

# Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

**Ken Nishikawa**

*National Space Science & Technology Center/UAH and KITP*



## **Collaborators:**

**J. Niemiec** (*Institute of Nuclear Physics PAN and KITP*)

**M. Medvedev** (*Univ. of Kansas*)

**B. Zhang** (*Univ. Nevada, Las Vegas*)

**P. Hardee** (*Univ. of Alabama, Tuscaloosa*)

**Å. Nordlund** (*Neils Bohr Institute and KITP*)

**J. Frederiksen** (*Neils Bohr Institute*)

**M. Pohl** (*ISU-> U Potsdam/DESY and KITP*)

**H. Sol** (*Meudon Observatory*)

**Y. Mizuno** (*Univ. Alabama in Huntsville/CSPAR*)

**D. H. Hartmann** (*Clemson Univ.*)

**M. Oka** (*UC Berkley*)

**G. J. Fishman** (*NASA/MSFC*)

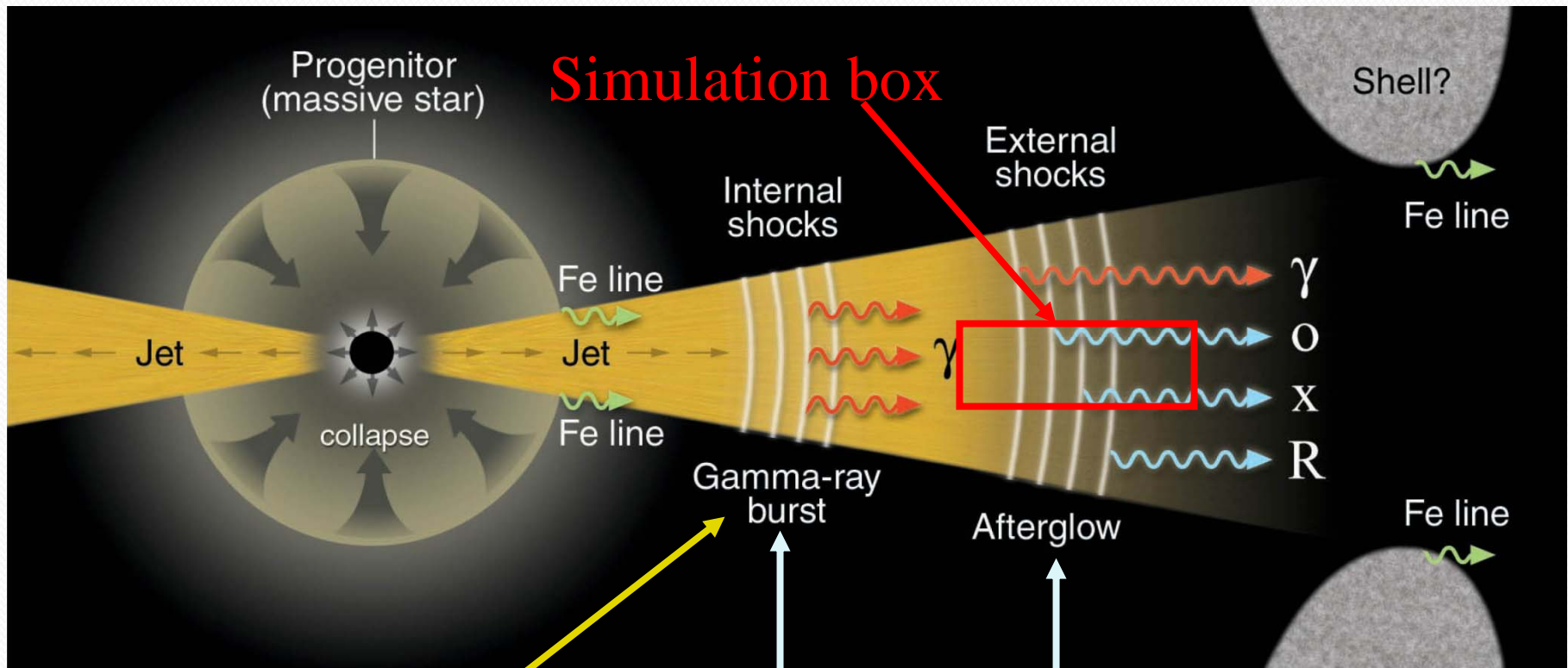
**Particle Acceleration in Astrophysical Plasmas, July 27 - October 2, 2009,  
Kavli Institute for Theoretical Physics, Santa Barbara, CA**

# Outline of talk

- Recent 3-D particle simulations of relativistic jets
  - \*  **$e^\pm$ pair jet** into  **$e^\pm$ pair,  $\gamma = 15$**   
shock structures
- Radiation from two electrons
- **New initial results of radiation from jet electrons which are traced in the simulations self-consistently**
- Future plans of our simulations of relativistic jets

# Schematic GRB from a massive stellar progenitor

(Meszaros, Science 2001)



Prompt emission

Gamma-ray burst

Afterglow

Polarization ?

