Energy partitioning of magnetic reconnection in electron-ion plasmas

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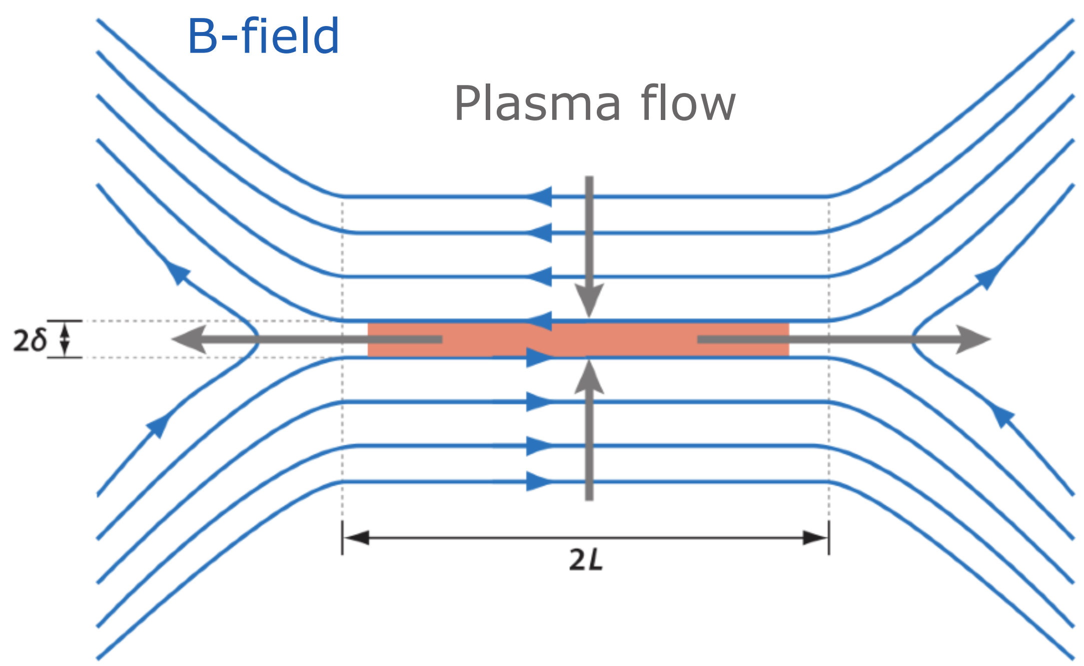
NINS 自然科学研究機構 National Institutes of Natural Sciences

Magnetic reconnection may explain nonthermal emissions in space physics and astrophysics

Reconnection Geometry

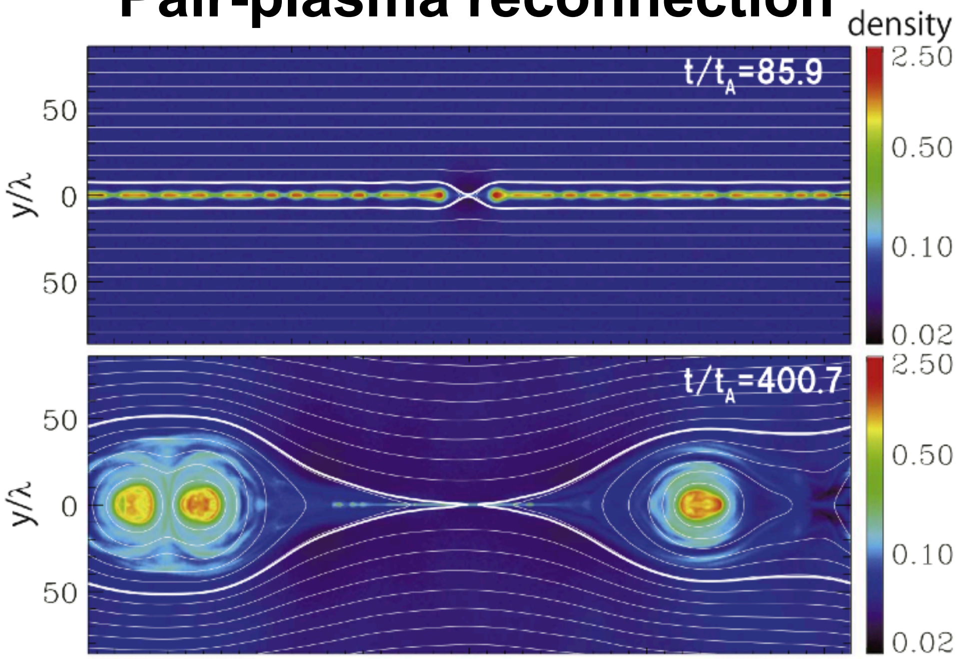


Zweibel, E. & Yamada, Annu. Rev. Astron. Astrophys. 47, 291–332 (2009).

- Magnetic reconnection converts magnetic energy into bulk plasma flows, thermal heating, and nonthermal energetic particles
- Particle acceleration mechanisms and resulting energy spectra are being intensely studied (Guo et al. PRL 2014, Sironi & Spitkovsky ApJL 2014, Cerutti et al. ApJ 2014, Nalewajko et al. ApJ 2015)
- The partitioning of the dissipated magnetic energy into various possible channels (thermal/nonthermal electrons/ions) is not yet understood

Hoshino (POP 2022, ApJ) 2023 studied thermal and nonthermal partitioning of pair plasma reconnection for varied temperature and guide field strength

Pair-plasma reconnection

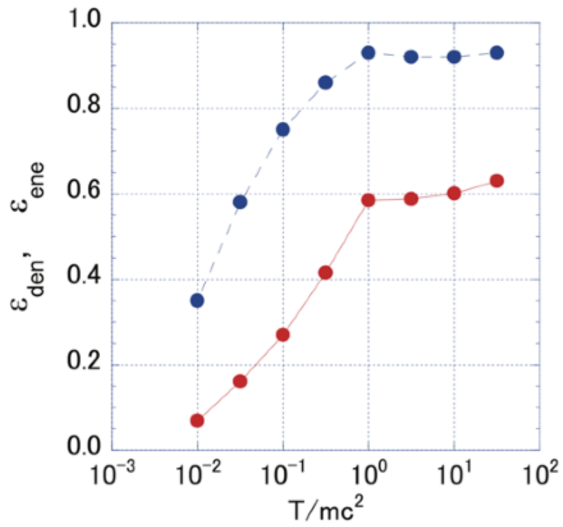


Spectral fitting function:

$$N_{\mathrm{M}+\kappa}(\gamma) = N_{\mathrm{M}}(\gamma) + N_{\kappa}(\gamma),$$

$$N_{\mathrm{M}}(\gamma) = n_{\mathrm{M}}\gamma\sqrt{\gamma^2 - 1}\,\exp\left(-\frac{\gamma - 1}{T_{\mathrm{M}}/mc^2}\right),$$

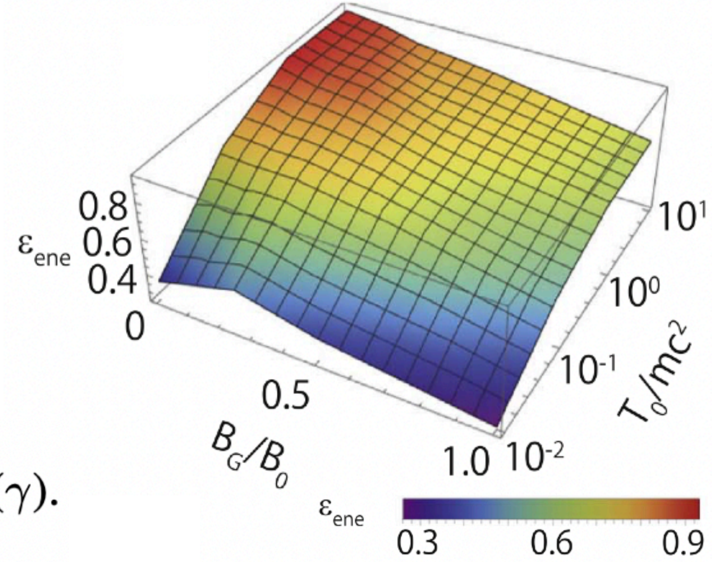
$$N_{\kappa}(\gamma) = n_{\kappa}\gamma\sqrt{\gamma^2 - 1}\left(1 + \frac{\gamma - 1}{\kappa T_{\kappa}/mc^2}\right)^{-(1+\kappa)} f_{\mathrm{cut}}(\gamma).$$



