated plasma is rapidly unconfined *(Liang & Nishimura PRL 91, 175005 2004)*

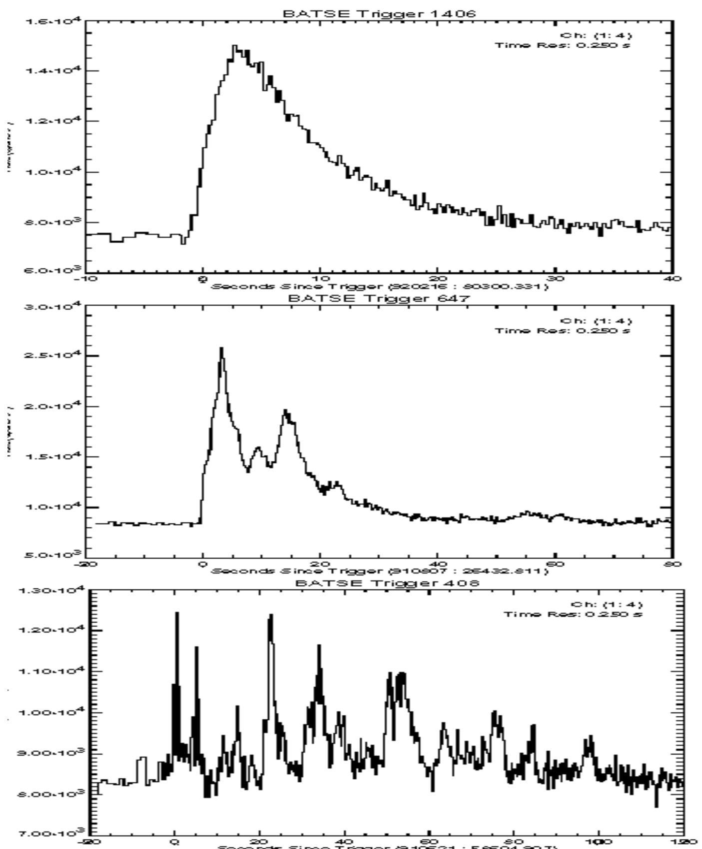
$\Omega_e/\omega_{pe} = 10$







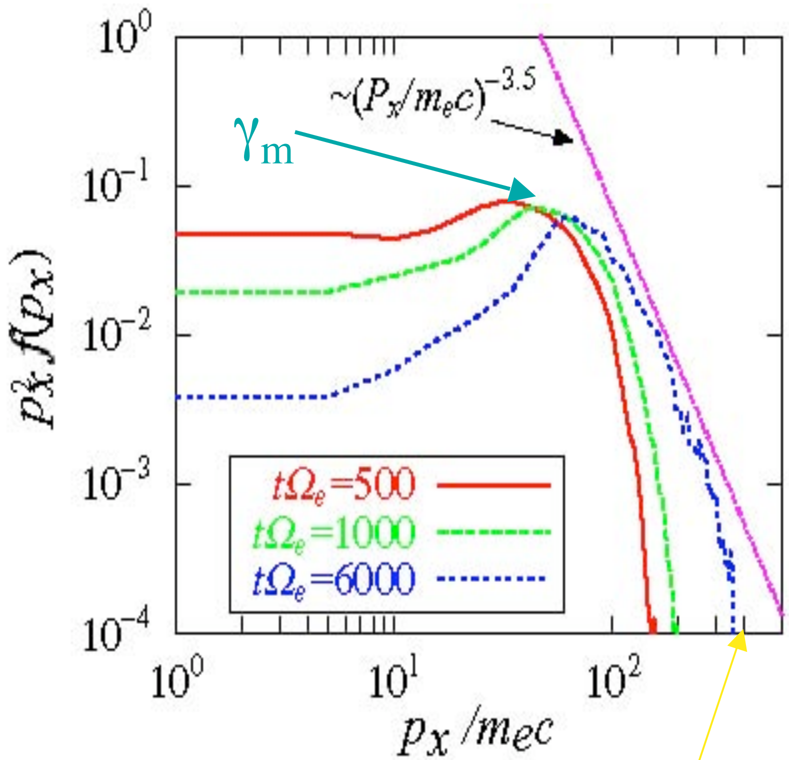
hard-to-soft GRB spectral evolution

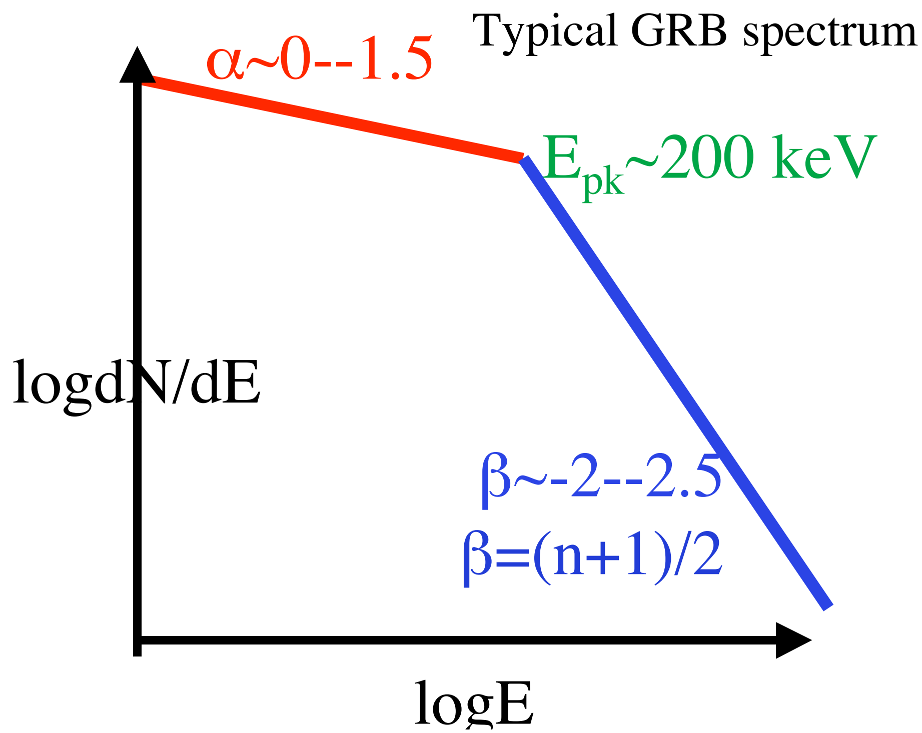


diverse and complex BATSE light curves

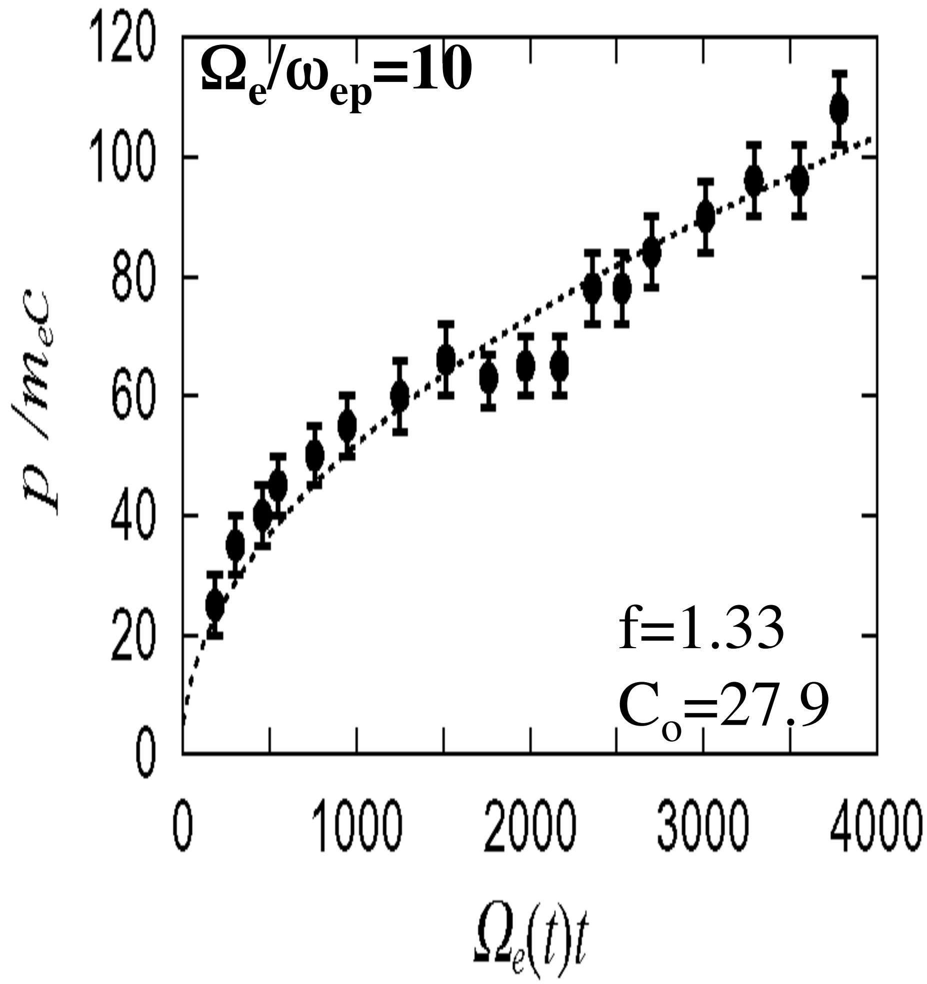
Fourier peak wavelength scales as ~ $c.\gamma_m/\omega_{pe}$