Accelerated particles emit waves at shocks

# 3-D simulation

with MPI code

injected at  $z = 25\Delta$

*jet*

Weibel inst

Weibel inst

Z

X

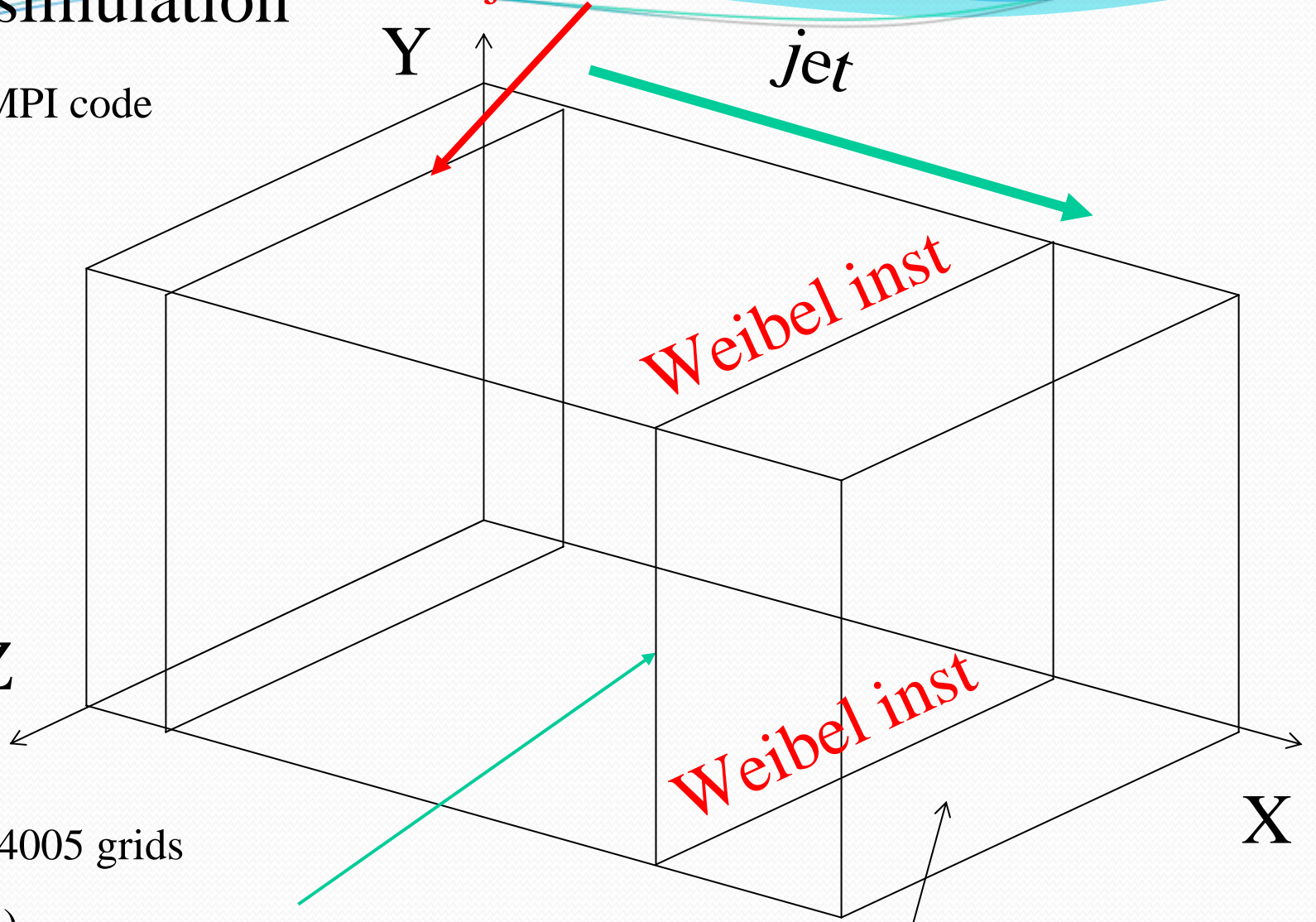
131×131×4005 grids

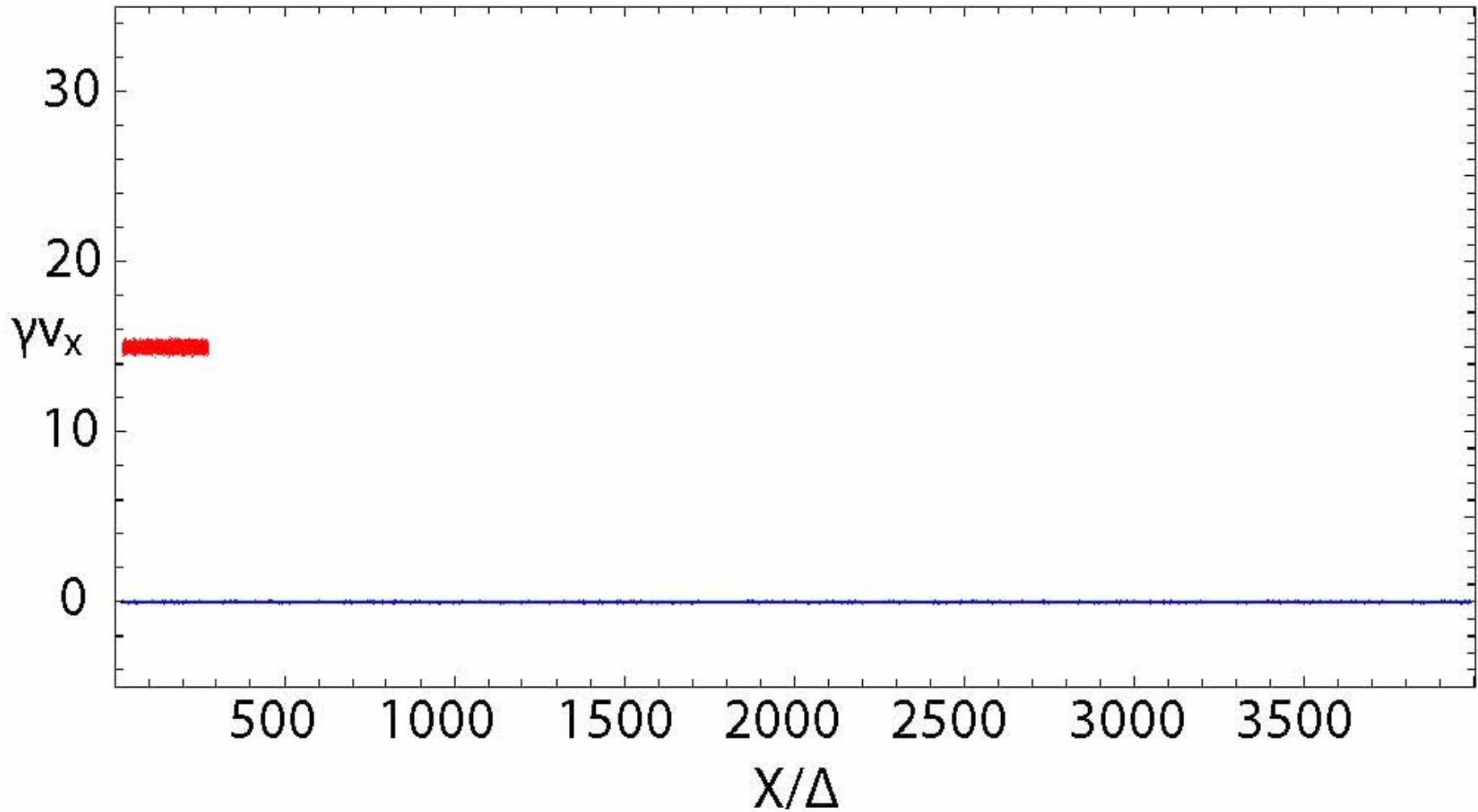
(not scaled)

1.2 billion particles

jet front

ambient plasma





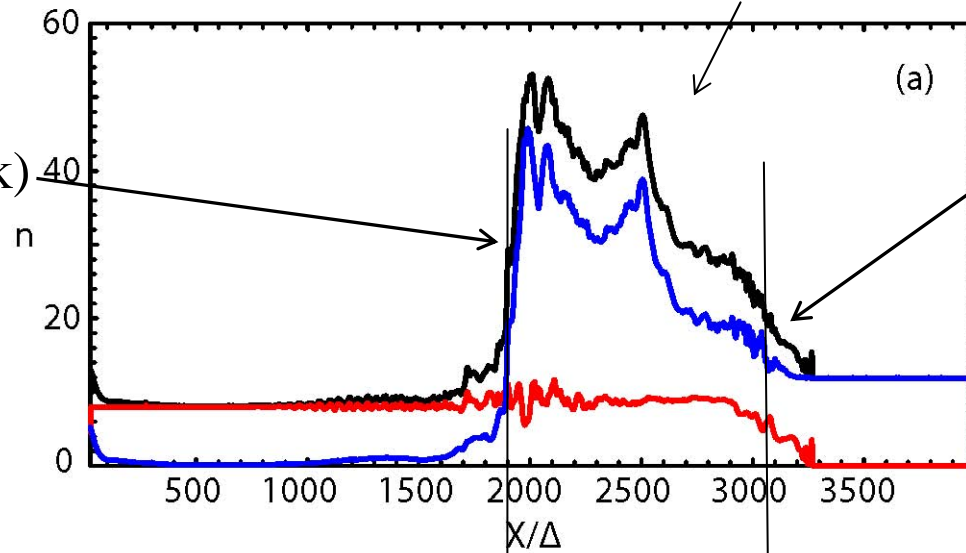
(Nishikawa et al. ApJ, 698, L10, 2009)