Nonthermal energy fraction

Nonthermal particle number fraction

M. Hoshino PoP 29 042902 (2022)

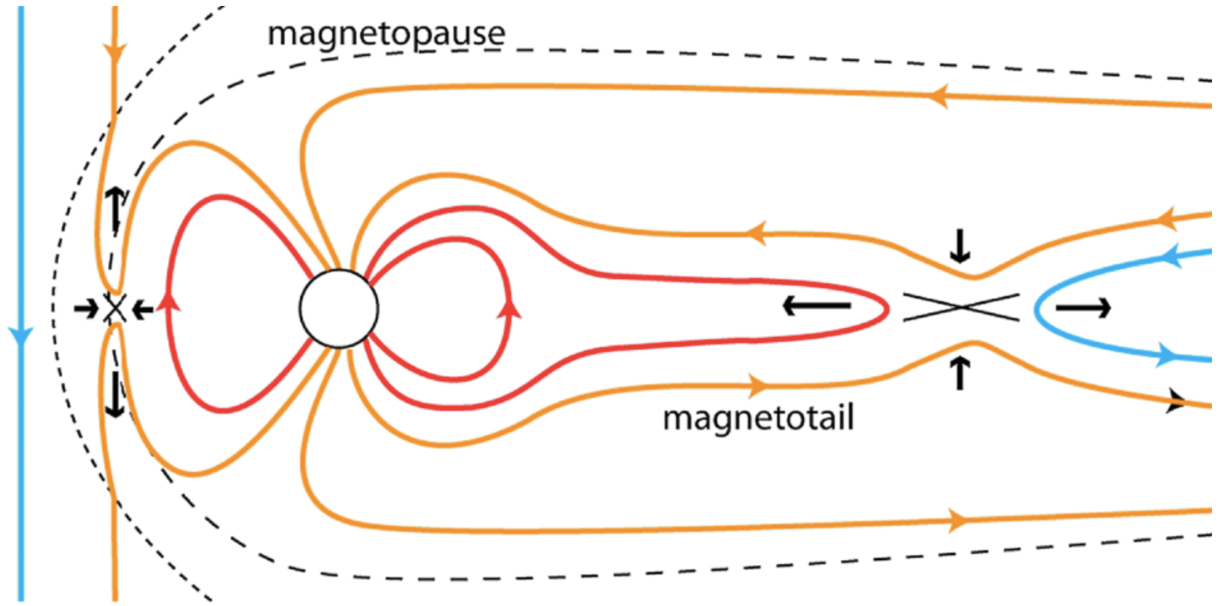


Guide field dependence of nonthermal energy fraction

M. Hoshino ApJ 946 77 (2023)

Example application: Magnetic reconnection in the Earth's magnetosphere

Magnetotail reconnection



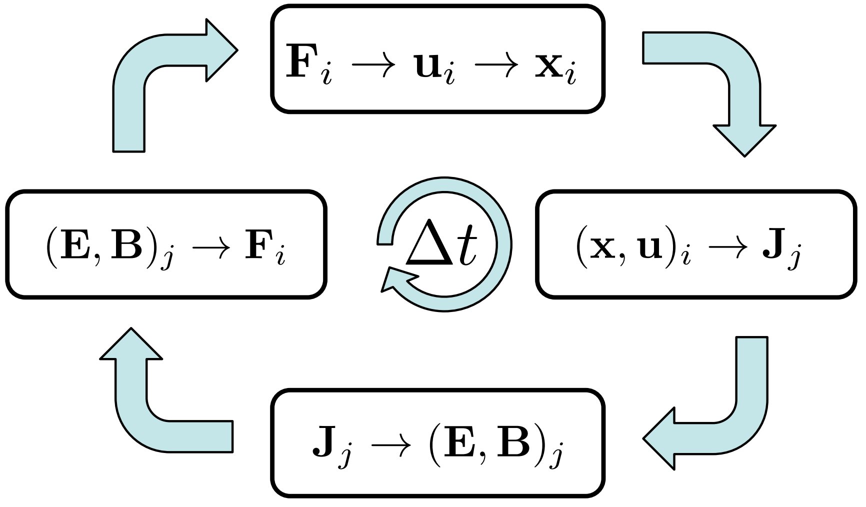
Eastwood et al. 2017

- Magnetic reconnection is thought to play a key role in substorm disruptions in the Earth's magnetotail
- Nonthermal energetic electrons and ions with power-law energy spectra are routinely observed in association with substorms (Turner et al. 2016, Imada et al. 2015)
- The production of these nonthermal particles and the development of an ion to electron temperature ratio $T_i/T_e \approx 5$ is not fully understood

Simulations are run using the OSIRIS particle-in-cell (PIC) code on Supercomputer Fugaku (RIKEN, Japan)

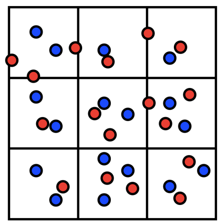
PIC Simulation Loop

$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{1}{\gamma c}\mathbf{u} \times \mathbf{B}\right)$$



$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{J}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

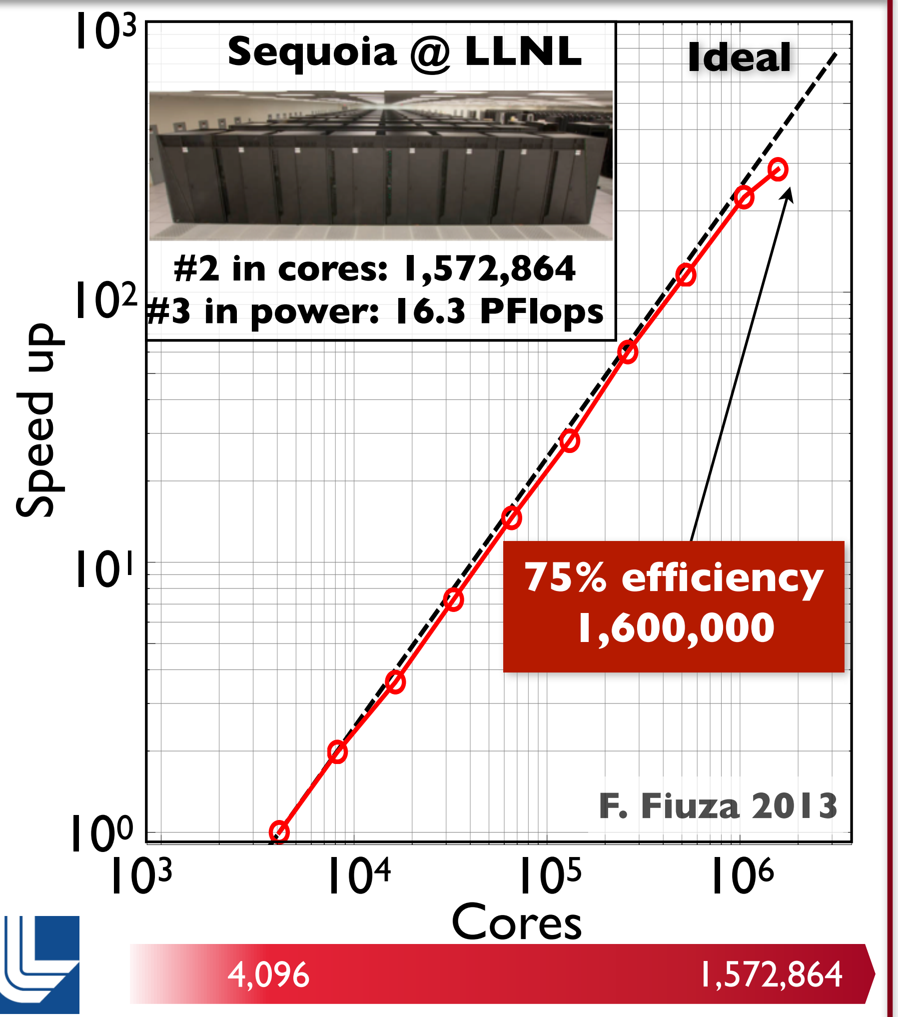


OSIRIS: a state-of-the-art PIC code

Osiris 3.0

TÉCNICO LISBOA

UCLA



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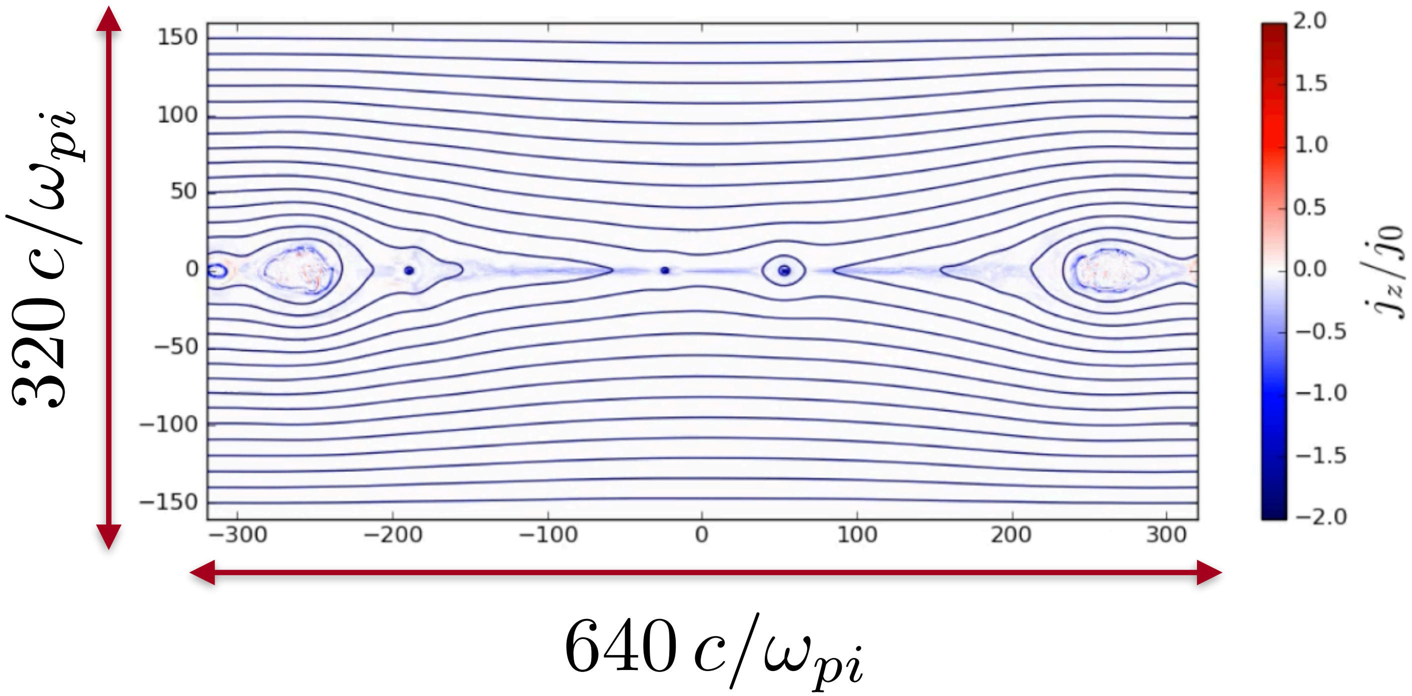
Simulation initial conditions



$n_{ppc} = 64$ $\quad n_{bg}/n_0 = 0.05$

$m_i/m_e = 100$ $\quad \Delta x/(c/\omega_{pe}) = 0.5$

$T/m_e c^2 = 0.0625 - 384$

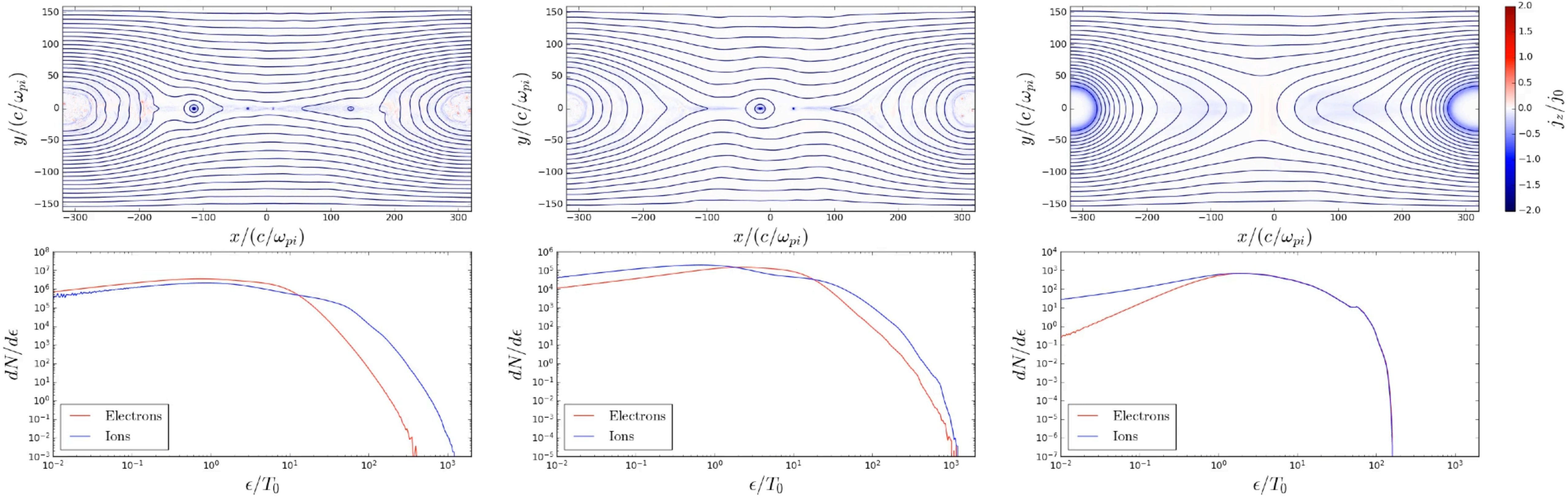
- Two-dimensional Harris current sheets
- Reconnection triggered in the center of the domain by a perturbation in the initial magnetic field
- Uniform background plasma provides a steady inflow of magnetized plasma