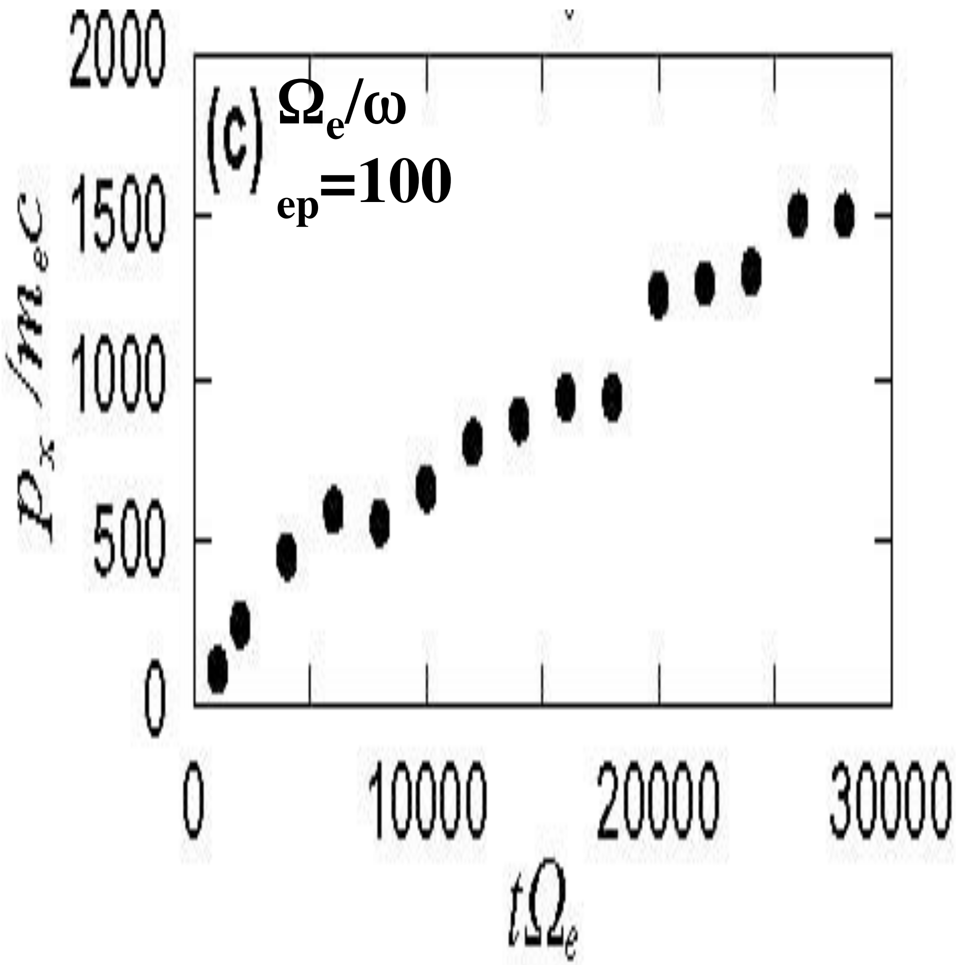
TPA produces Power-Law spectra with low-energy cut-off. Peak Lorentz factor γ_m corresponds roughly to the profile/group velocity of the EM pulse





the maximum $\gamma_{max} \sim e \int E(t)\beta_z dt\ /mc$ where E(t) is the comoving electric field

