Particle-in-cell Simulations for Gamma-ray Burst Jets

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Outline

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- Why do we need particle-in-cell (or kinetic) plasma simulations for GRB jets?
- Particle-in-cell (PIC; microscopic level) & magnetohydrodynamics (MHD; macroscopic level), both can be used to describe relativistic jets
- PIC can explain the generation of magnetic field, particle acceleration, and emission of radiation in a self-consistent way
- PIC can provide insights into the processes at work in the GRBs; possible answers for shocks, magnetic reconnection, and flares
- Nevertheless, we need two main ingredients:
  - a scalable numerical code for very large simulation system
  - compare the synthetic spectra with those obtained from observations

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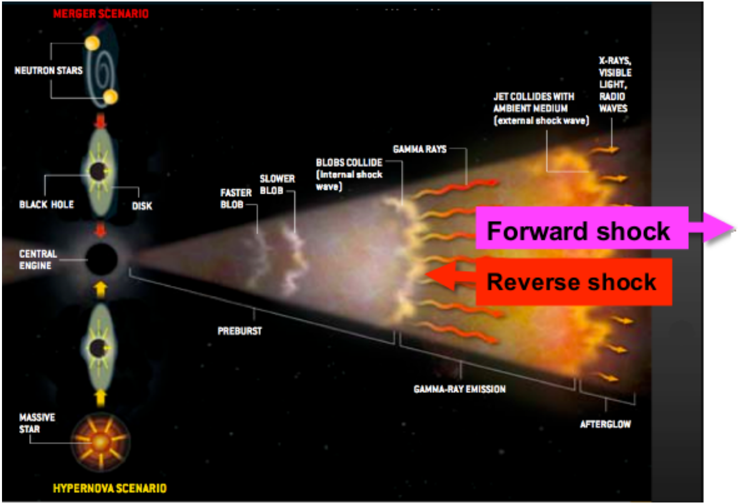
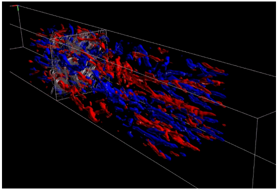
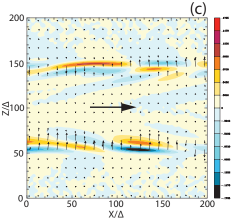


Figure: Image credit: www.nasa.gov

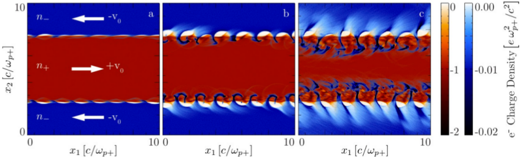
Kinetic instabilities without helical magnetic field

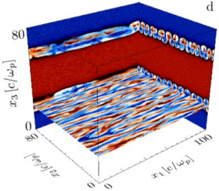
- Weibel instability (filamentation) Nishikawa et al. (2008) and KHI (vortex-like) for core-sheath jets Nishikawa et al. (2014)





- PIC simulation of counter-stream flows (Alves 2012)