Current sheet evolution and energy spectra for varied initial temperatures

$$T/m_e c^2 = 0.0625$$

$$T/m_e c^2 = 1$$

$$T/m_e c^2 = 384$$

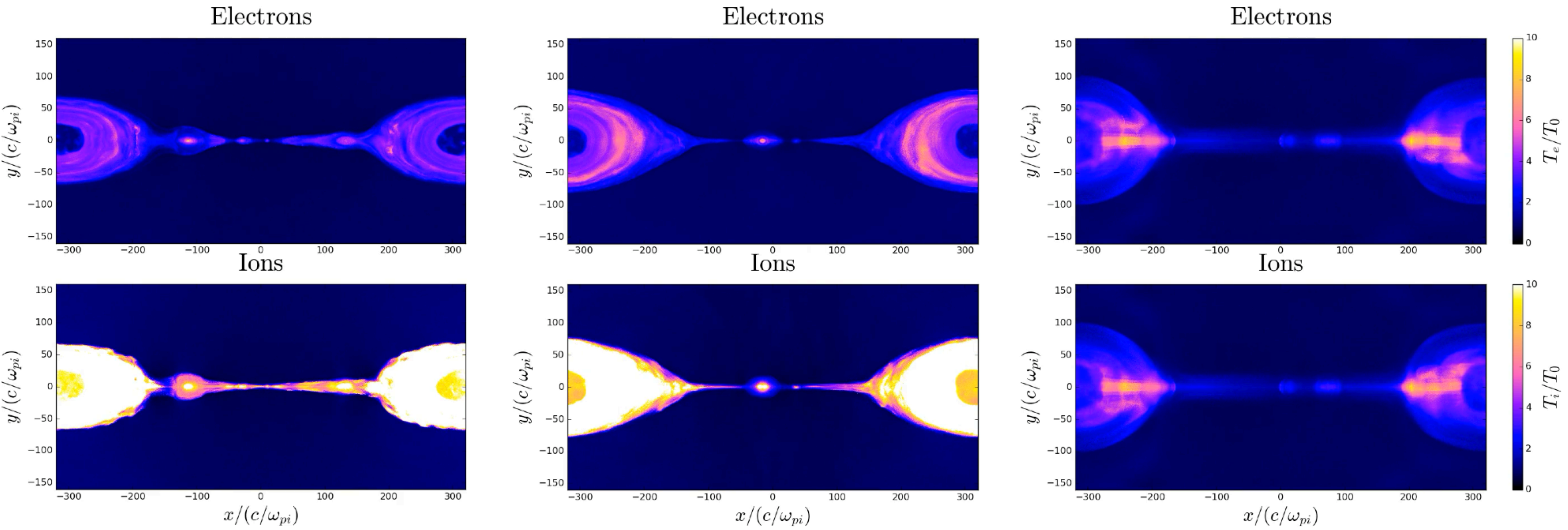


Thermal heating comparison for varied initial temperatures

$T/m_e c^2 = 0.0625$

$T/m_e c^2 = 1$

$T/m_e c^2 = 384$

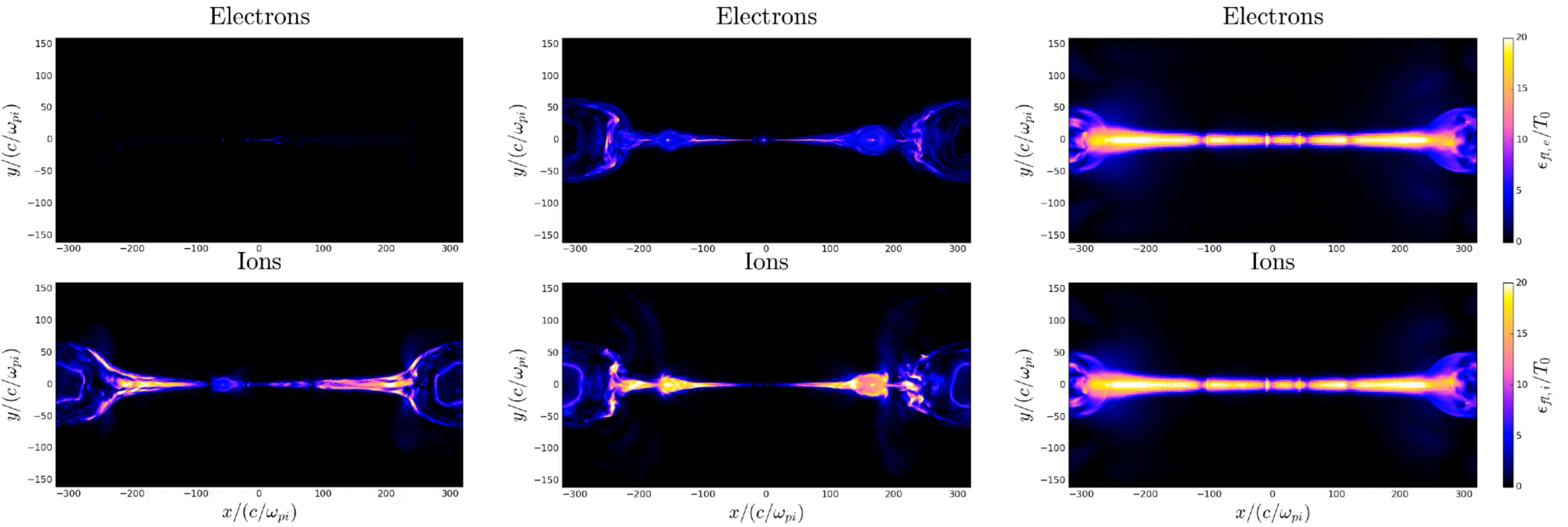


Bulk flow energy comparison for varied initial temperatures

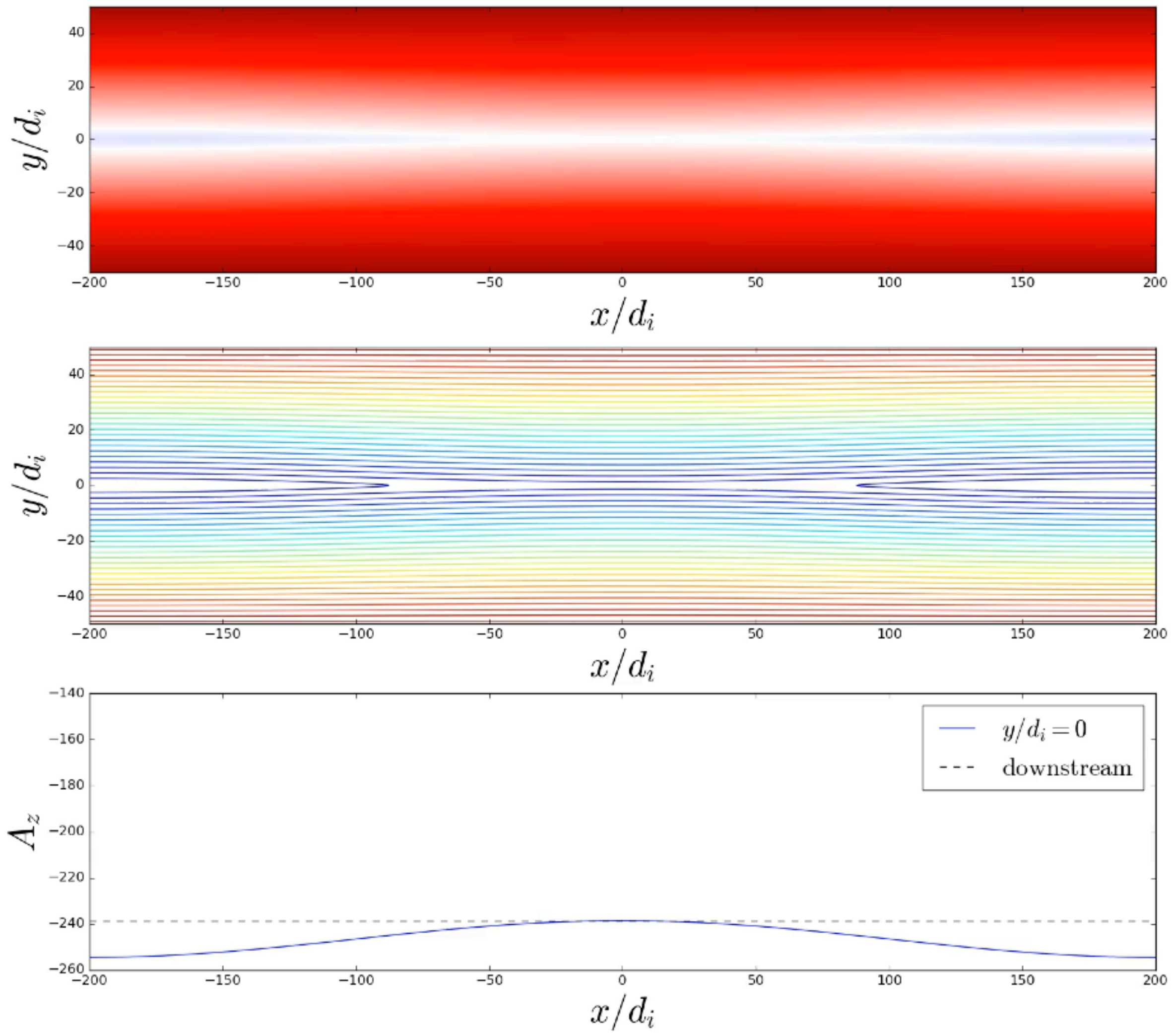
$$T/m_ec^2 = 0.0625$$

$$T/m_ec^2 = 1$$

$$T/m_ec^2 = 384$$



Energy spectra are calculated by integrating downstream particles



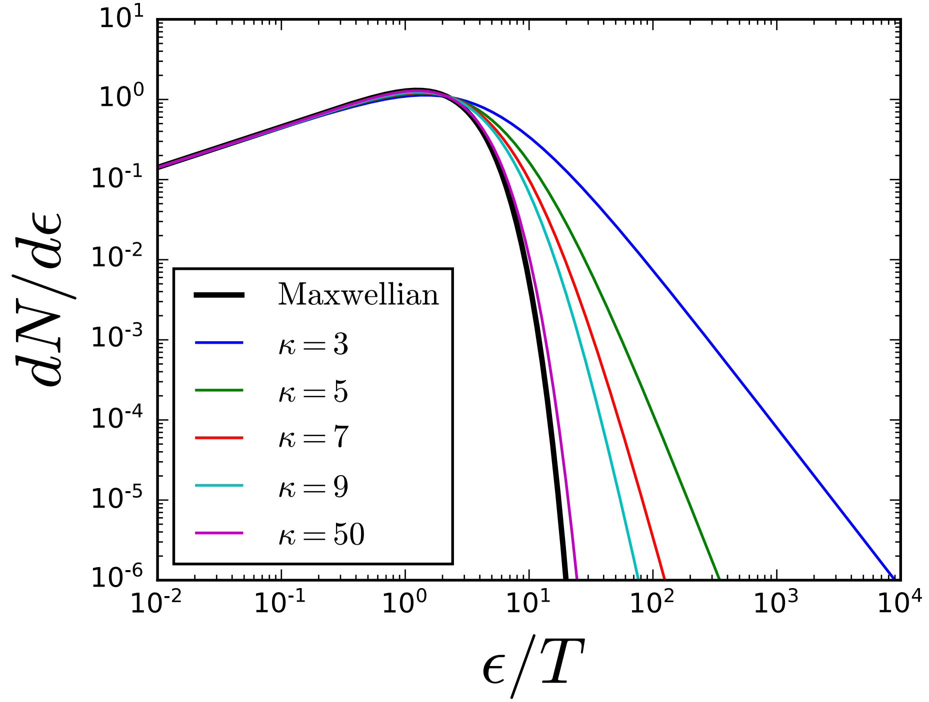
- Out-of-plane vector potential calculated by inverting $\mathbf{B} = \nabla \times \mathbf{A}$