# Shock velocity and bulk velocity

# contact discontinuity

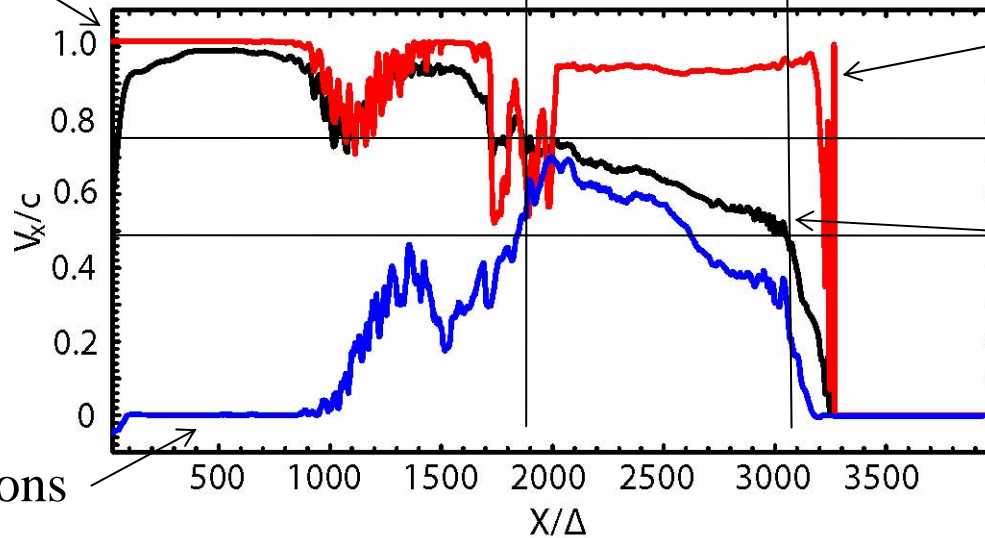
trailing shock  
(reverse shock)

leading shock  
(forward shock)

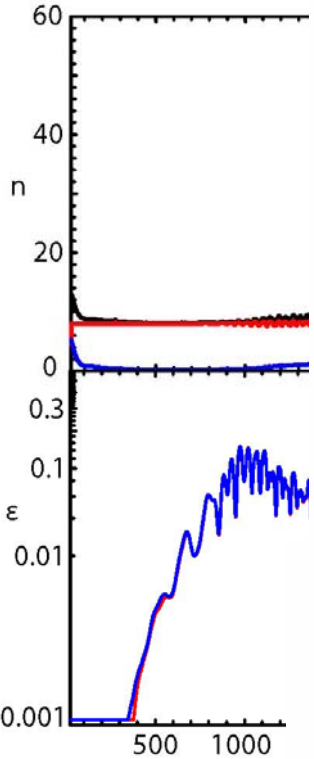


jet electrons

Fermi acceleration ?

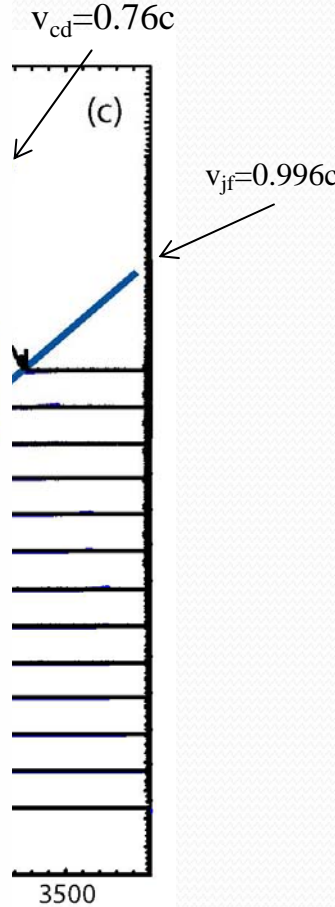
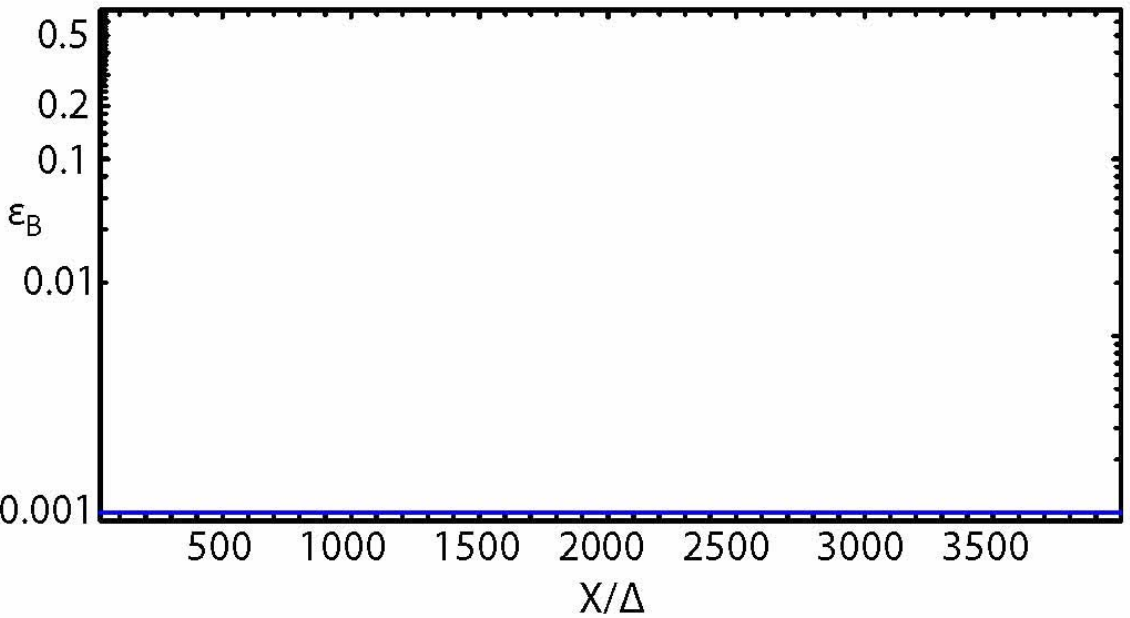
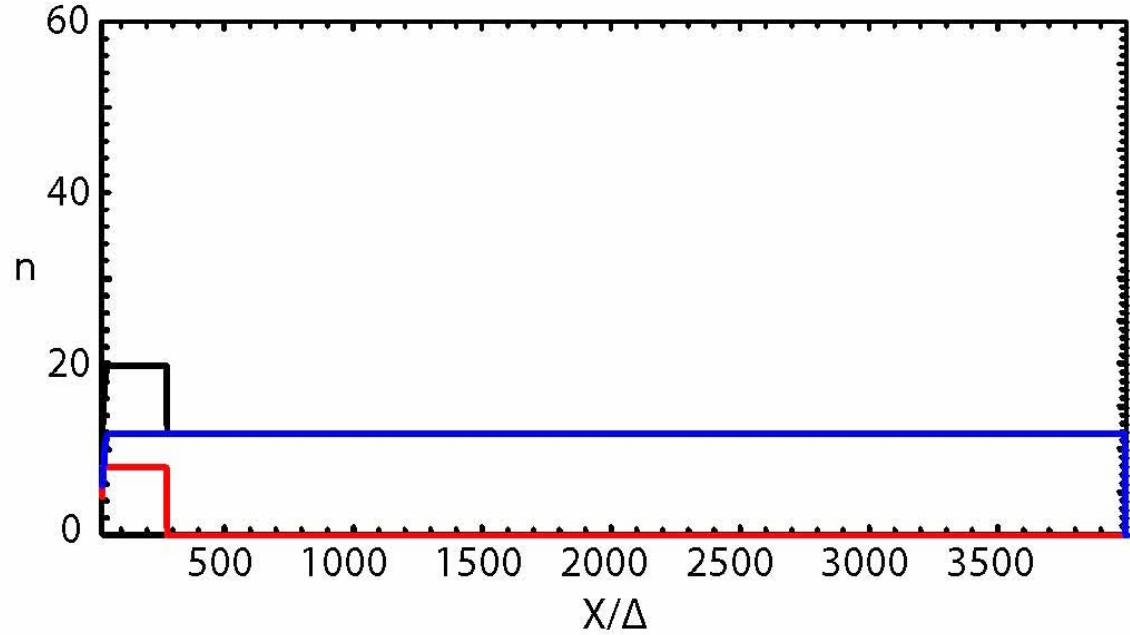


ambient electrons



(a) electron density, magnetic field energy ( $\epsilon_B$ ), and kinetic energy at  $t = 1000$ .