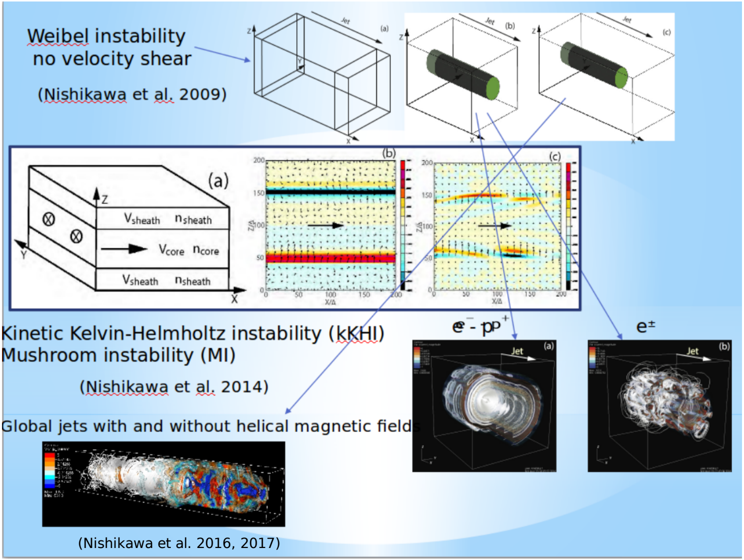




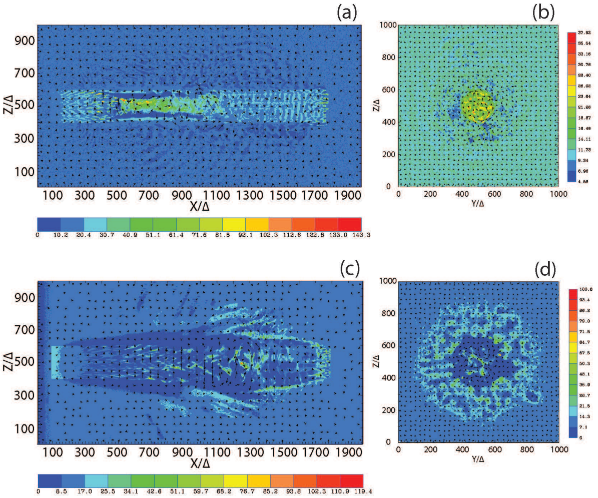
Kelvin-Helmholtz instability

Mushroom instability

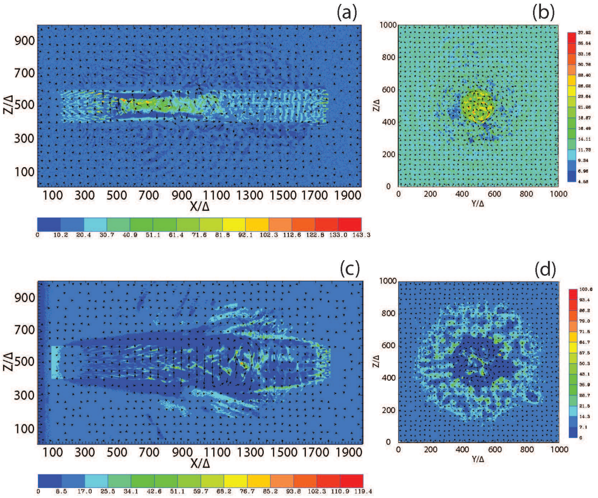
3D relativistic PIC code, developed for plasma jets based on TRISTAN code (Nishikawa et al. 2009, 2014, 2016, 2017)



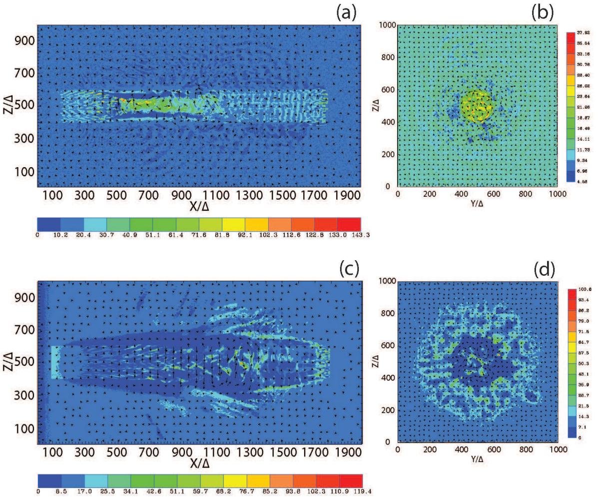
- system size $(2005\Delta, 1005\Delta, 1005\Delta)$, jet radius 100Δ
- $n_{\rm jt} = 8$ and $n_{\rm am} = 11.1$, total particles 48.8 billions
- $\lambda_{\rm s} = c/\omega_{\rm pe} = 10.4\Delta$, $\lambda_{\rm D} = 1.4\Delta$, $\gamma = 15$



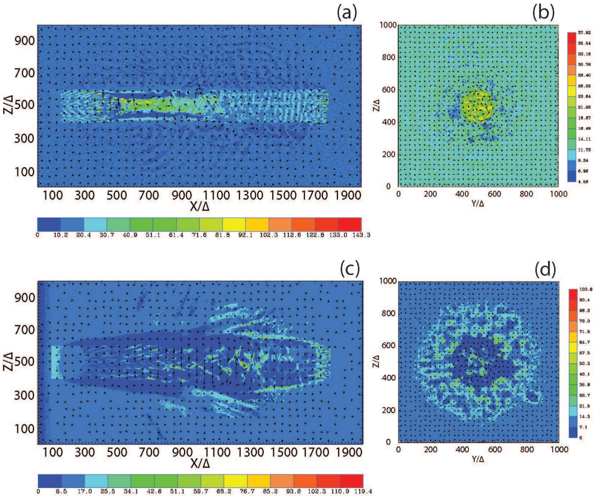
- colors: electron density; arrows: magnetic field
- (a-b) e^--p^+ jet; (c-d) $e^{\pm}$ jet
- (b) at $500X/\Delta$; (d) at $1200X/\Delta$