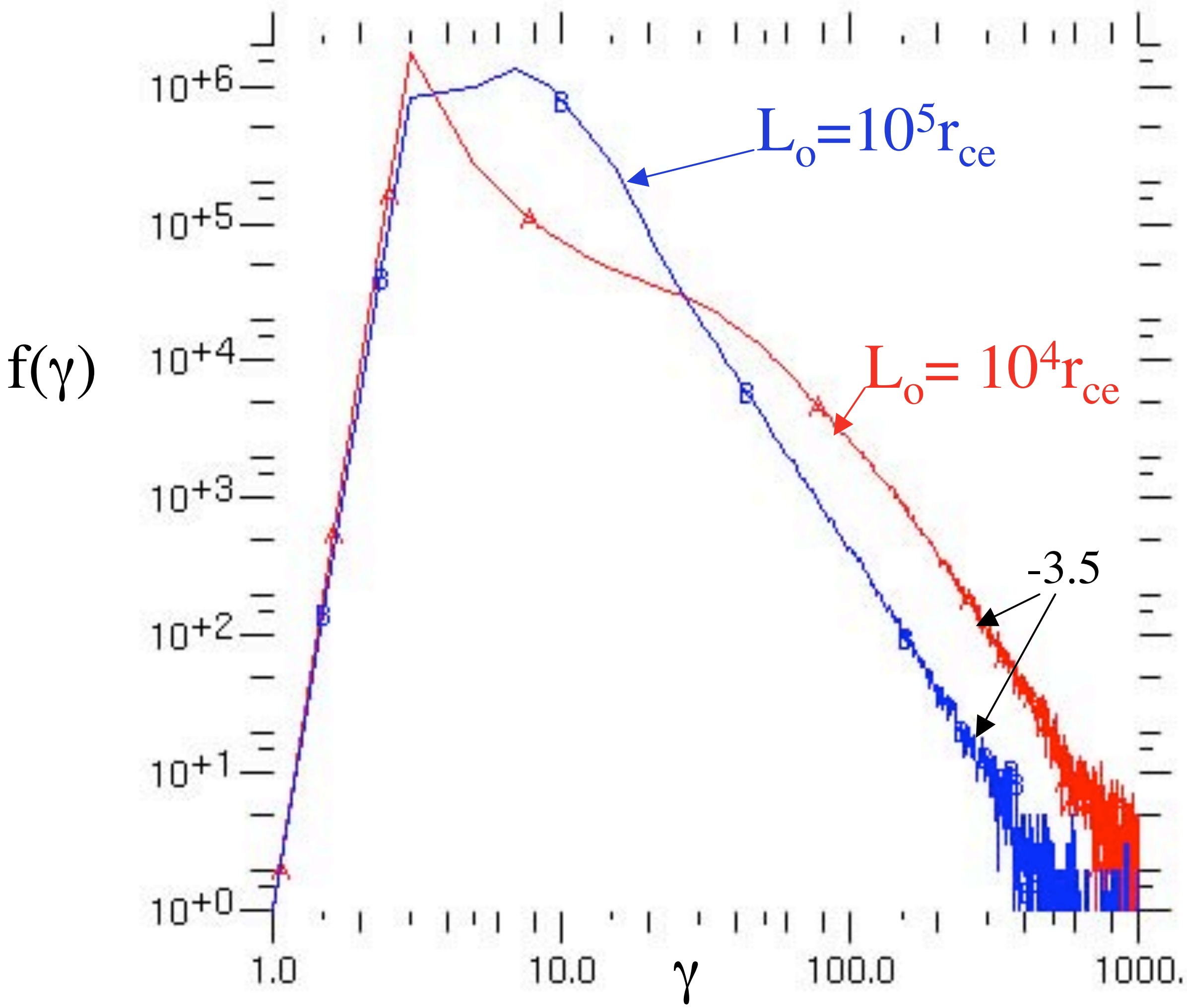




$$\gamma_m(t) = (2f\Omega_e(t)t + C_o)^{1/2} \qquad t \geq L_o/c$$

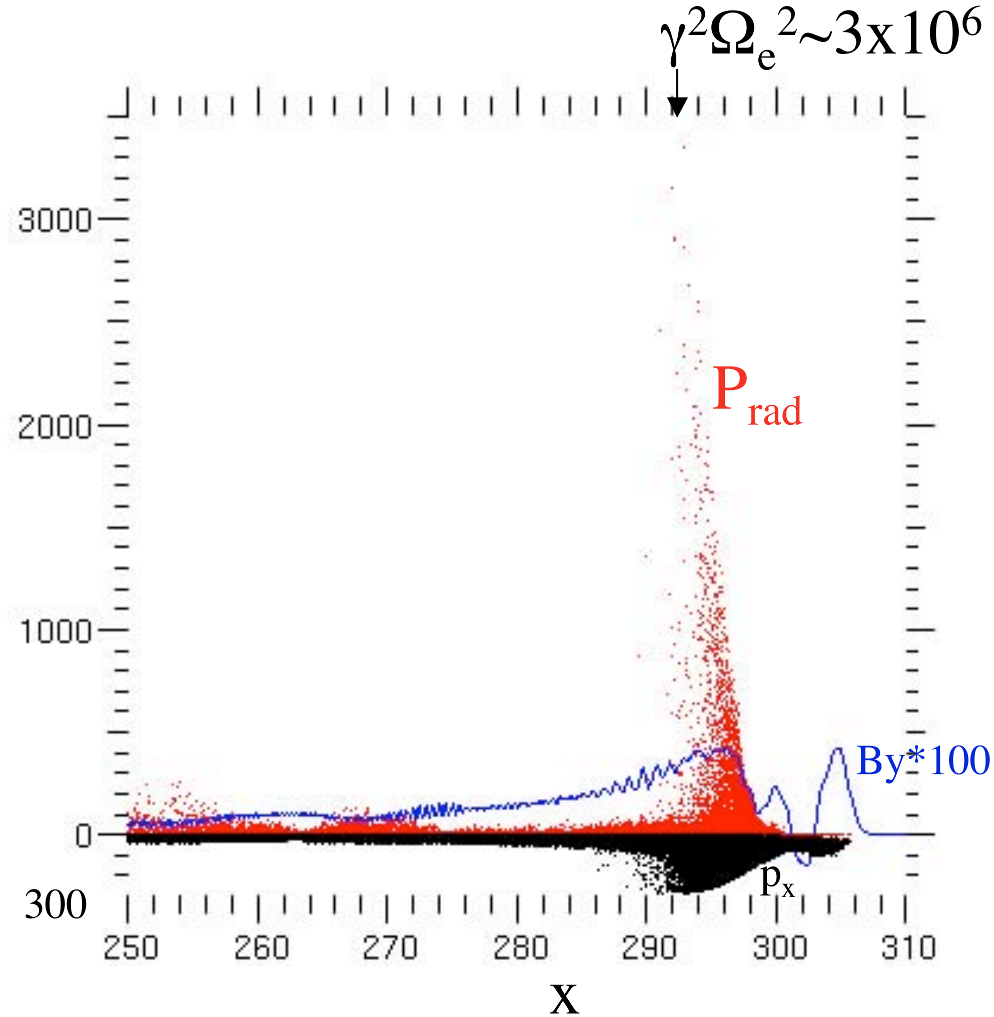
Bulk Lorentz factor grows as ~square-root of time

The power-law index (p ~ 3 - 4) is remarkably robust independent of initial plasma size or temperature and only weakly dependent on B



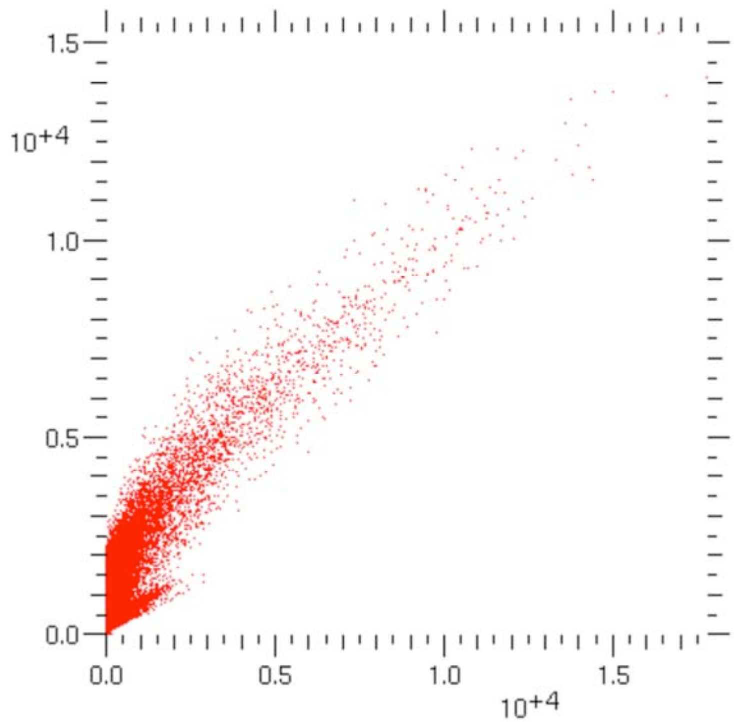
Photon Index
$n=(p+1)/2$
~ 2 -2.5

P_{rad} from TPA << P_{syn}



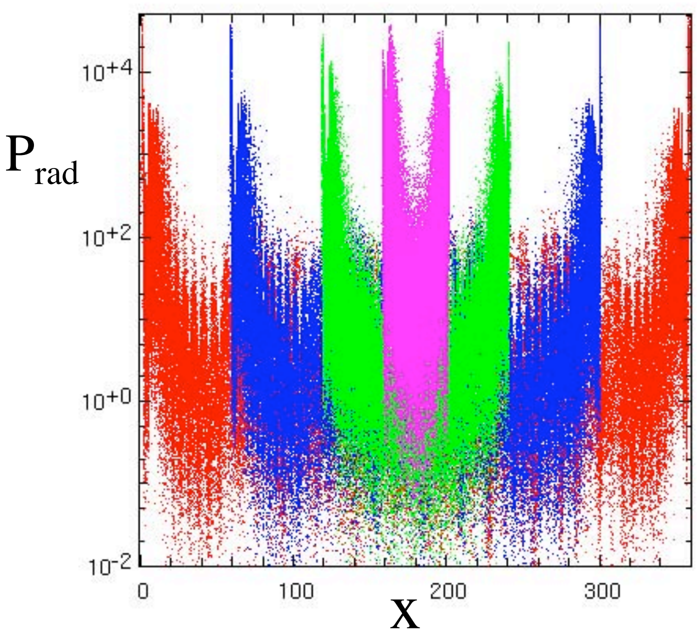
In TPA, we also find $P_{rad} \sim P_{analytic}$ for the highest energy particles