(Nishikawa et al)



(c) electron density. The predicted density, and the

# Shock velocity and structure based on 1-D HD analysis

moving contact discontinuity (CD)

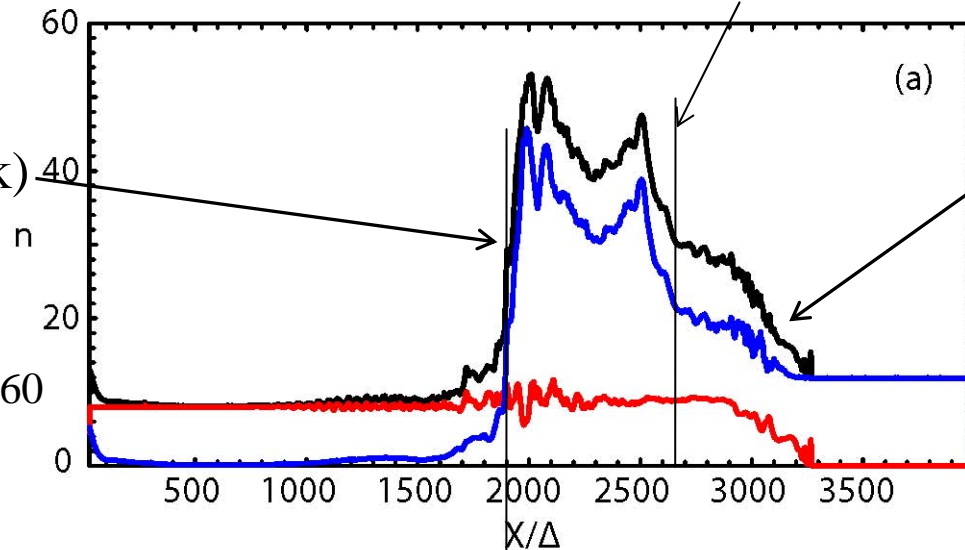
trailing shock  
(reverse shock)

in CD frame

$$n_{sj} / \gamma'_{cd} n_j = 3.36$$

$$\beta_s = 0.417 \quad \gamma'_{cd} = 5.60$$

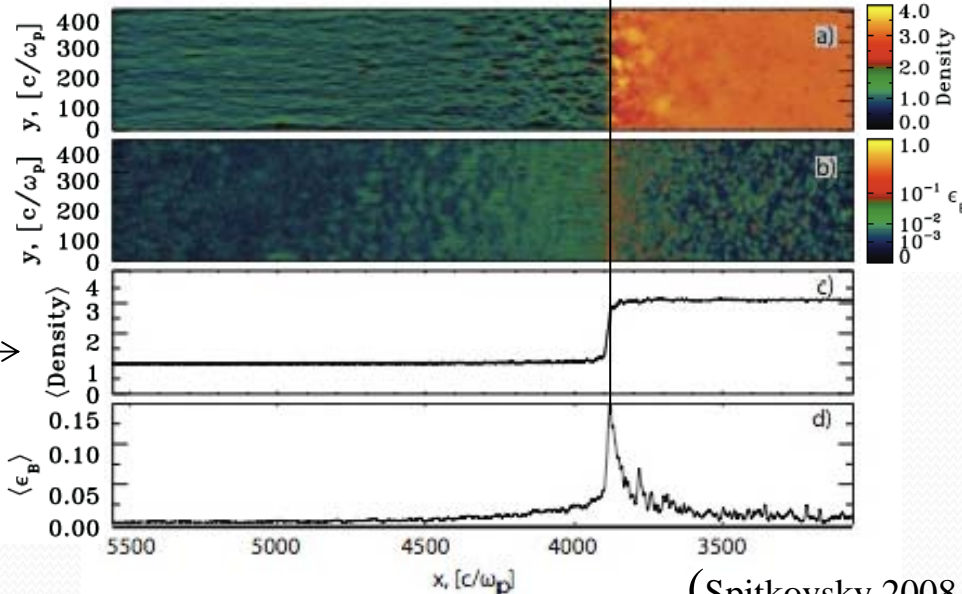
$$4/3 < \Gamma = 3/2 < 5/3$$



leading shock  
(forward shock)

(Nishikawa et al. 2009)

fixed CD



Density →

$$n_2 / \gamma_0 n_1 = 3.13$$

$$\beta_c = 0.47$$

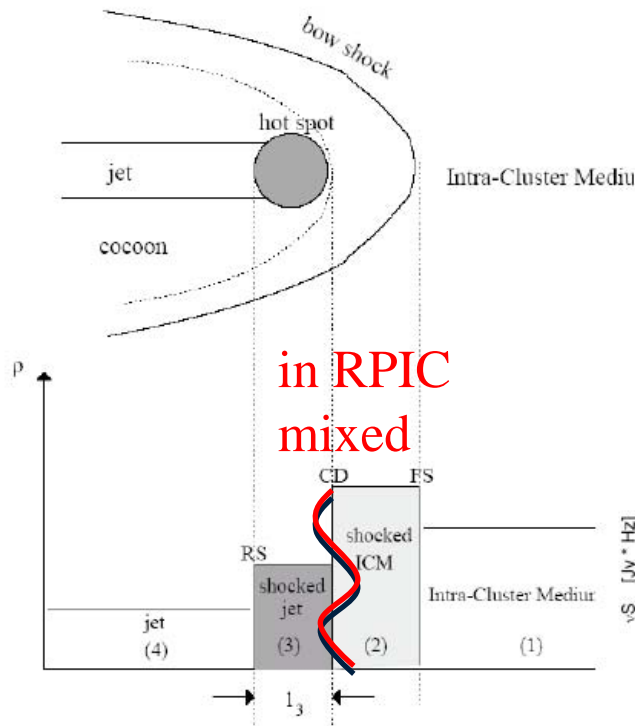
$$\gamma_0 = 15$$

(Spitkovsky 2008 (adapted))