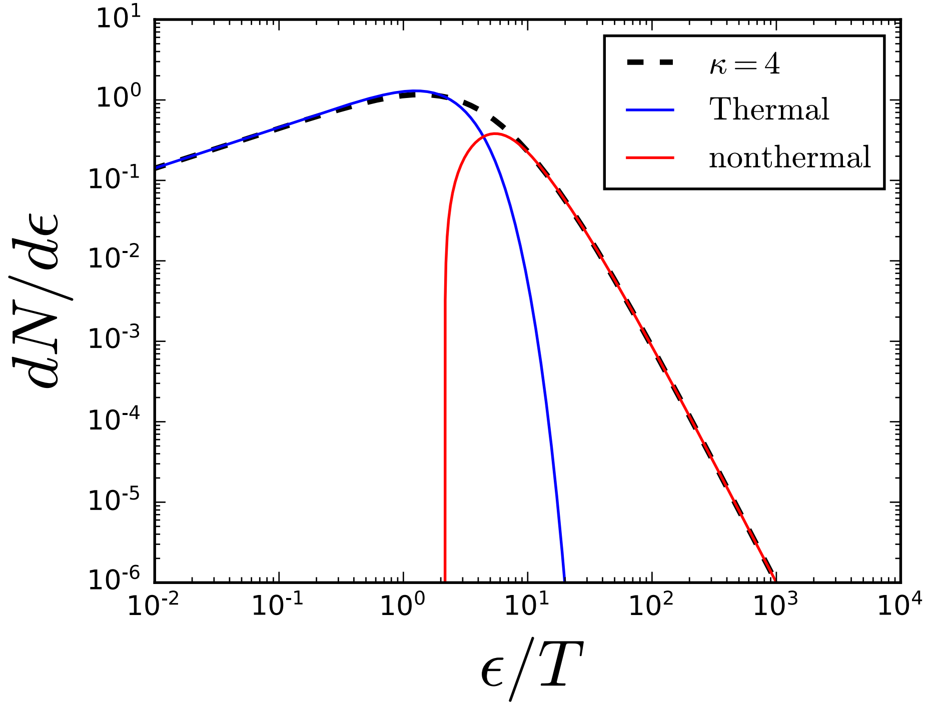
  Red: Upstream
  Blue: Downstream

- Isocontours of the out-of-plane vector potential give the magnetic field lines

- The downstream region can now be defined by the maximum value of the vector potential over a line-out through the current sheet

Energy spectra are fit to the sum of a Maxwellian and a kappa distribution





Kappa distribution:

$$f_\kappa(\gamma) = \gamma\sqrt{\gamma^2 - 1}\left(1 + \frac{\gamma - 1}{\kappa T_\kappa / mc^2}\right)^{-(1+\kappa)}$$

Large energy limit is a power-law:

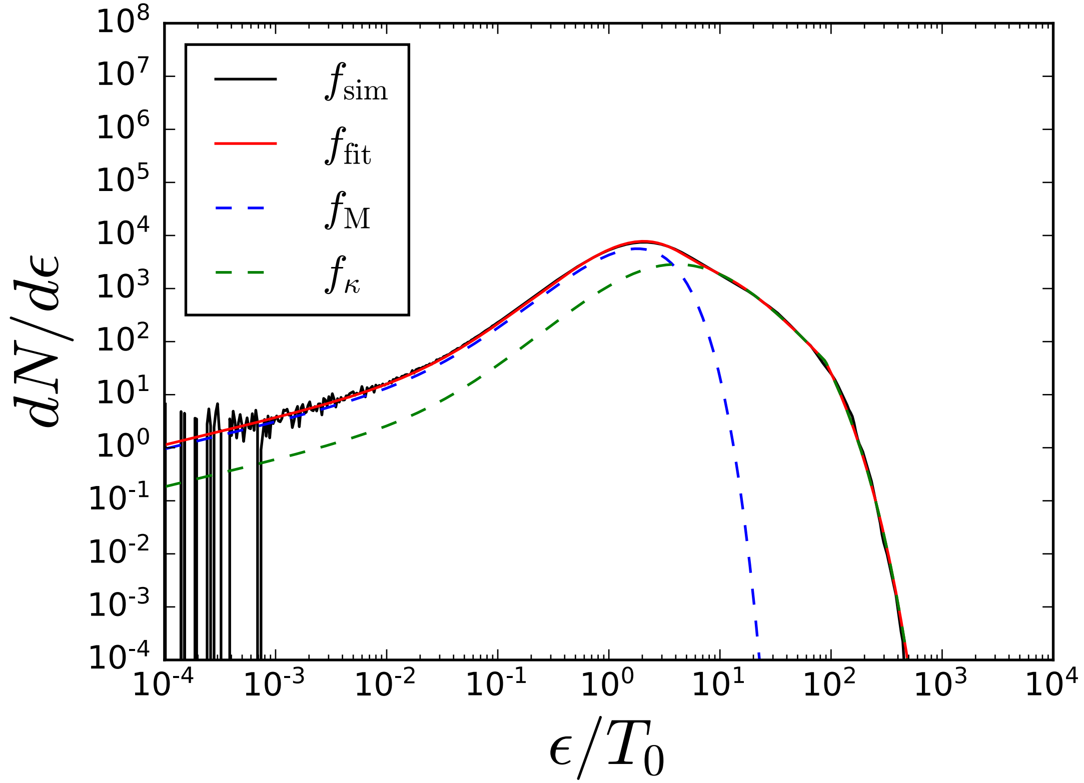
$$\lim_{\gamma\to\infty} f_\kappa(\gamma) = (\kappa T_\kappa/mc^2)^{(1+\kappa)}\gamma^{1-\kappa}$$

Large κ limit is a Maxwellian:

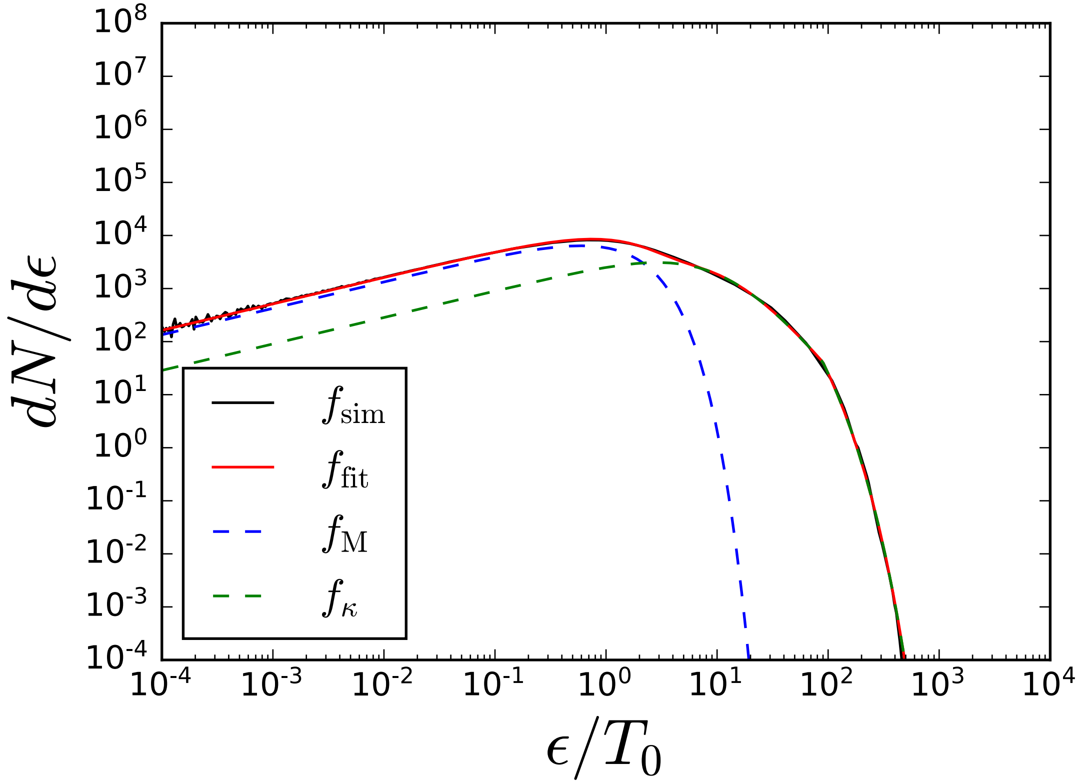
$$\lim_{\kappa\to\infty} f_\kappa(\gamma) = \gamma\sqrt{\gamma^2 - 1}\exp\left(-\frac{\gamma - 1}{T_\kappa/mc^2}\right)$$