P_{rad}

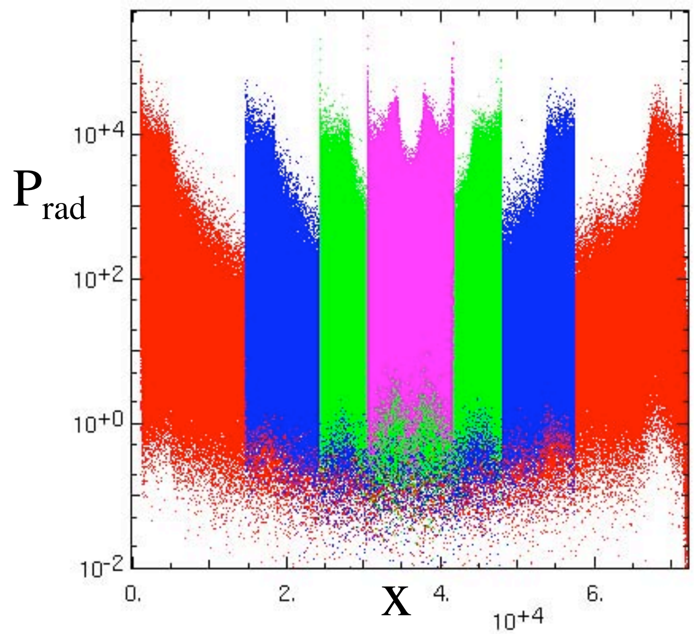


$P_{analytic} \sim \Omega_e{}^2 \gamma^2 \sin^4\alpha$

In TPA jets, P_{rad} asymptotes to ~ constant level at late times as increase in γ is compensated by decrease in α and B



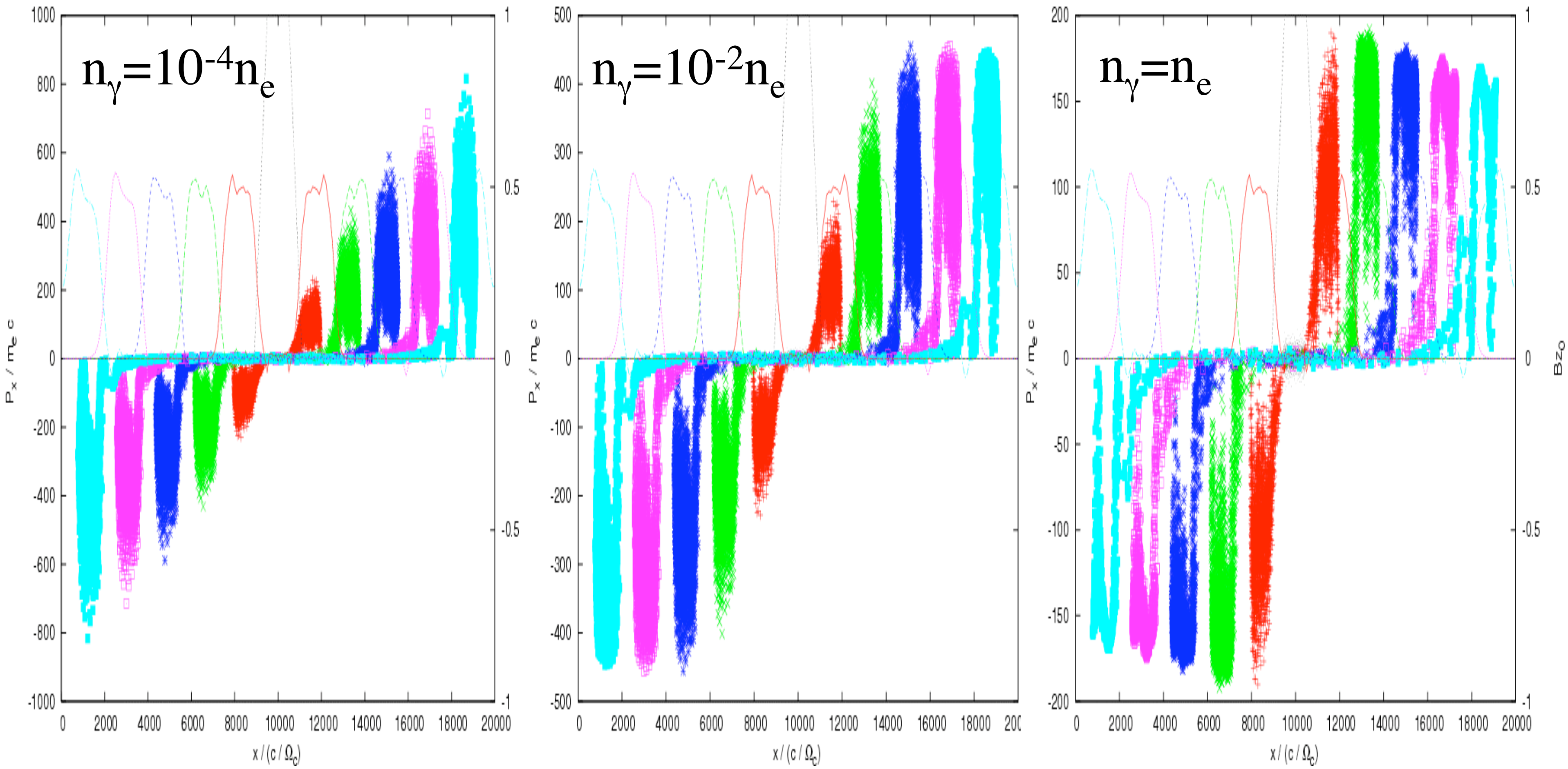
$L_o=120c/\Omega_e$



$L_o=10^5c/\Omega_e$

$p_o=10$

Inverse Compton scattering against ambient photons can slow or stop PF acceleration *(Sugiyama et al 2005)*



1 eV photon field Ω_e/ω_{pe}=100

We have studied radiation from Collisionless Shocks

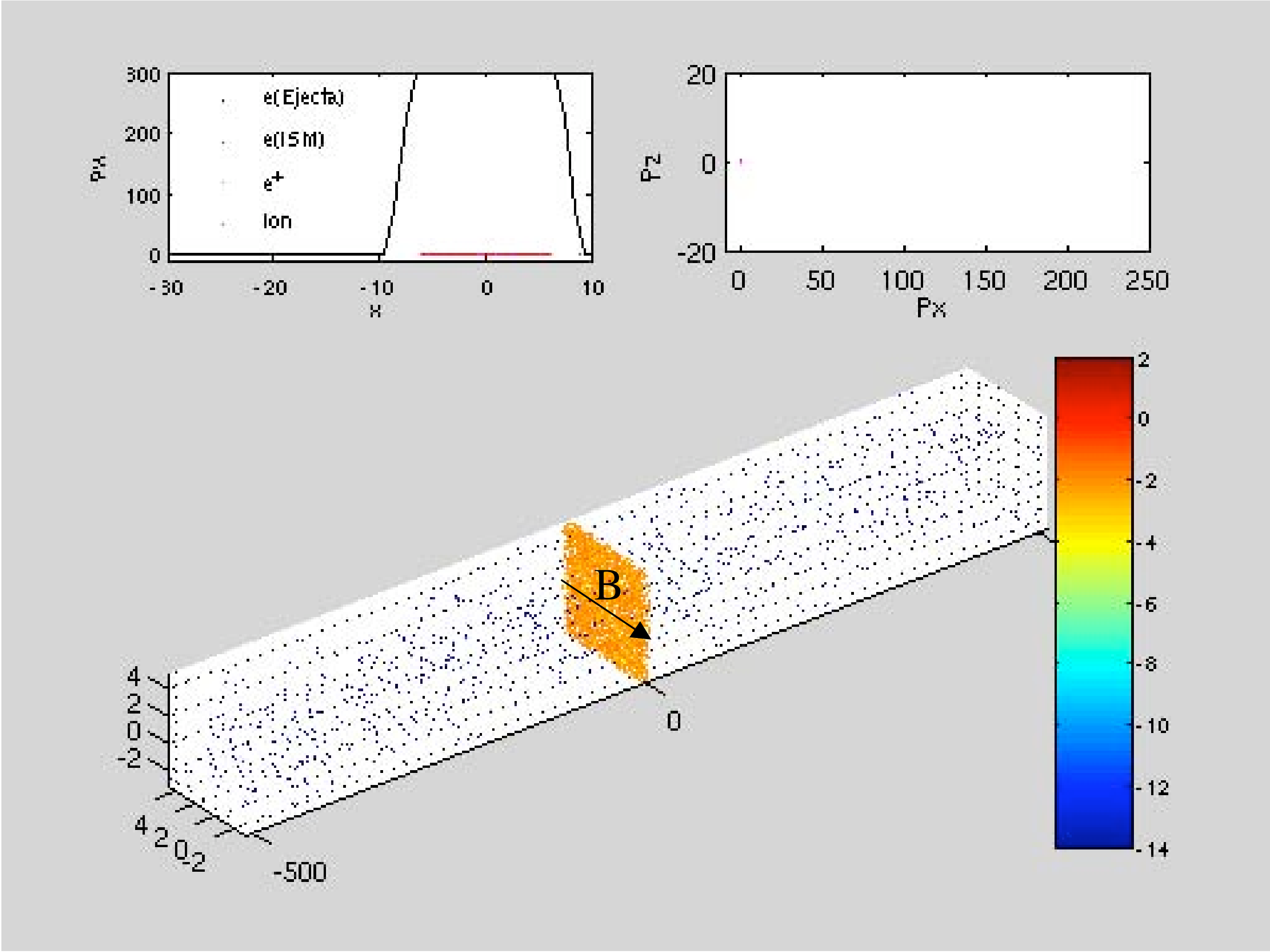
3 Examples:

1. e+e-/e+e- Magnetic Shock (B^2 ~ bulk KE)

2. e+e- /e-ion Magnetic Shock (B^2 ~ bulk KE)

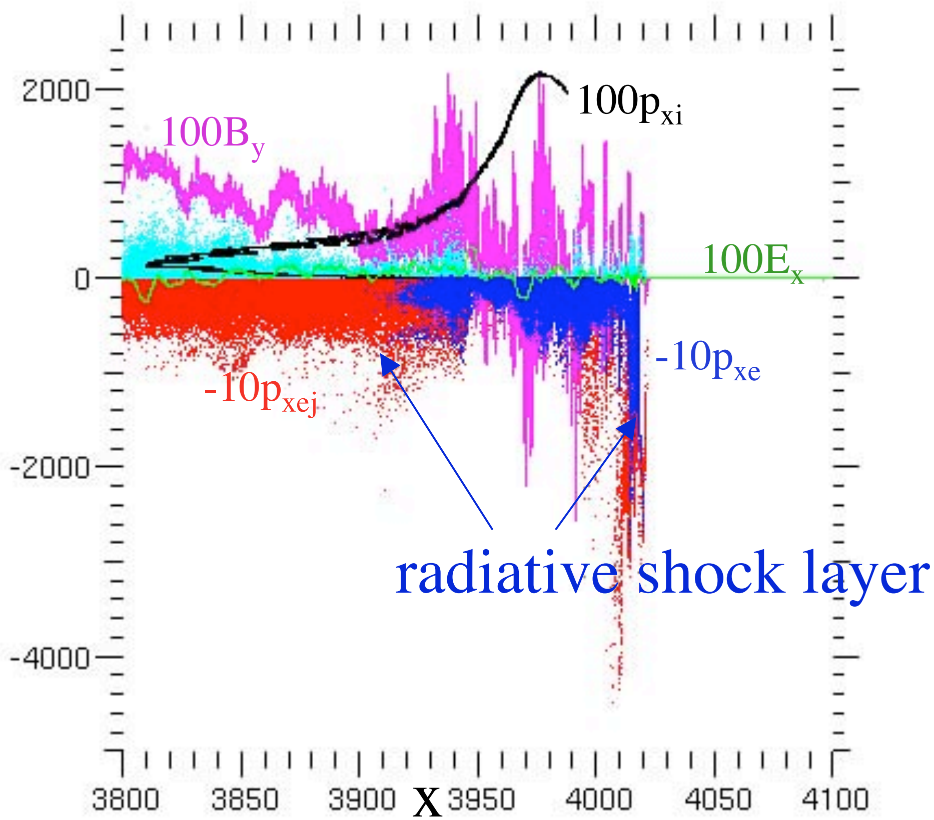
3. e+e- Nonmagnetic Shocks (B^2 << bulk KE)

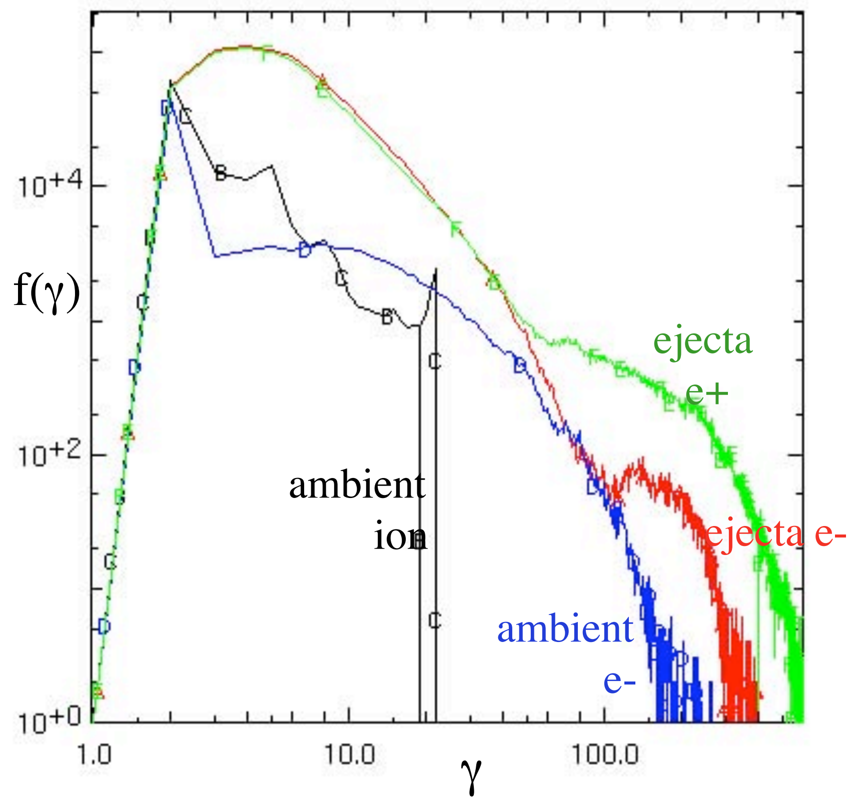
Poynting jet running into cool e-ion ambient plasma



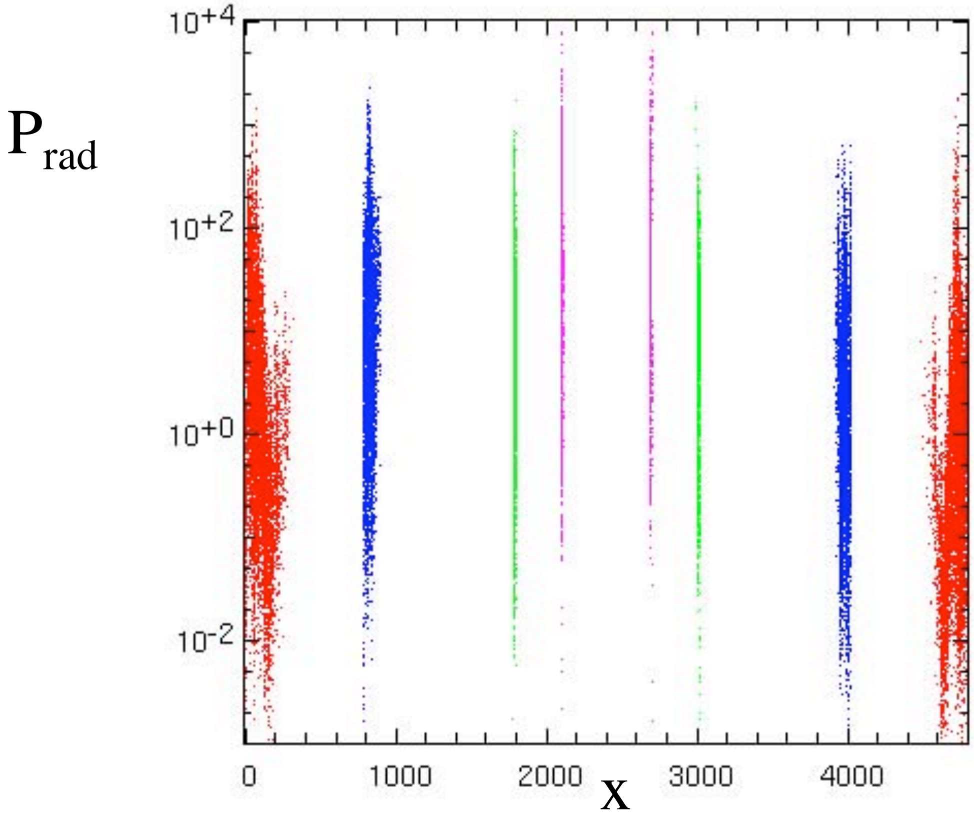
(movie by Noguchi)

Magnetized collisionless shock produced by collision of e+e- Poynting Jet with cold e-ion plasma .