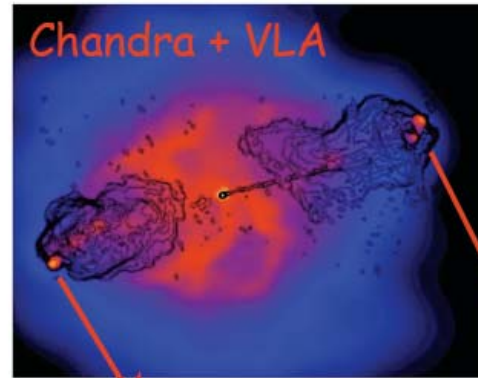


# Terminal Hotspots

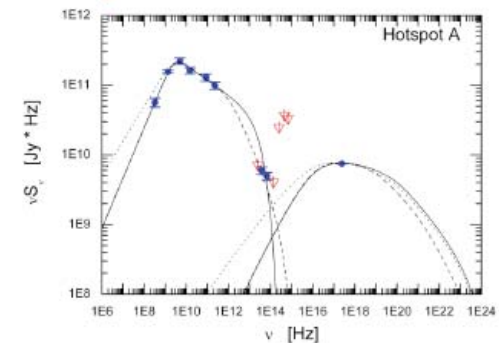
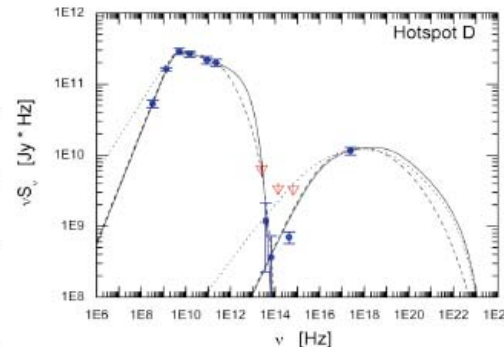
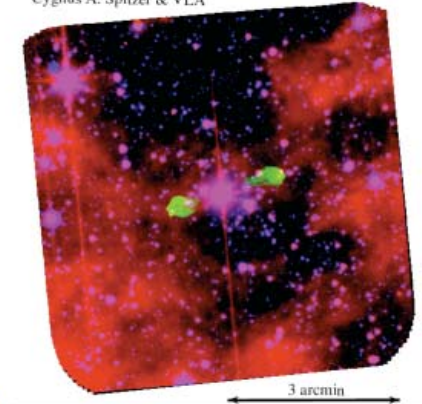
Kino & Takahara 04



Hotspots in powerful radio sources are understood as the terminal regions of relativistic jets, where bulk kinetic power transported by the outflows from the active centers is converted at a strong shock (formed due to the interaction of the jet with the ambient gaseous medium) to the internal energy of the jet plasma.



Cygnus A: Spitzer & VLA



Hotspots of exceptionally bright radio galaxy Cygnus A ( $d_L = 250$  Mpc) can be resolved at different frequencies (VLA, Spitzer, Chandra), enabling us to understand how (mildly) relativistic shocks work (LS+ 07).

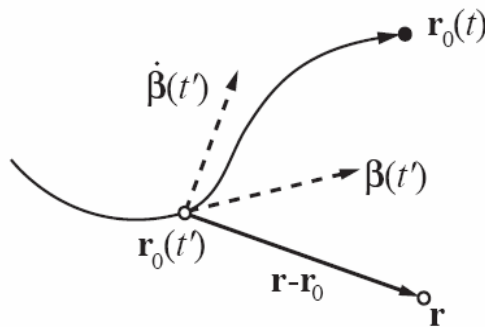
from the talk by L. Stawarz

## Radiation from particles in collisionless shock

To obtain a spectrum, “just” integrate:

$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 c q^2}{16\pi^3} \left| \int_{-\infty}^{\infty} \frac{\mathbf{n} \times [(\mathbf{n} - \boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}}]}{(1 - \boldsymbol{\beta} \cdot \mathbf{n})^2} e^{i\omega(t' - \mathbf{n} \cdot \mathbf{r}_0(t')/c)} dt' \right|^2$$

where  $\mathbf{r}_0$  is the position,  $\boldsymbol{\beta}$  the velocity and  $\dot{\boldsymbol{\beta}}$  the acceleration



**New approach:** Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

Hededal, Thesis 2005 (astro-ph/0506559)

Nishikawa et al. 2008 (astro-ph/0802.2558)

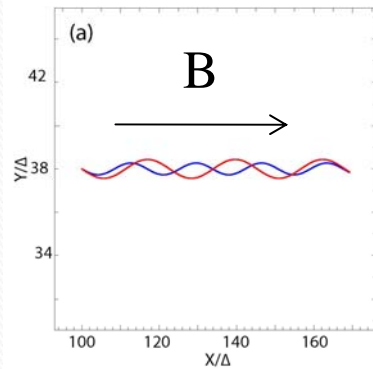
Sironi & Spitkovsky, 2009 (astro-ph/0908.3193)

Martins et al. 2009, Proc. of SPIE Vol. 7359

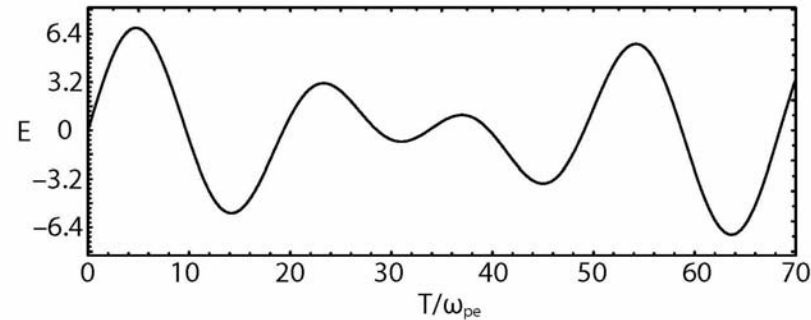
(see also two posters by J. Martins and S. Martins)

# Synchrotron radiation from propagating electrons in a uniform magnetic field

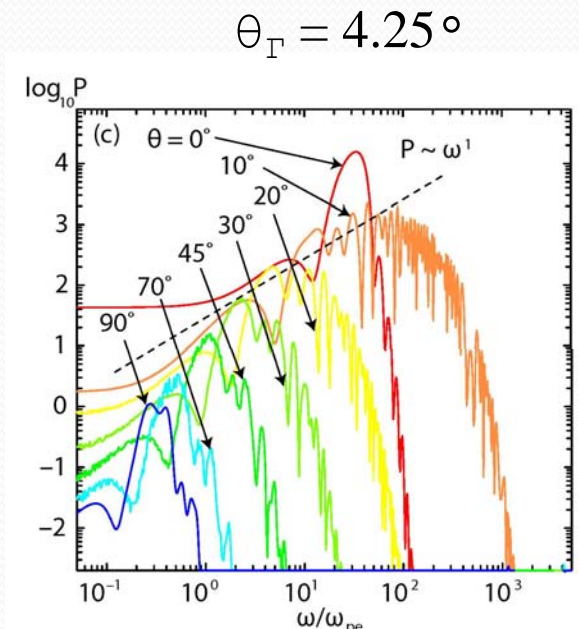
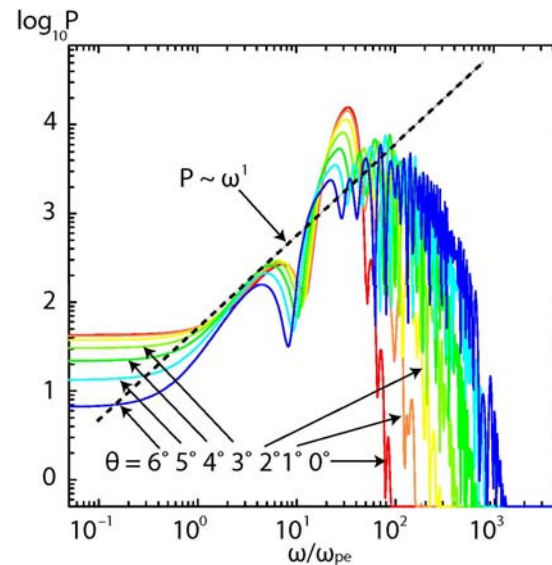
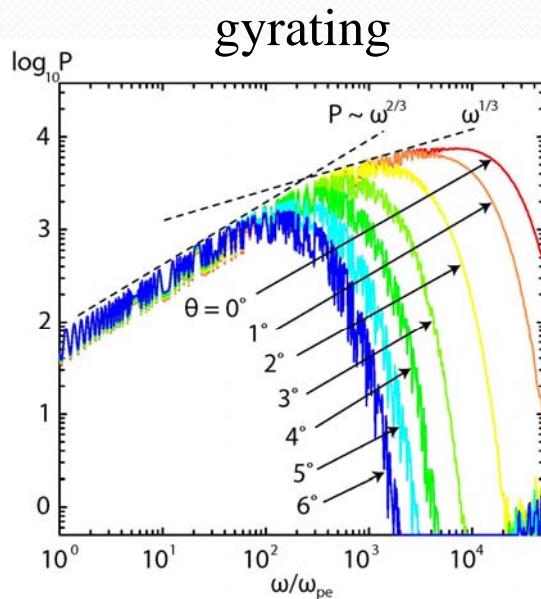
electron trajectories