- (a) e^{-}-p^{+} plasma: jet collimation $500 - 700X/\Delta$ due to toroidal magnetic field generated by kKHI and MI; no collimation after $1000X/\Delta$



- (c) $e^{\pm}$ plasma: mixed jet & ambient particles at velocity shear; Weibel instability excited at $1250X/\Delta$; particles move away from jet at the velocity shear due to kKHI



- HMF structure from Mizuno et al. (2015)
- $(L_x, L_y, L_z) = (645\Delta, 131\Delta, 131\Delta)$
- $n_{\rm jt} = 8$ and $n_{\rm am} = 12$
- jet with radius $r_{\rm jt} = 20\Delta$ is injected in the middle of the $y - z$ plane $((y_{\rm jc}, z_{\rm jc}) = (63\Delta, 63\Delta))$ at $x = 100\Delta$
- $\lambda_{\rm s} = c/\omega_{\rm pe} = 10.\Delta$
- $\lambda_{\rm D} = 0.5\Delta$
- $v_{\rm jt,th,e} = 0.014c$, $v_{\rm am,th,e} = 0.030c$
- $m_{\rm p}/m_{\rm e} = 1836$ $\gamma_{\rm jt} = 15$, $v_{\rm am} = 0$

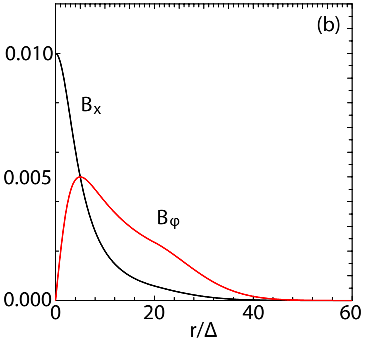
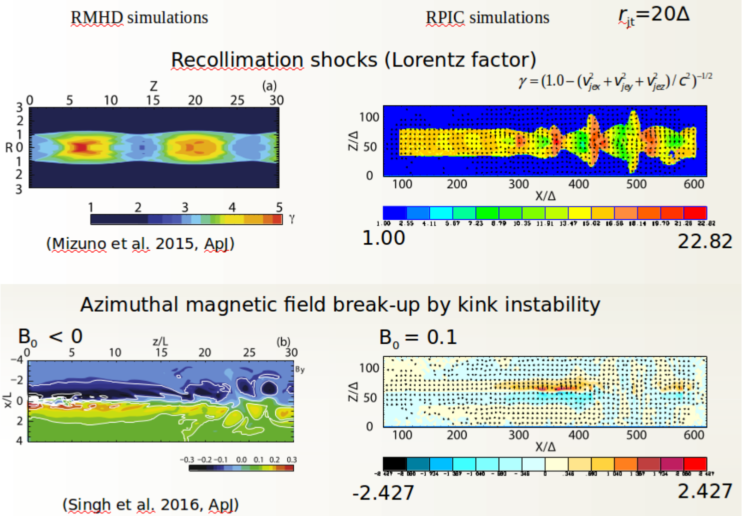
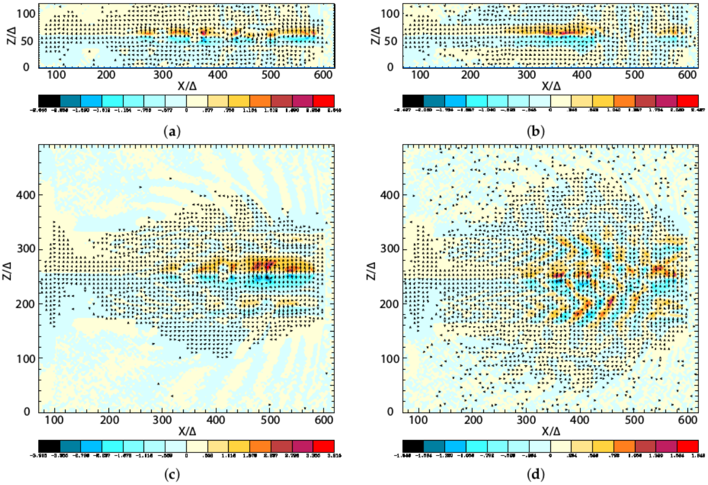


Figure: Magnetic field component profiles across the jet. Field structure taken with damping applied outside of the jet with length-scale b = 200. Jet boundary is located at $r_{\rm jet} = 20\Delta$. (Nishikawa et al. 2016) We also use jets with radius $r_{\rm jt} = 40\Delta$, 80Δ, 120Δ.