The radiative shock layer bifurcates and gets thicker with time due to ion drag, but max P_{rad} stays ~ constant



swept-up e-

SUMMARY

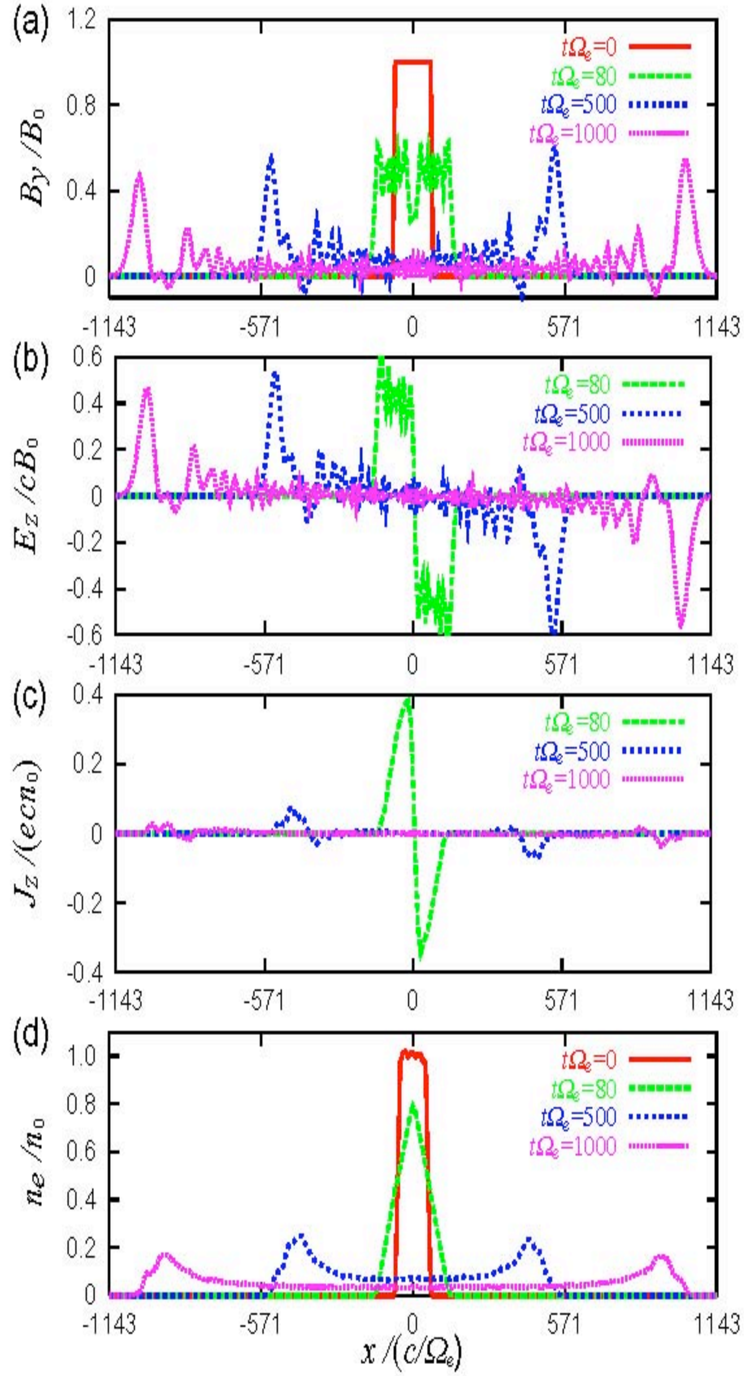
1. Radiation power of Poynting Flux acceleration are orders of magnitude below classical synchrotron formula due to Force ~ parallel to velocity. This feature may be generic and also apply to some Collisionless Shocks.

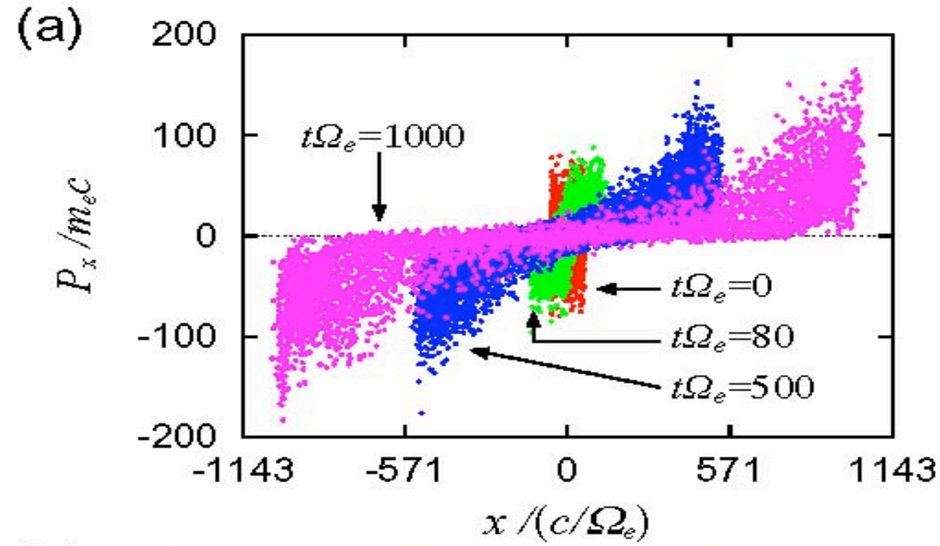
2. Structure and radiation power of collisionless shocks are highly sensitive to magnetization and ion loading. Shocked radiative layer is much thicker and bifurcates in e-ion shocks..

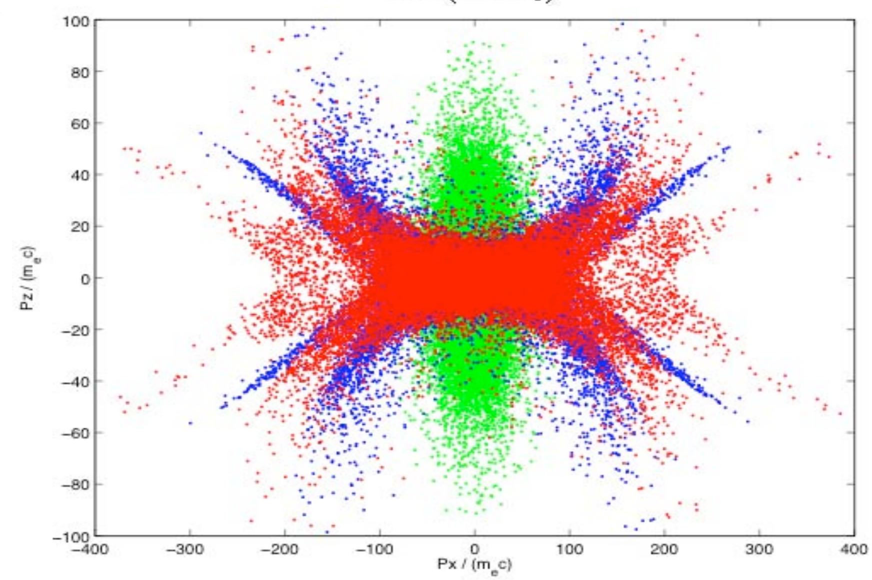
3. Inverse Compton of external photons may dominate synchrotron and SSC.