radiation electric field observed at long distance



spectra with different viewing angles

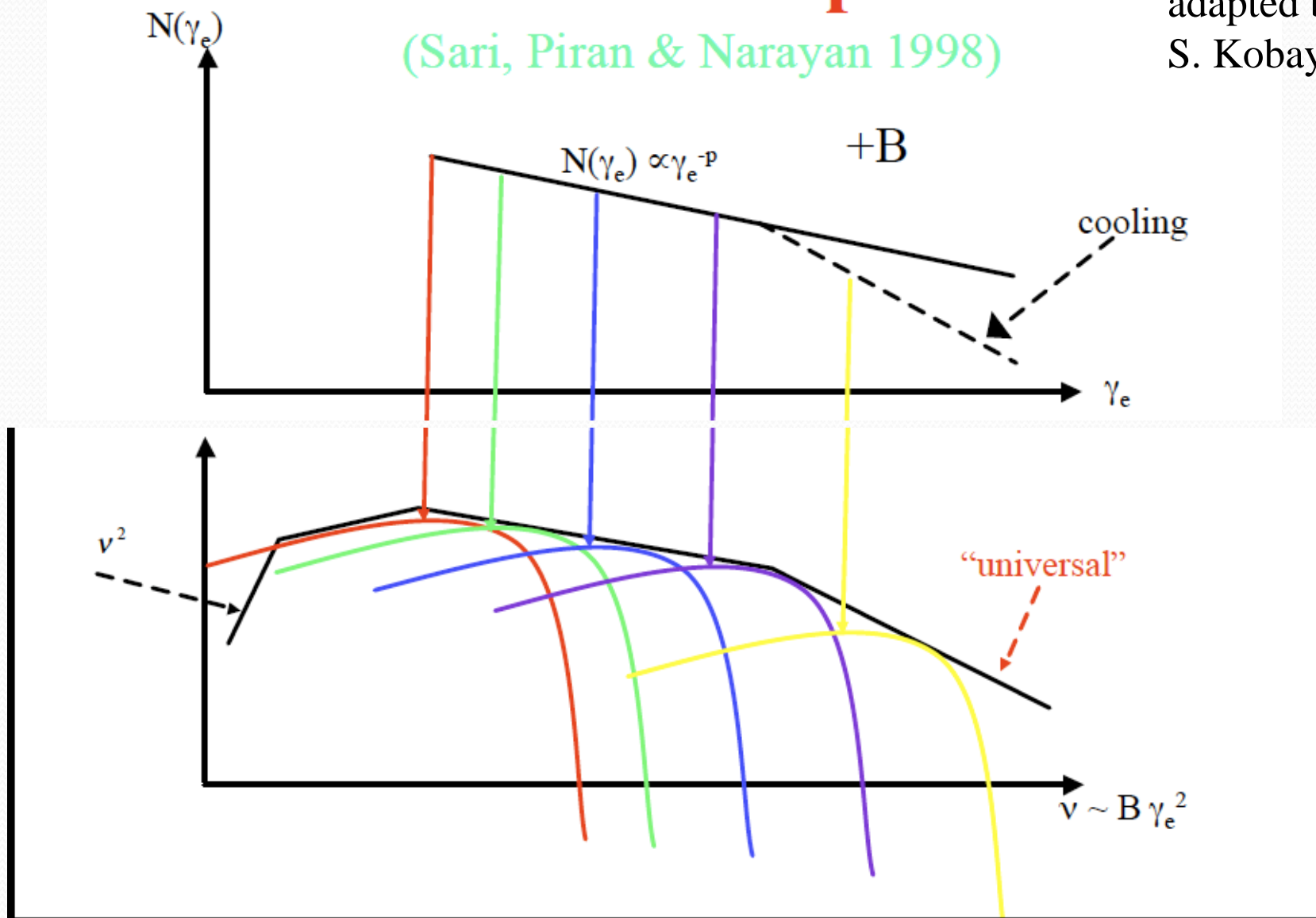


# Synchrotron Emission: radiation from accelerated

## Theoretical Spectra

(Sari, Piran & Narayan 1998)

adapted by  
S. Kobayashi

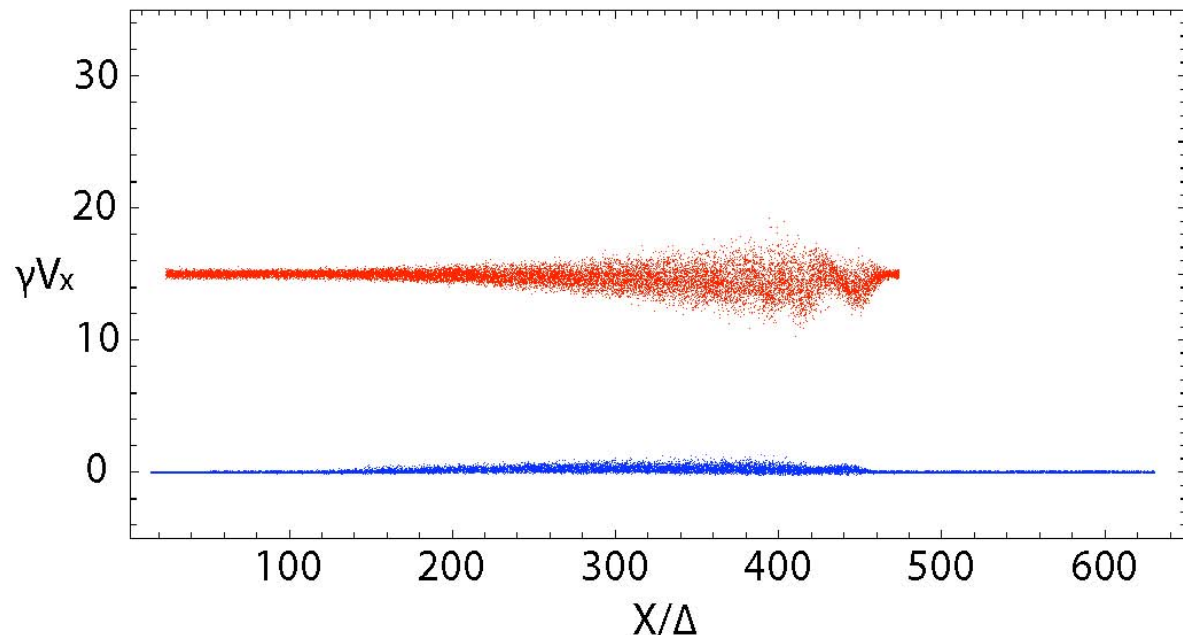
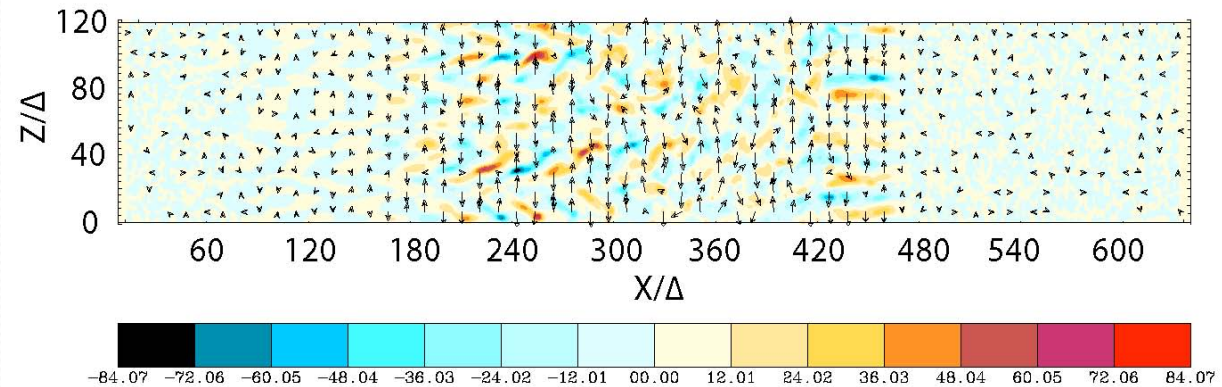