RMHD simulations
RPIC simulations
r_{jt}=20Δ
Recollimation shocks (Lorentz factor)
$\gamma = (1.0 - (v_{jex}^2 + v_{jey}^2 + v_{jez}^2)/c^2)^{-1/2}$
(a)
Z
R
γ
Z/Δ
X/Δ
1.00
22.82
(Mizuno et al. 2015, ApJ)
Azimuthal magnetic field break-up by kink instability
B_0 < 0
B_0 = 0.1
(b)
z/L
x/L
By
-2.427
2.427
(Singh et al. 2016, ApJ)

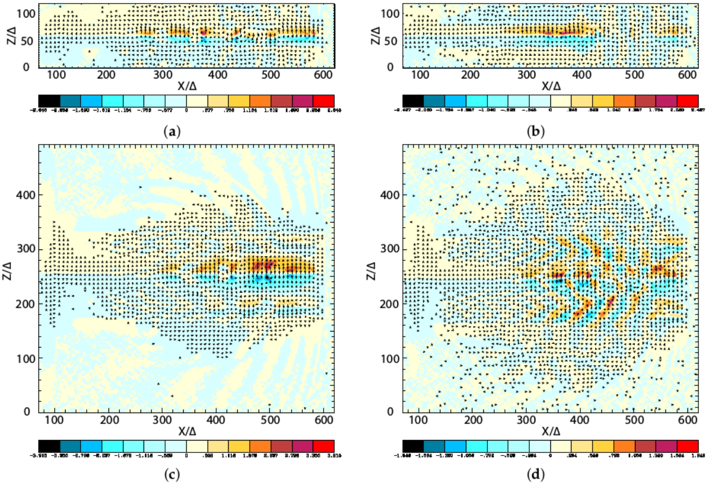
PIC simulations with helical magnetic fields for GRB jets

- isocontour plots of B_y at the center of jets, $t = 500\,\omega_{\rm pe}^{-1}$
- (a,c) e^--p^+ jet, (b,d) $e^\pm$ jet; $r_{\rm jt} = 20$ and 80Δ



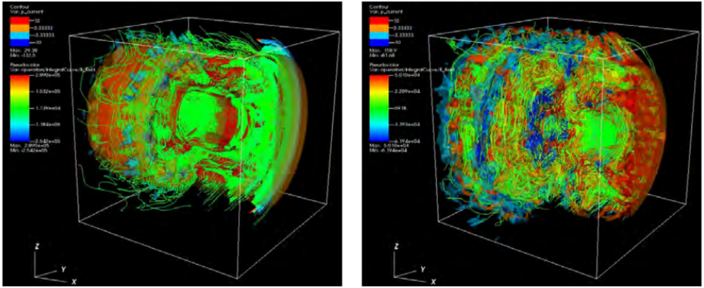
(Nishikawa et al. 2017, Galaxies)

- for thicker jet, disruption of helical magnetic fields is seen
- caused by instabilities and/or reconnection



(Nishikawa et al. 2017, Galaxies)

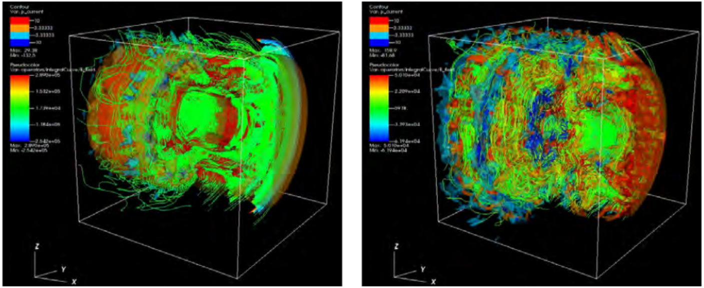
- 3D isosurface plots of the J_x intensity at $t = 500\,\omega_{\rm pe}^{-1}$
- (a) e^{-}-p^{+} jet, (b) $e^{\pm}$ jet; $r_{\rm jt} = 80\Delta$



(a) (b)

(Nishikawa et al. 2017, Galaxies)

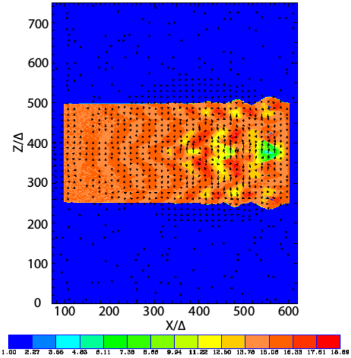
- plots show complicated patterns from instabilities
- helical magnetic field is disrupted: different from jet without helical magnetic field