4. Critical frequency of PF acceleration radiation is much lower than the classical synchrotron critical frequency.

Details of TPA expansion

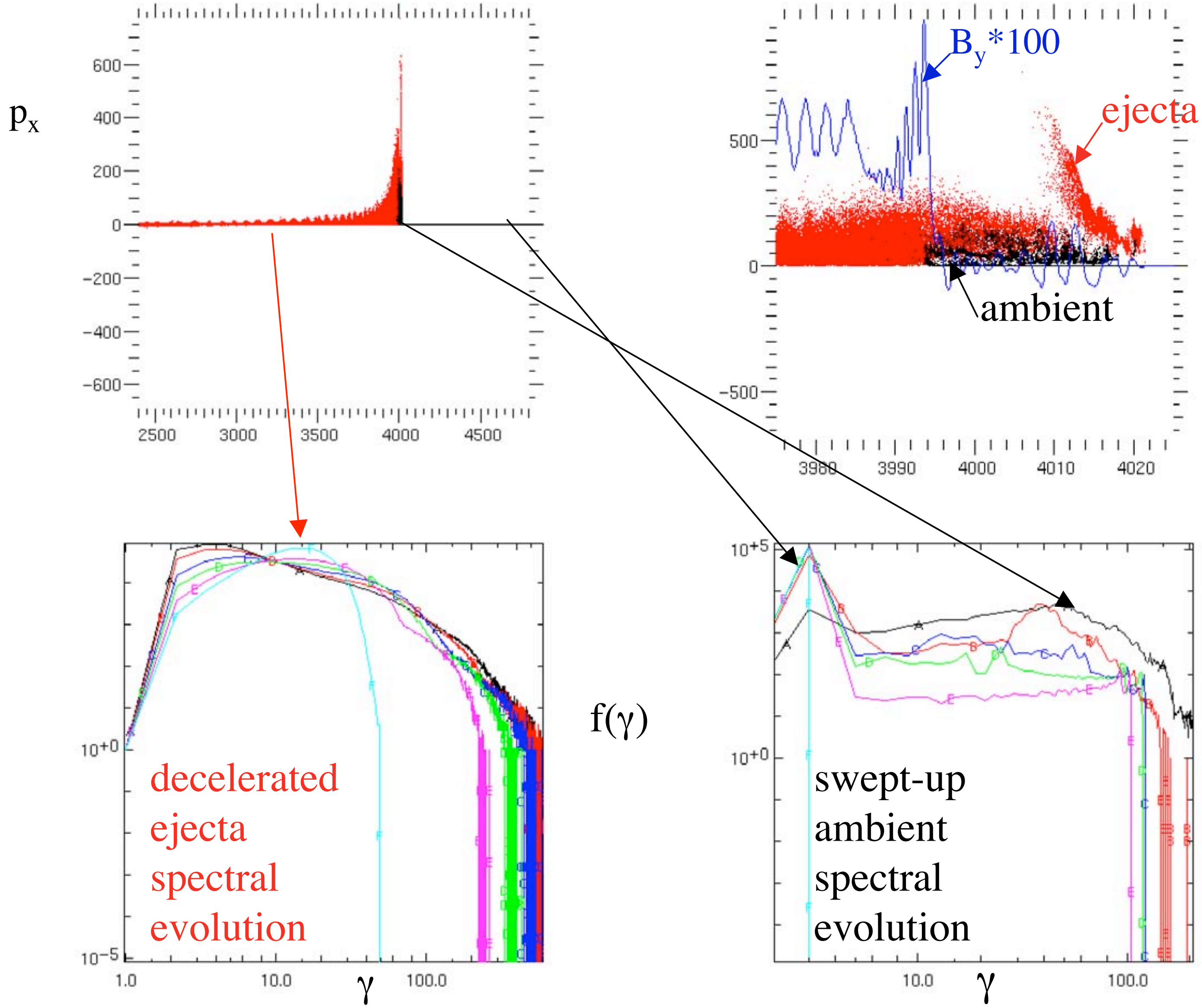




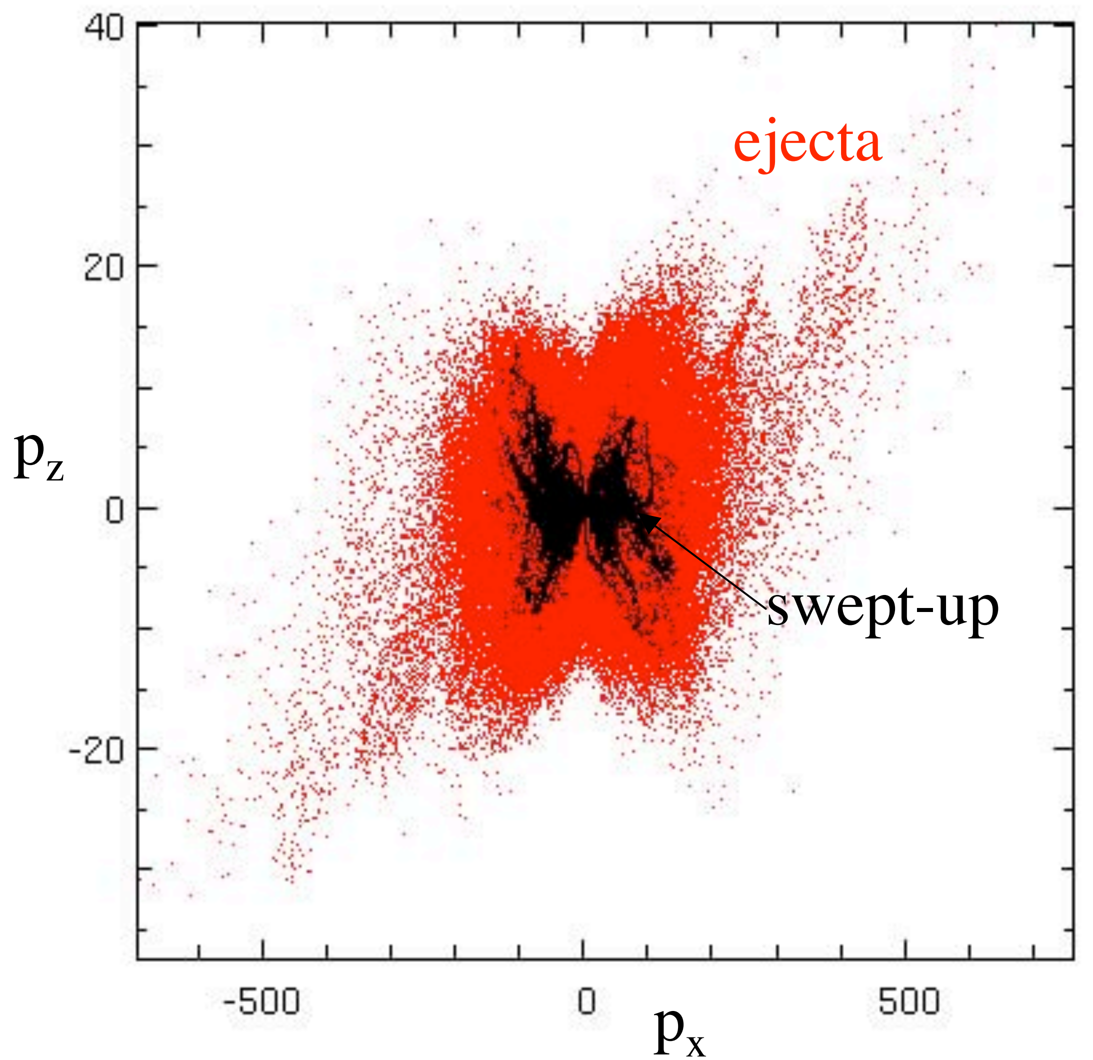


Momentum gets more and more Anisotropic with time: $p_z/p_x<<1$

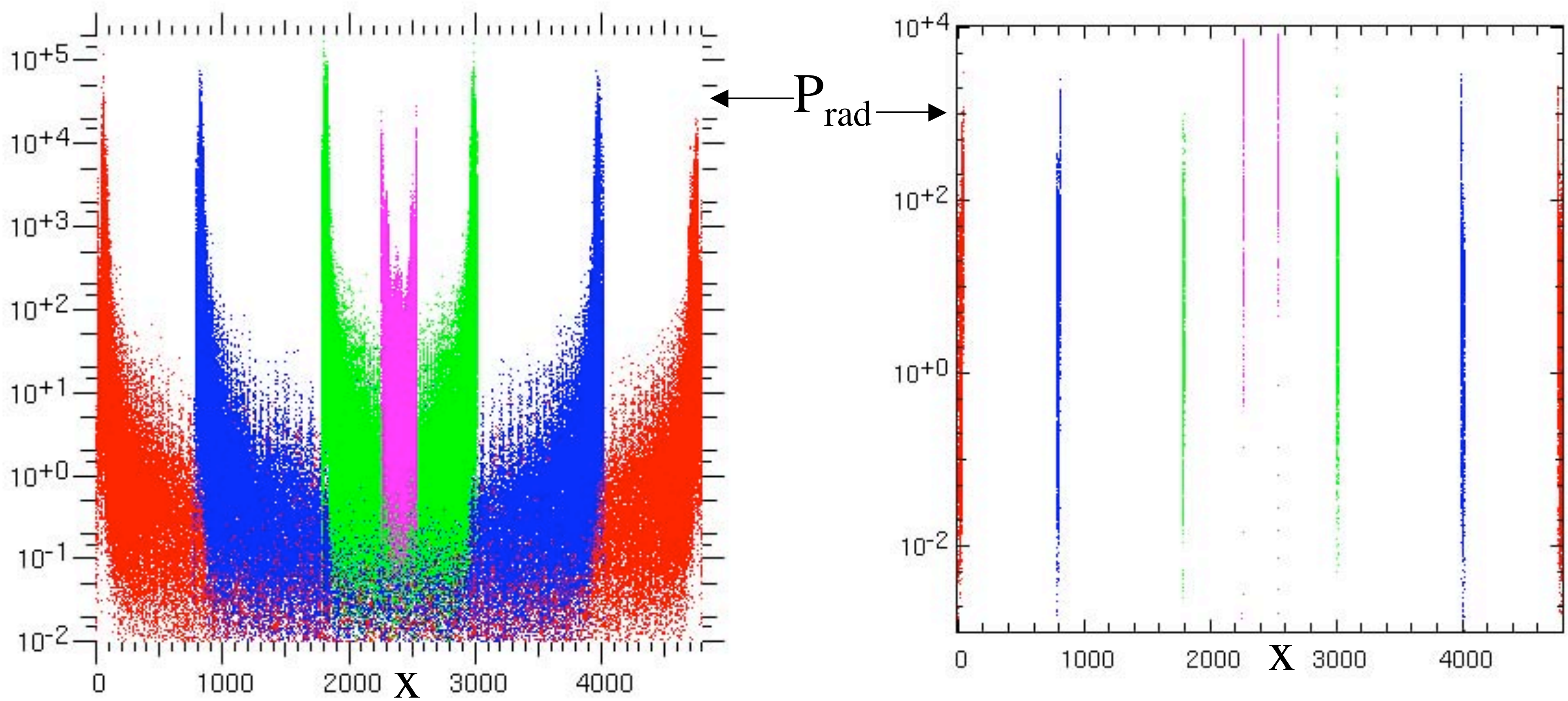
Magnetic Shock of e+e- sweeping up cold ambient e+e- shows broad ($\gg c/\Omega_e$, c/ω_{pe}) transition region with 3-phases ($n_{ej}=40n_o$)