Example energy spectrum fits

Electrons



Ions

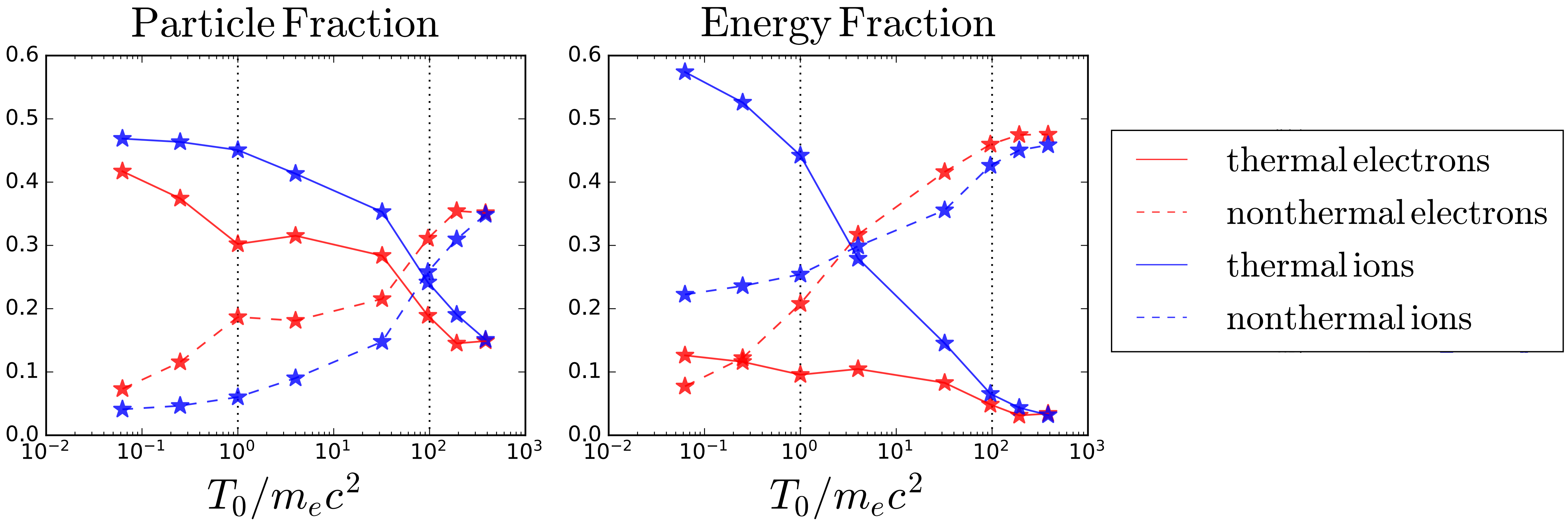


$$T/m_ec^2 = 32$$

Cutoff function included at high energies:

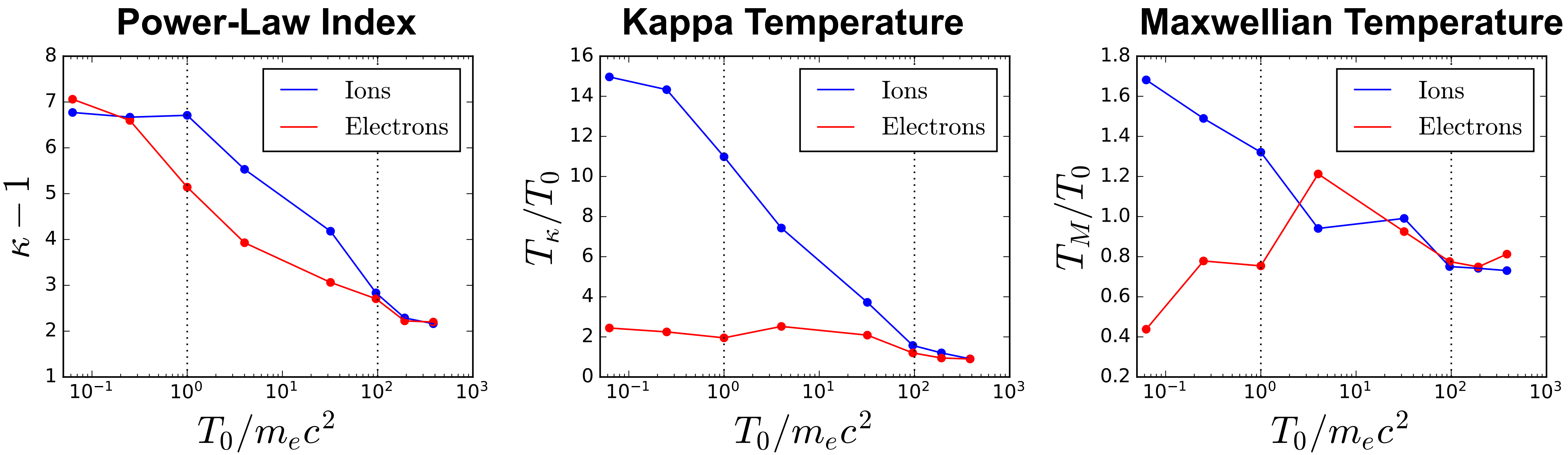
$$f_{cut}(\gamma) \propto \exp\left(-(\gamma - \gamma_{cut})^2/\gamma_{cut}\right)$$

Partitioning of thermal and nonthermal electrons and ions

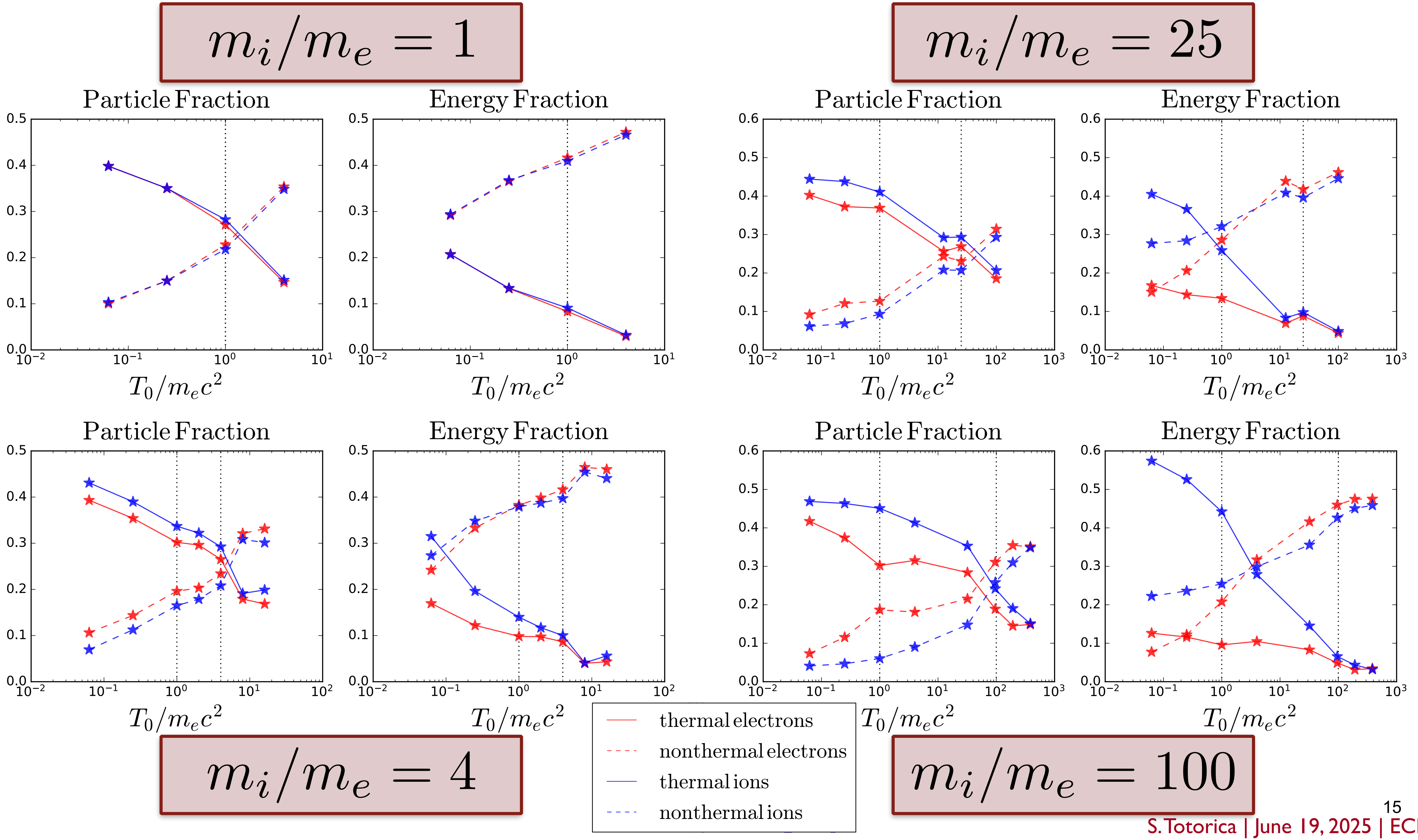


- Ions show preferential heating and nonthermal acceleration at nonrelativistic temperatures
- Acceleration efficiency is enhanced as the temperature approaches the rest mass energy for each species

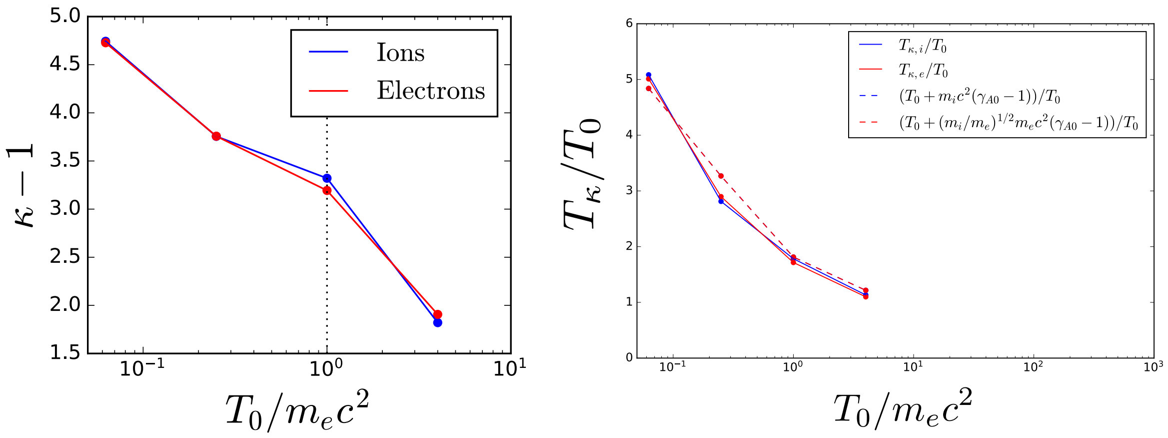
Fitted parameters of the Kappa and Maxwellian distributions



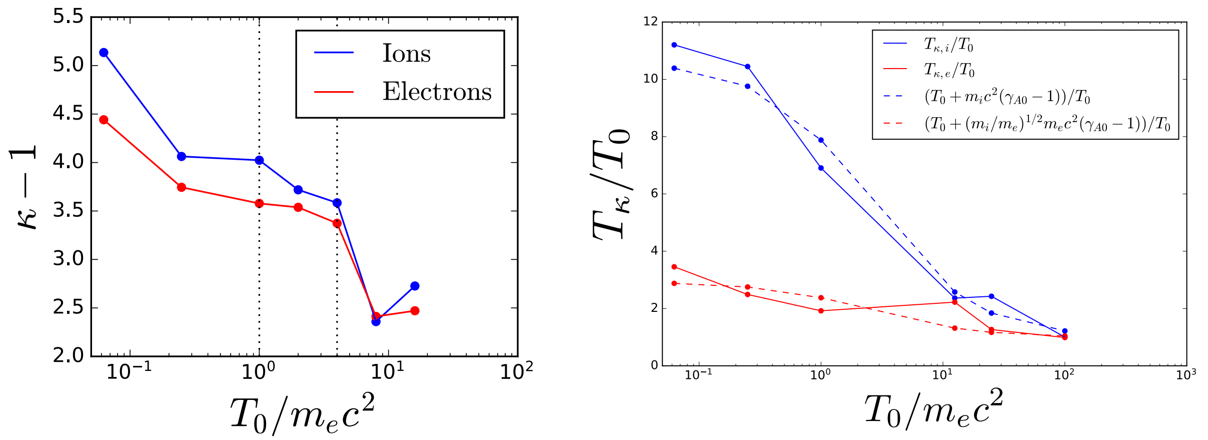
- Slight decrease in nonthermal acceleration at the highest energies likely due to system size limitations
- Convergence with system size currently under investigation