# Jitter radiation from electrons by tracing trajectories self-consistently

using a small simulation system

initial setup for jitter radiation

select electrons  
(12,150)  
in jet and ambient



# final condition for jitter radiation

15,000 steps

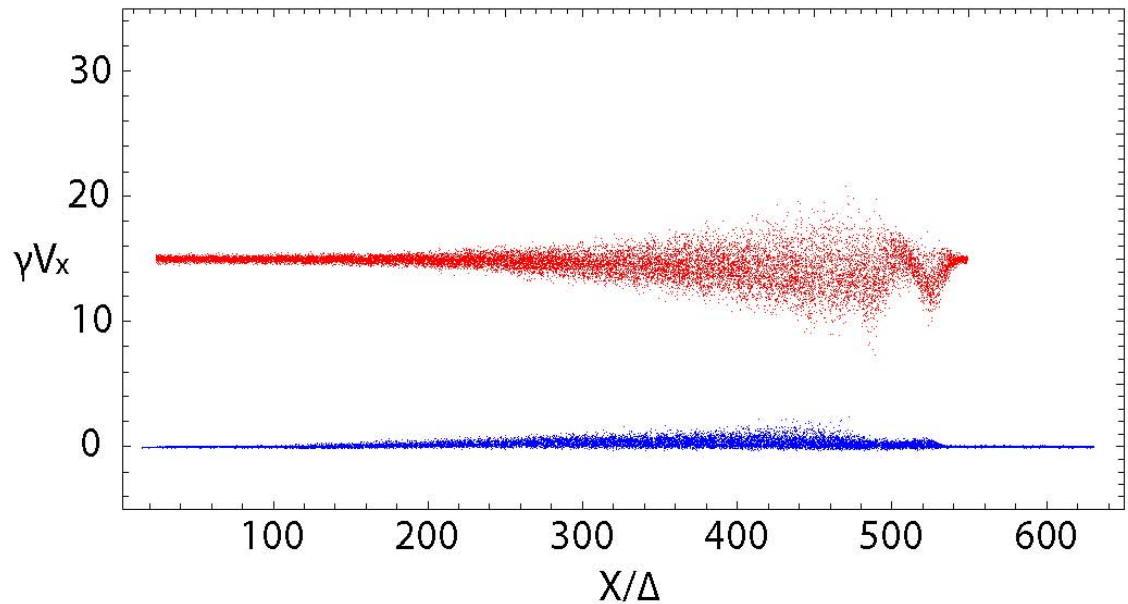
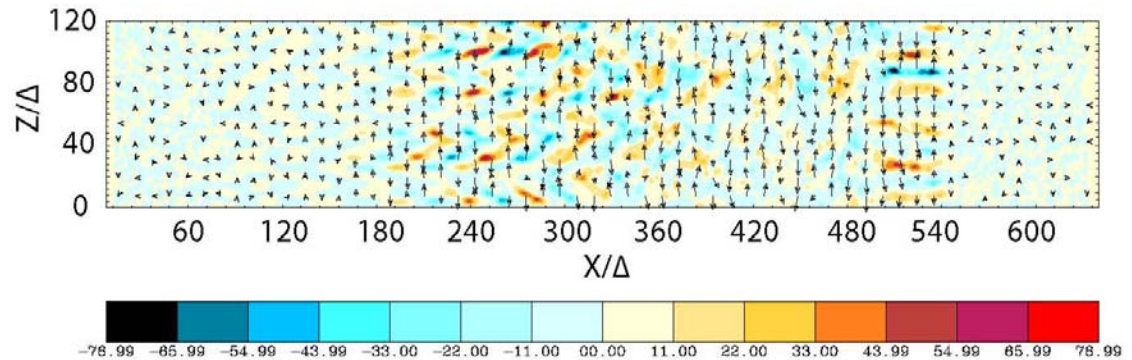
$$dt = 0.005 \omega_{pe}^{-1}$$

$$\omega_n = 100$$

$$\theta_n = 2$$

$$\Delta x_{jet} = 75\Delta$$

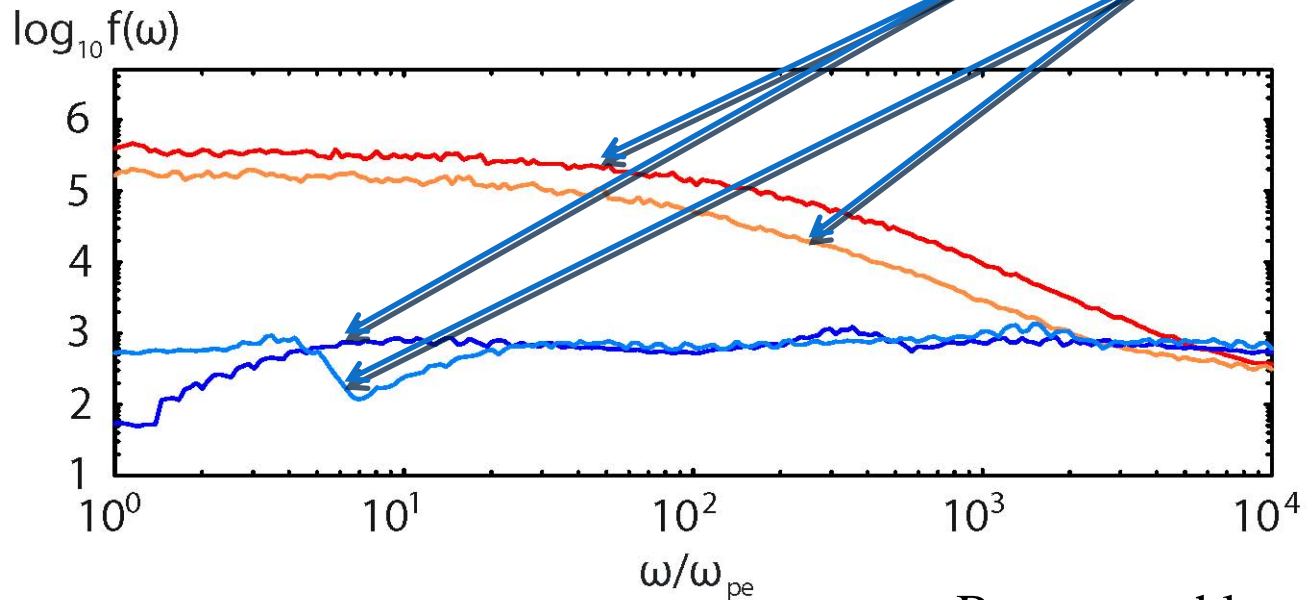
$$\Delta t_{jitt} = 75 \omega_{pe}^{-1}$$