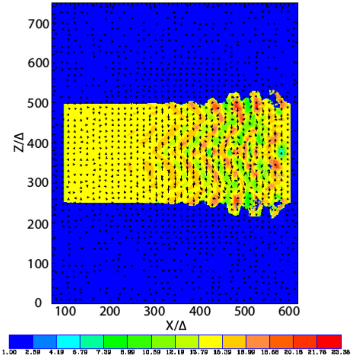
(a) (b)

(Nishikawa et al. 2017, Galaxies)

- for particle acceleration, 2D plots of the Lorentz factor of jet electrons
- (a) e^--p^+ jet, (b) $e^\pm$ jet; $r_{\rm jt} = 120\Delta$, $t = 500\,\omega_{\rm pe}^{-1}$



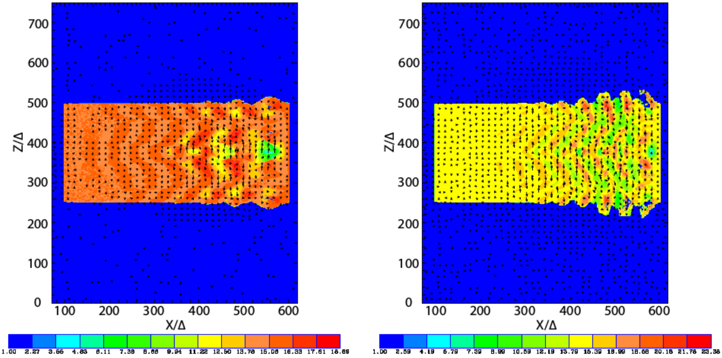
(a)



(b)

(Nishikawa et al. 2017, Galaxies)

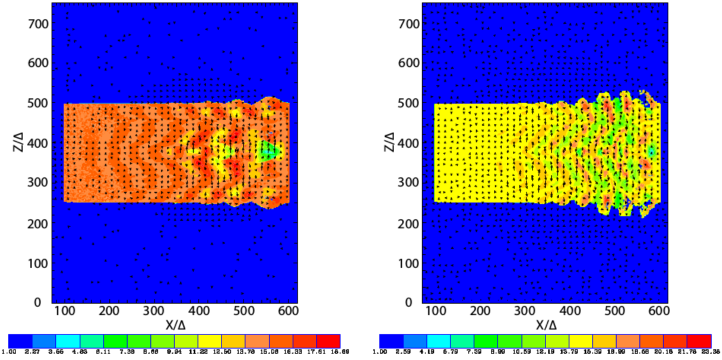
- patterns of the Lorentz factor coincided with the changing directions of local, generated magnetic fields
- arrows (black spots) show magnetic fields in (x, z) plane



(a) (b)

(Nishikawa et al. 2017, Galaxies)

- structures at the edge of jets are generated by the kKHI
- recollimation-like shock is found more clearly in the e^--p^+ jet (corn-shaped weaker Lorentz factor with light green)



(a) (b)

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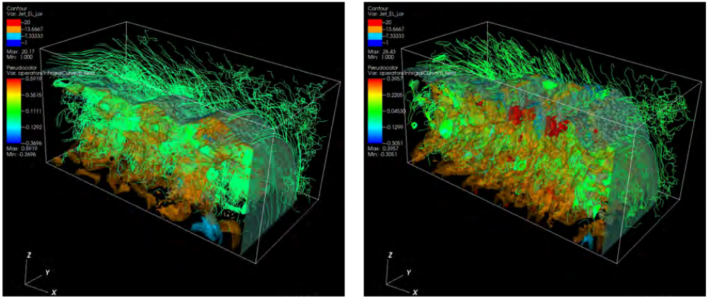
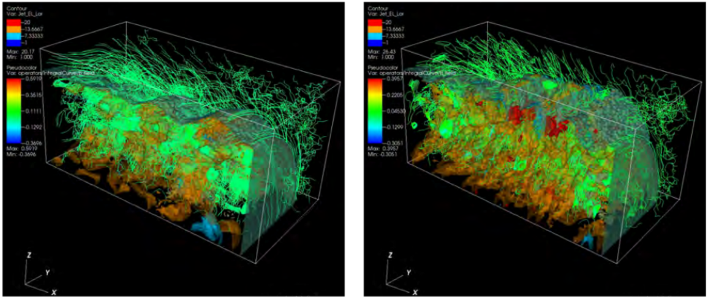
- for particle acceleration, 3D isosurface plots of the Lorentz factor of jet electrons
- (a) e^{-}-p^{+} jet, (b) $e^{\pm}$ jet; $r_{\rm jt} = 120\Delta$, $t = 500\,\omega_{\rm pe}^{-1}$
- color scales for the contour (upper left) for (a,b) are red: 20.0; orange: 13.67; right blue: 7.33; blue: 1