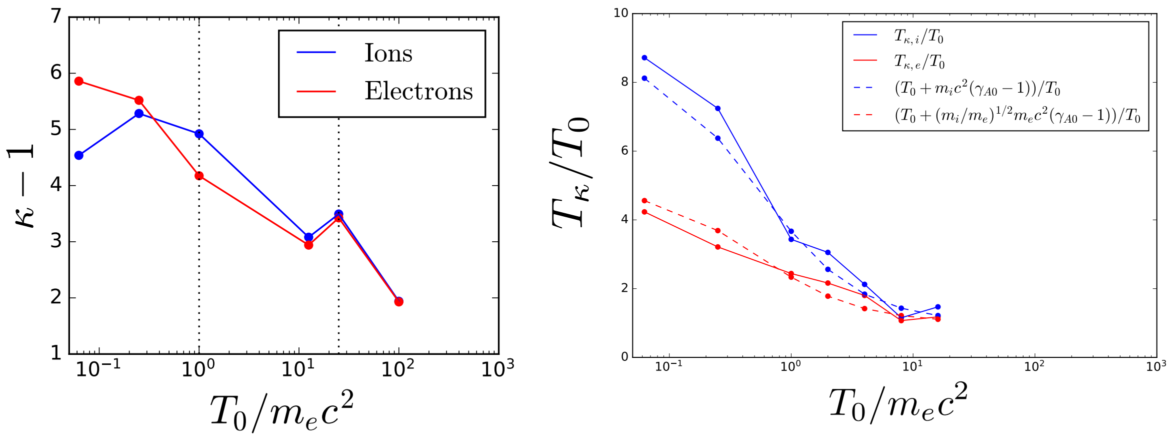

$m_i/m_e = 1$
$m_i/m_e = 25$
$m_i/m_e = 4$
$m_i/m_e = 100$
Particle Fraction
Energy Fraction
T_0/m_ec^2
thermal electrons
nonthermal electrons
thermal ions
nonthermal ions