# Calculated spectra for jet electrons and ambient electrons

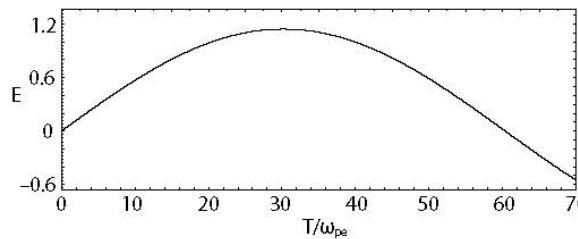
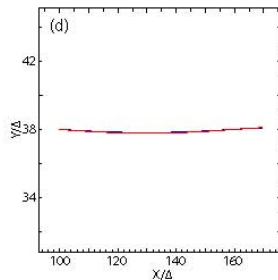
$$\gamma = 15$$

$$\theta = 0^\circ \text{ and } 5^\circ$$

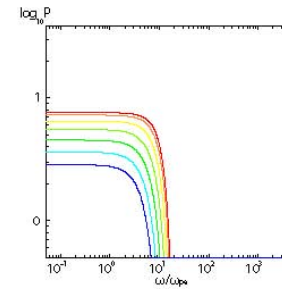


Case D

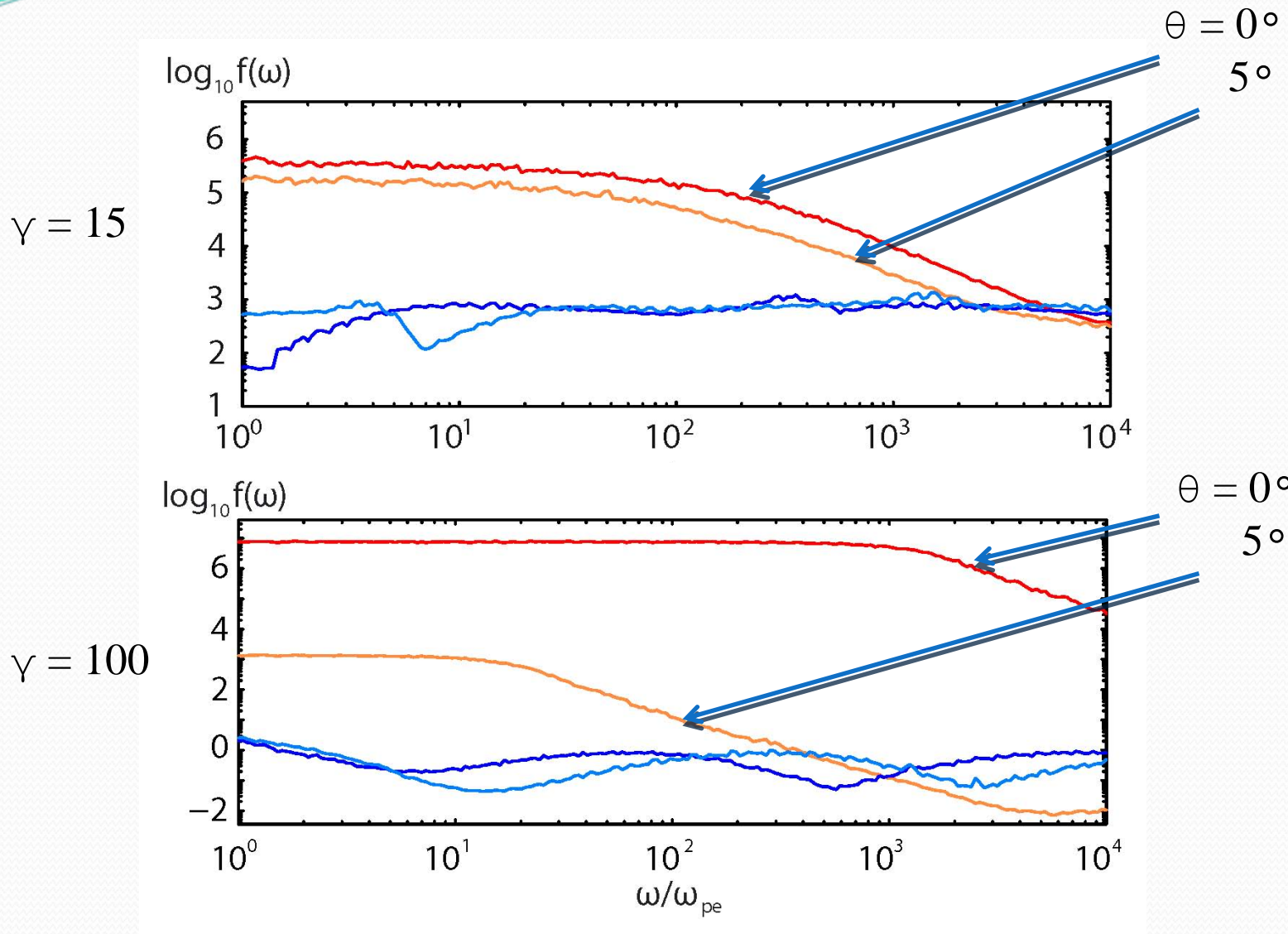
$$\gamma = 7.11$$



Bremsstrahlung



# Dependence on Lorentz factors of jets





## Summary

- Simulation results show **electromagnetic stream instability driven by streaming  $e^\pm$  pairs are responsible for the excitation of near-equipartition, turbulent magnetic fields and a structure with leading and trailing shocks.**
- Shock is similar to the shock in simulations with the constant contact discontinuity.
- The spectrum from jet electrons in a weak magnetic field in a small system shows a Bremsstrahlung like spectrum with higher frequency enhancement with turbulent magnetic field.
- The magnetic fields created by Weibel instability generate highly inhomogeneous magnetic fields, which is responsible for **jitter radiation** (Medvedev, 2000, 2006; Fleishman 2006).

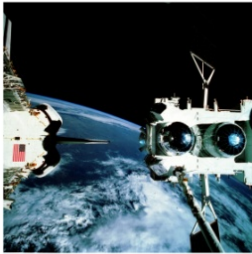
## *Future plans of our simulations of relativistic jets*

- **Calculate radiation with larger systems for different parameters in order to compare with observational data**
- **Include inverse Compton radiation beside synchrotron radiation**
- **Simulations with magnetic fields including turbulent magnetic fields with pair plasma and electron-ion plasma**
- **Non-relativistic jet simulations for understanding SNRs**

# Gamma-Ray Large Area Space Telescope (*FERMI*)

(launched on June 11, 2008) <http://www-glast.stanford.edu/>

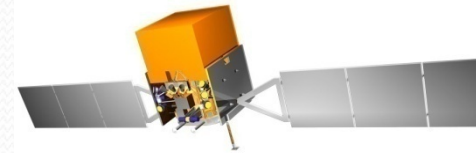
Compton Gamma-Ray  
Observatory (CGRO)



Burst And Transient  
Source Experiment

(BATSE) (1991-2000)

PI: Jerry Fishman



Fermi (GLAST)  
*All sky monitor*

- Large Area Telescope (LAT) PI: Peter Michaelson:  
gamma-ray energies between 20 MeV to about 300 GeV
- Fermi Gamma-ray Burst Monitor (GBM) PI: Bill Paciaas  
(UAH) (Chip Meegan (Retired;USRA)): X-rays and gamma  
rays with energies between 8 keV and 25 MeV  
(<http://gammaray.nsstc.nasa.gov/gbm/>)

*The combination of the GBM and the LAT provides a powerful tool for studying radiation from relativistic jets and gamma-ray bursts, particularly for time-resolved spectral studies over very large energy band.*