(a) (b)

(Nishikawa et al. 2017, Galaxies)

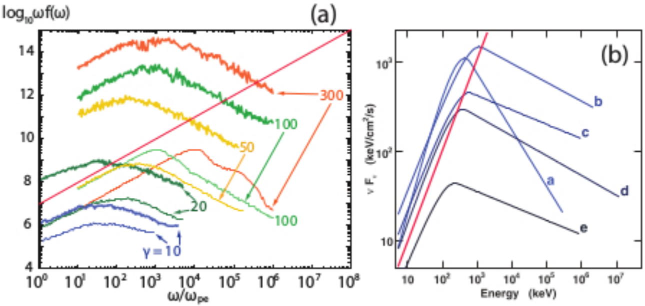
- lines show the magnetic field stream lines in the quadrant of the front part of jets
- plots of Lorentz factor in (y, z) plane show Mushroom instability in the circular edge of the jets
- red zones, possibly magnetic reconnection



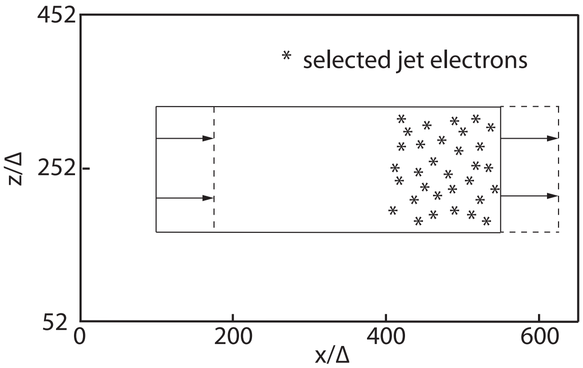
(a) (b)

(Nishikawa et al. 2017, Galaxies)

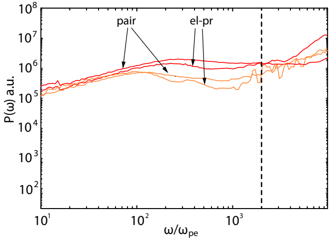
- use the method employed by Nishikawa et al. 2009 by integrating the retarded power, derived from Liénard-Wiechert potentials for selected electrons
- (a) shows calculated spectra for Lorentz factor 10, 20, 50, 100, and 300 with cold (thin lines) and warm (thick lines) electron jets
- (b) shows modeled Fermi spectra from early *a* to late *e* times of GRB080916C (Abdo et al. 2009, Science)



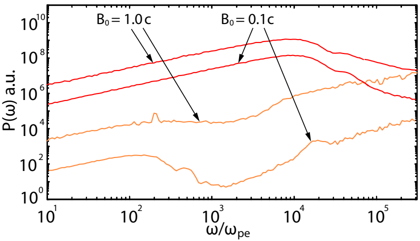
- wider jet $r_{\rm jt} = 80\Delta$
- select about 5000 jet electrons and follow them for 15000 steps ($\Delta t = 0.005\ \omega_{\rm pe}^{-1}$) for about $x = 75\Delta$



- for e^{-}-p^{+} and $e^{\pm}$ plasma jets
- for low ($\gamma = 15$) and high ($\gamma = 100$) Lorentz factors
- for weak ($b_0 = 0.1c$) and strong ($b_0 = 1.0c$) helical magnetic fields
- for head-on radiation (red lines) and 5°-off axis radiation (orange lines)
- dashed line corresponds to the Nyquist frequency



$\gamma = 15$



$\gamma = 100$

- simulation of jets containing helical magnetic fields show new type of growing instabilities
- presence of helical fields suppresses the growth of the kinetic instabilities, such as the Weibel instability, kKHI, and MI
- electron-proton jet shows recollimation-like shock structures in the current density, similar to recollimation shocks observed in RMHD simulations.
- electron-positron jet presents growth of a kink-like instability
- scalable global jet simulations for wider jets: distortion of the HMF, reconnection
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