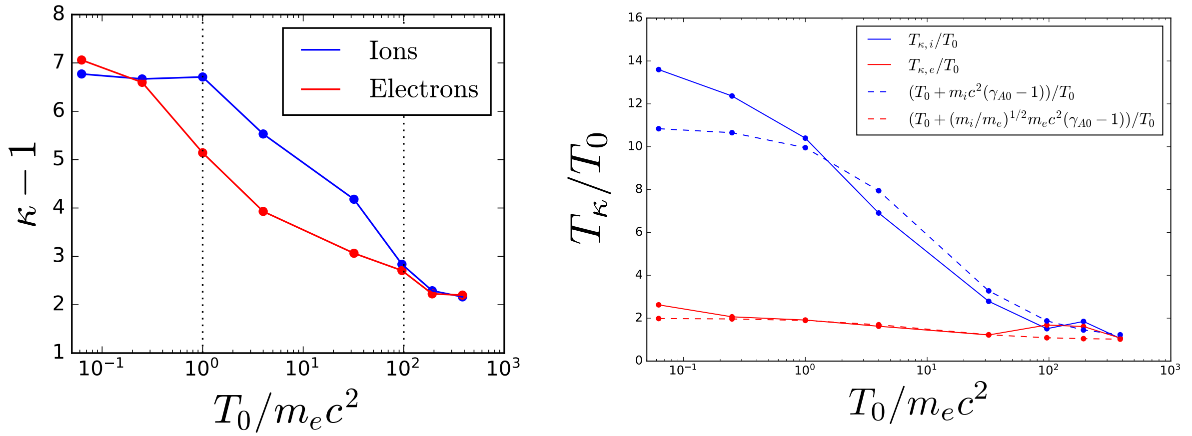
$m_i/m_e = 1$



$m_i/m_e = 25$



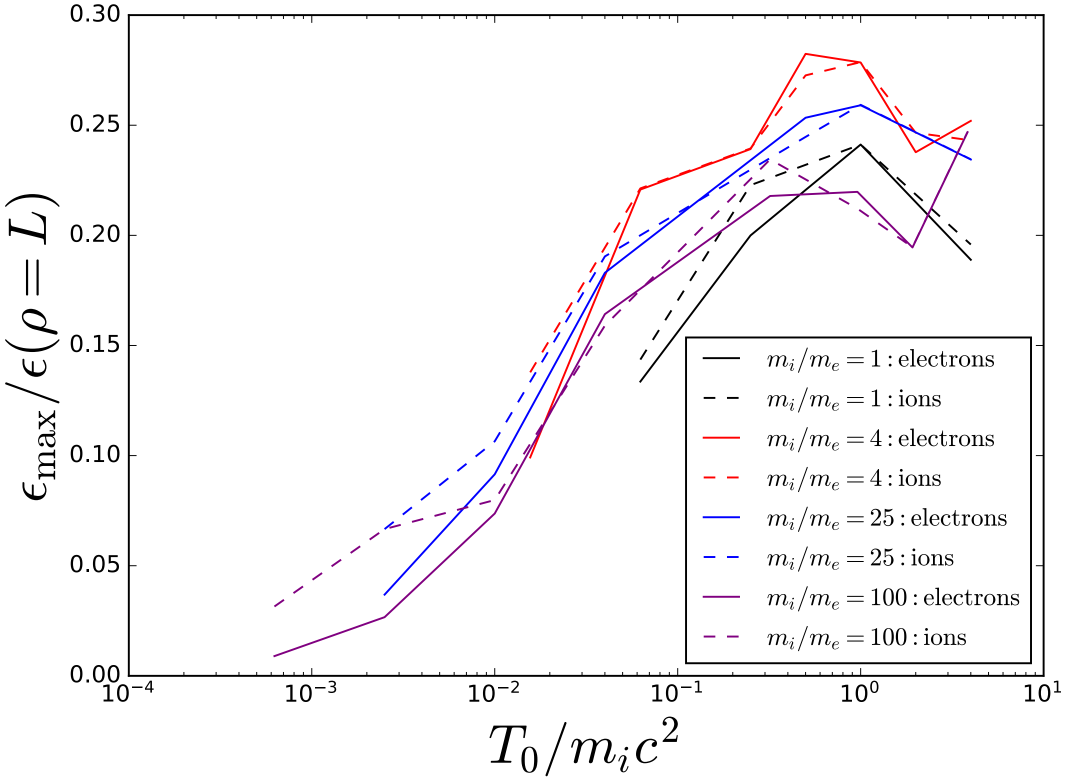


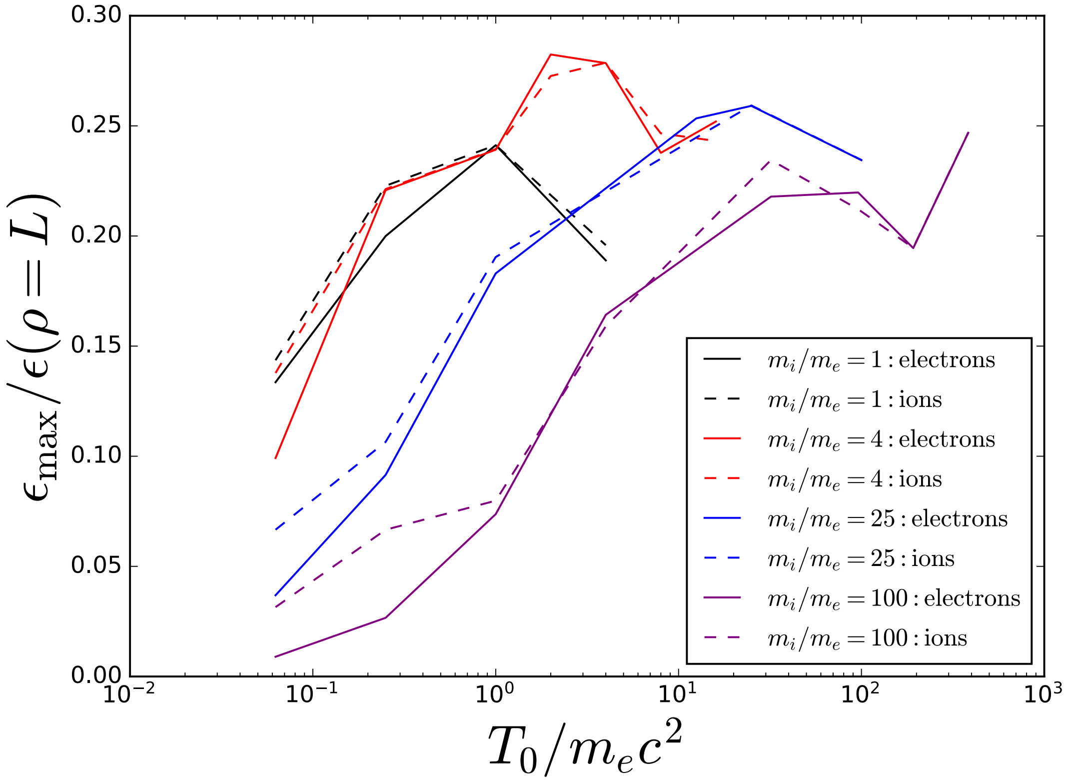


$m_i/m_e = 4$

$m_i/m_e = 100$

Maximum energy limited by system size

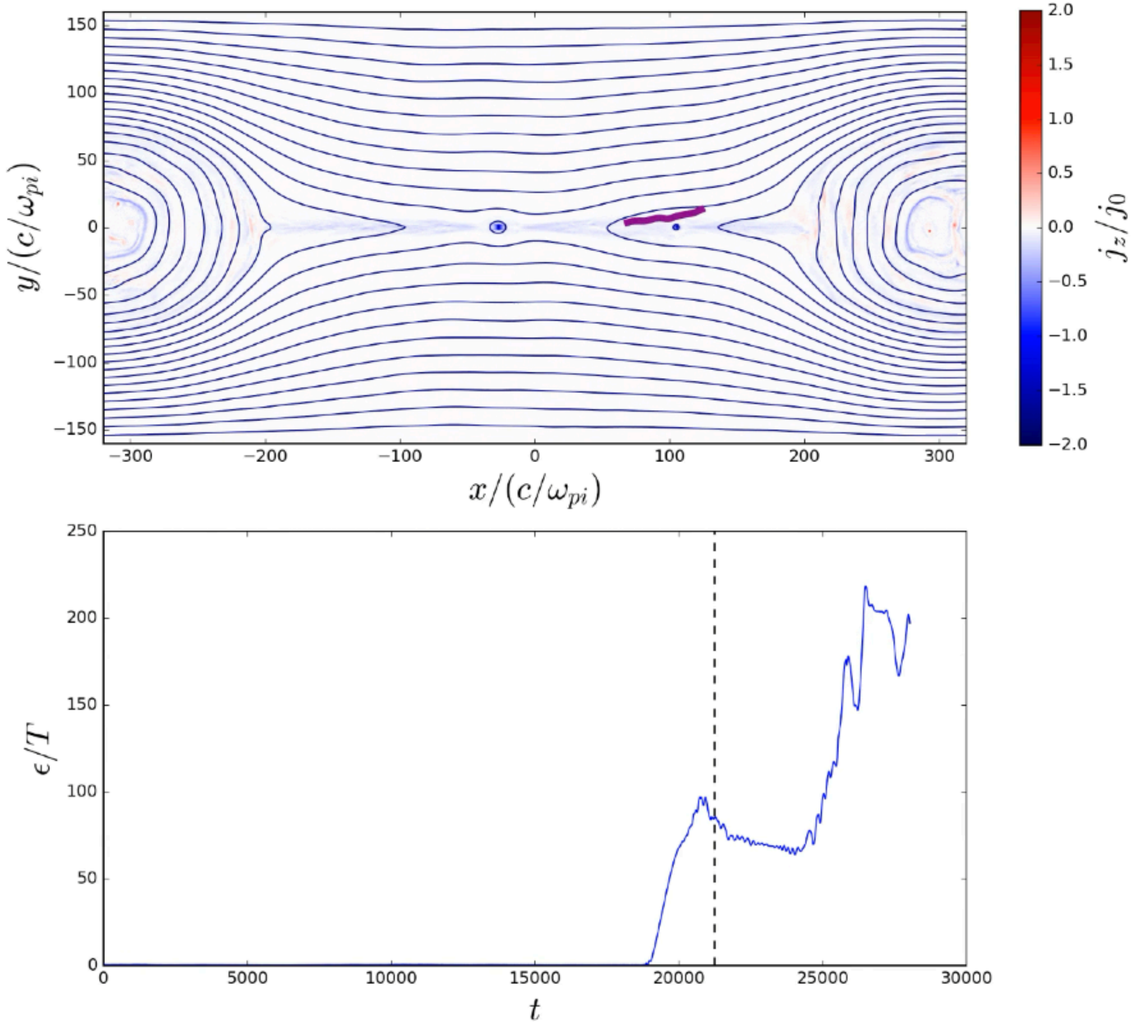




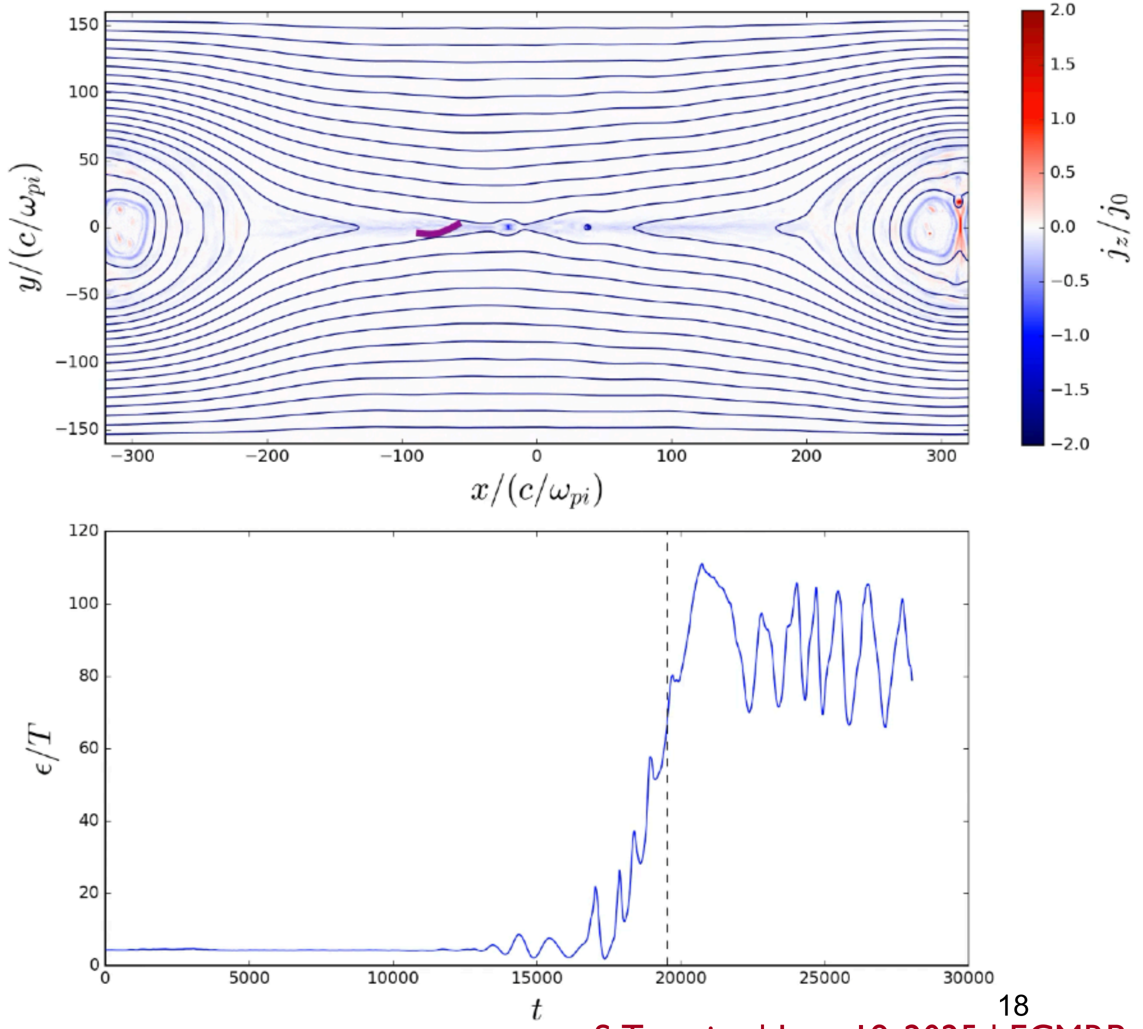
$$\rho = \gamma m v / qB \qquad \rho_{max} \approx L/4$$