Both ejecta and swept-up electrons are highly anisotropic: $p_z \ll p_x$



P_{rad} of swept-up electron is lower than P_{rad} of decelerating ejecta electron. The radiative layer is very thin

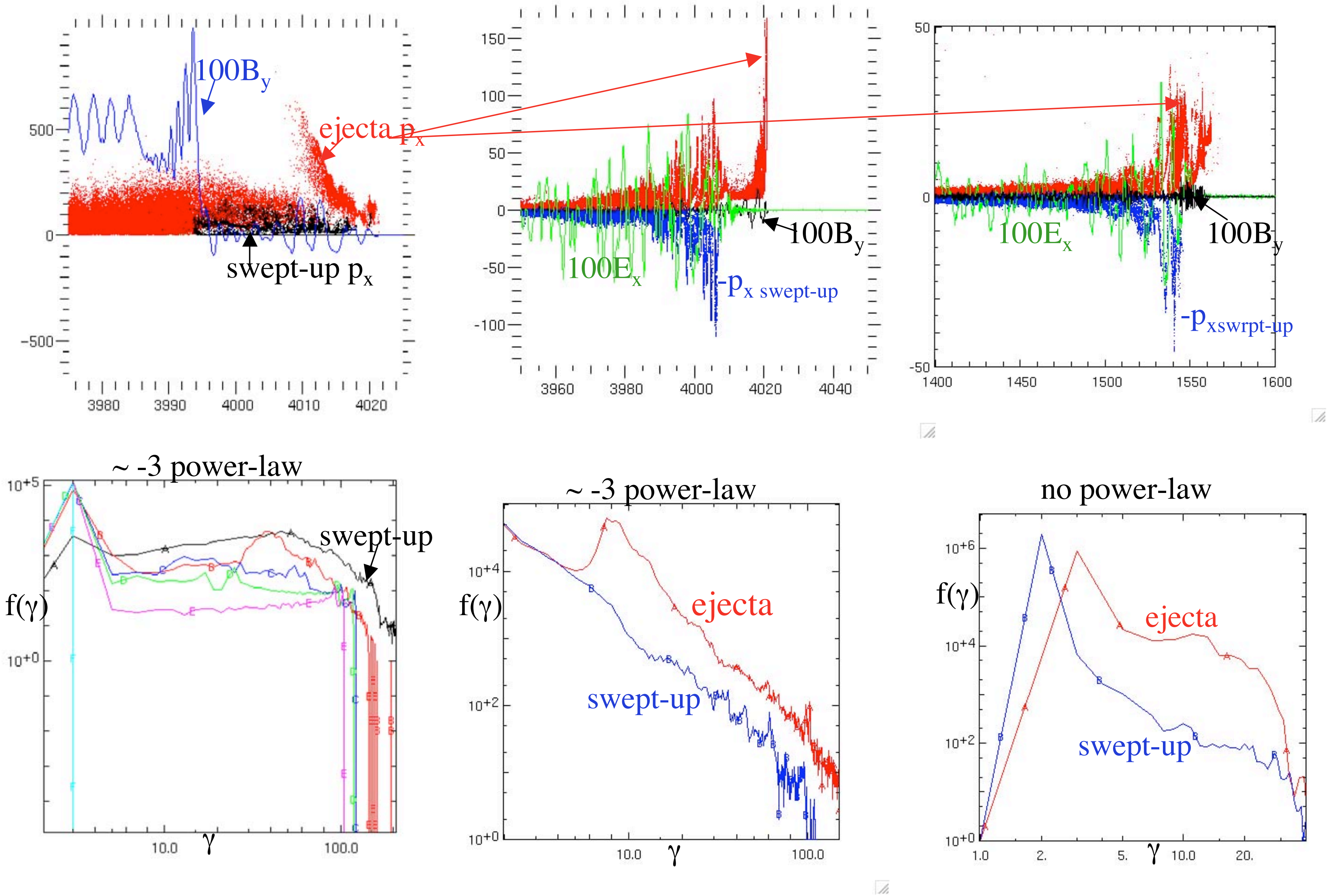


ejecta e-

Swept-up ambient e-

Comparison of collisionless shocks: e+e- shocking B=0 e+e- cold plasma

ejecta: hi-B, hi-γ   weak-B, moderate γ   B=0, low γ



Nonmagnetic e+e-/e+e- shock: Radiation not Dominated By Weibel turbulence