Nonthermal particle trajectories: $T_e/m_ec^2 = 0.0625$

Nonthermal Electron Trajectories

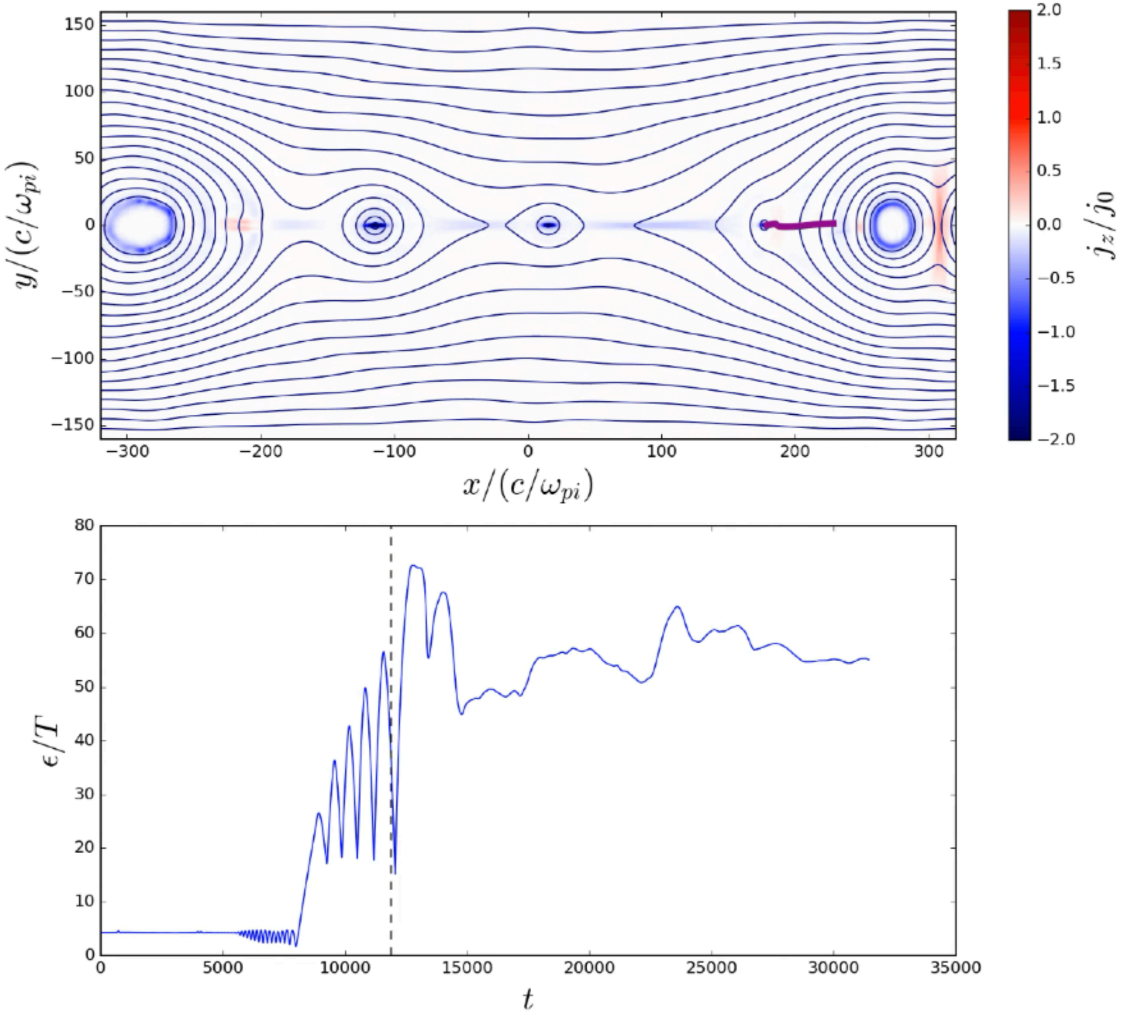


Nonthermal Ion Trajectories

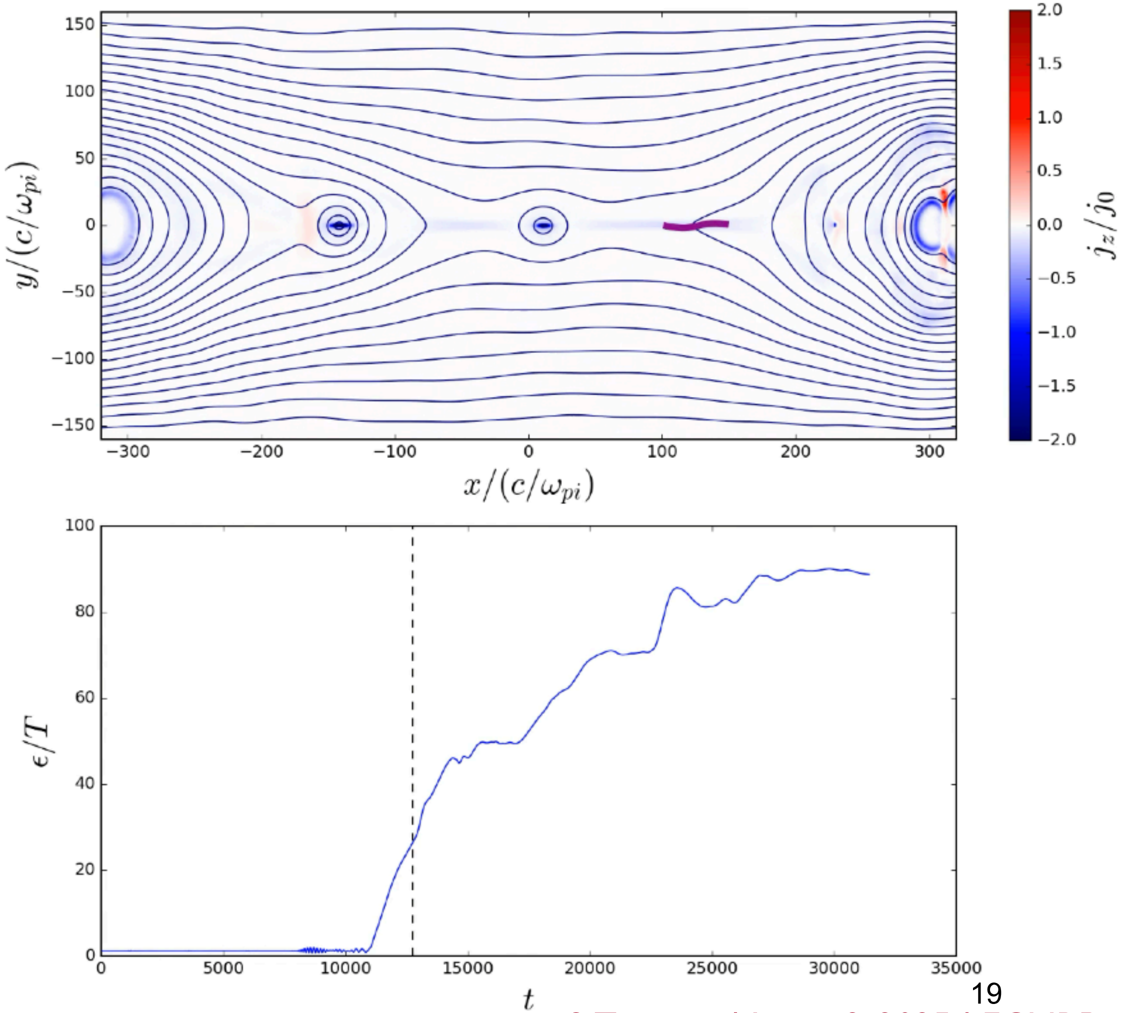


Nonthermal particle trajectories: $T_e/m_ec^2 = 12.5$

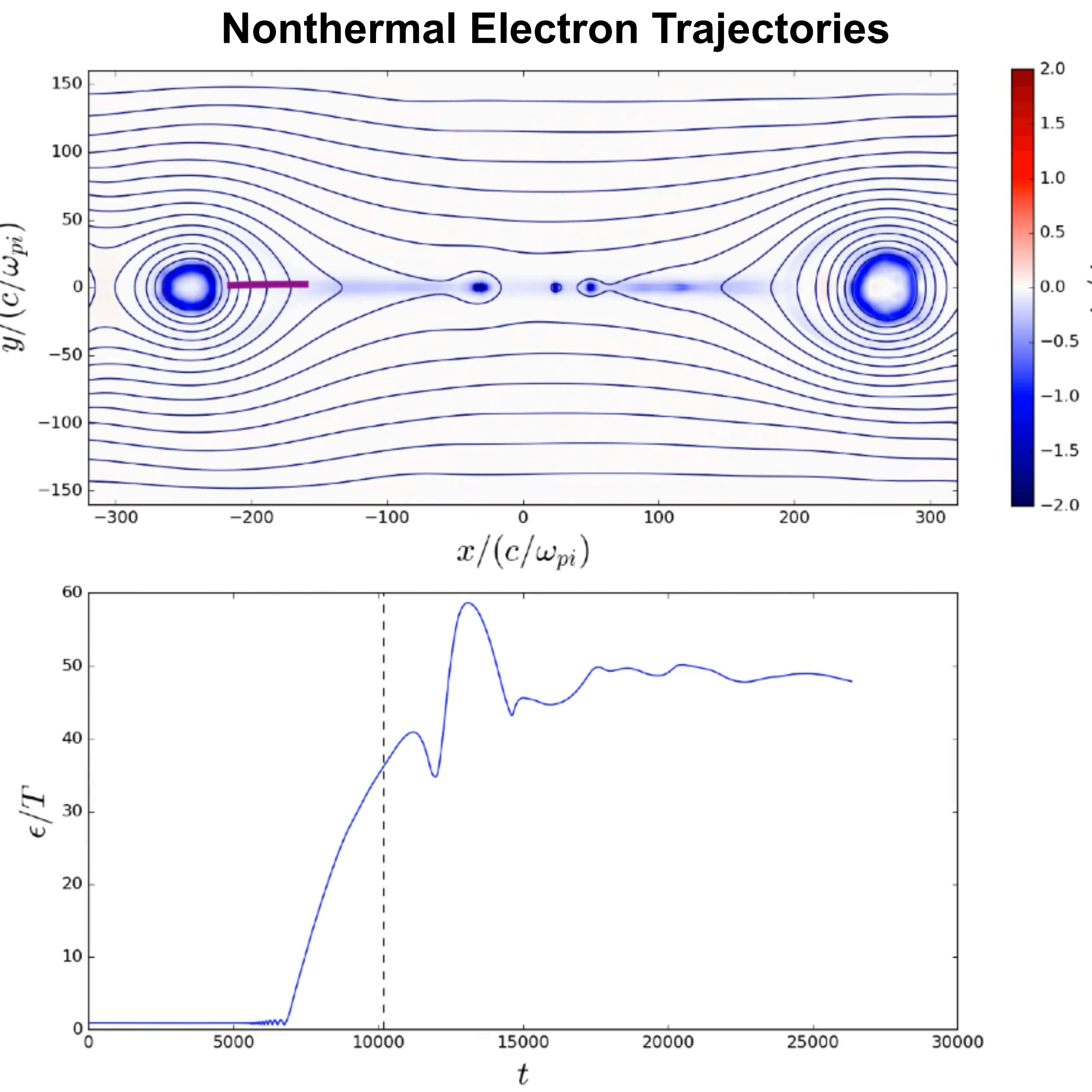
Nonthermal Electron Trajectories

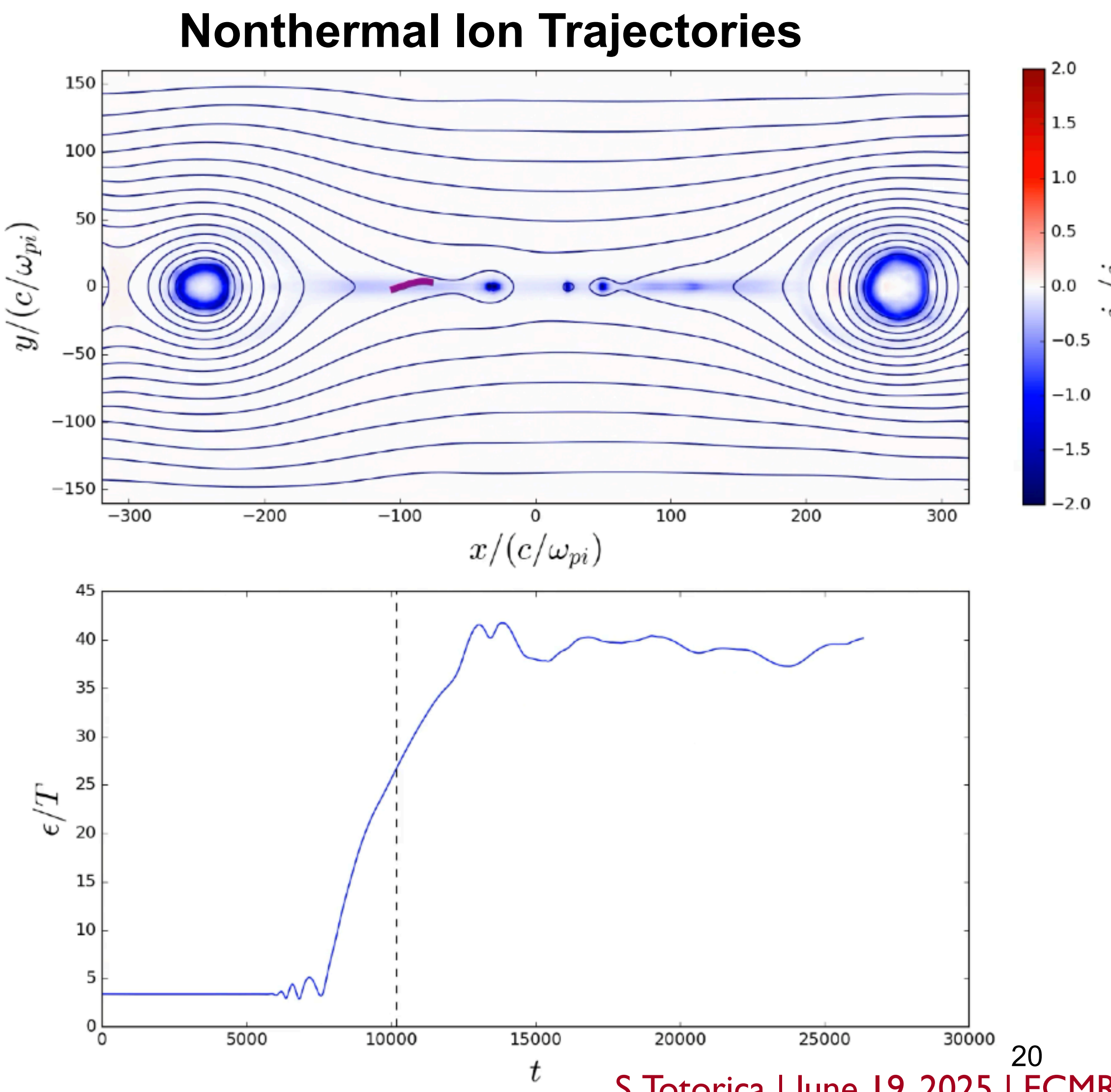


Nonthermal Ion Trajectories



Nonthermal particle trajectories: $T_e/m_ec^2 = 100$



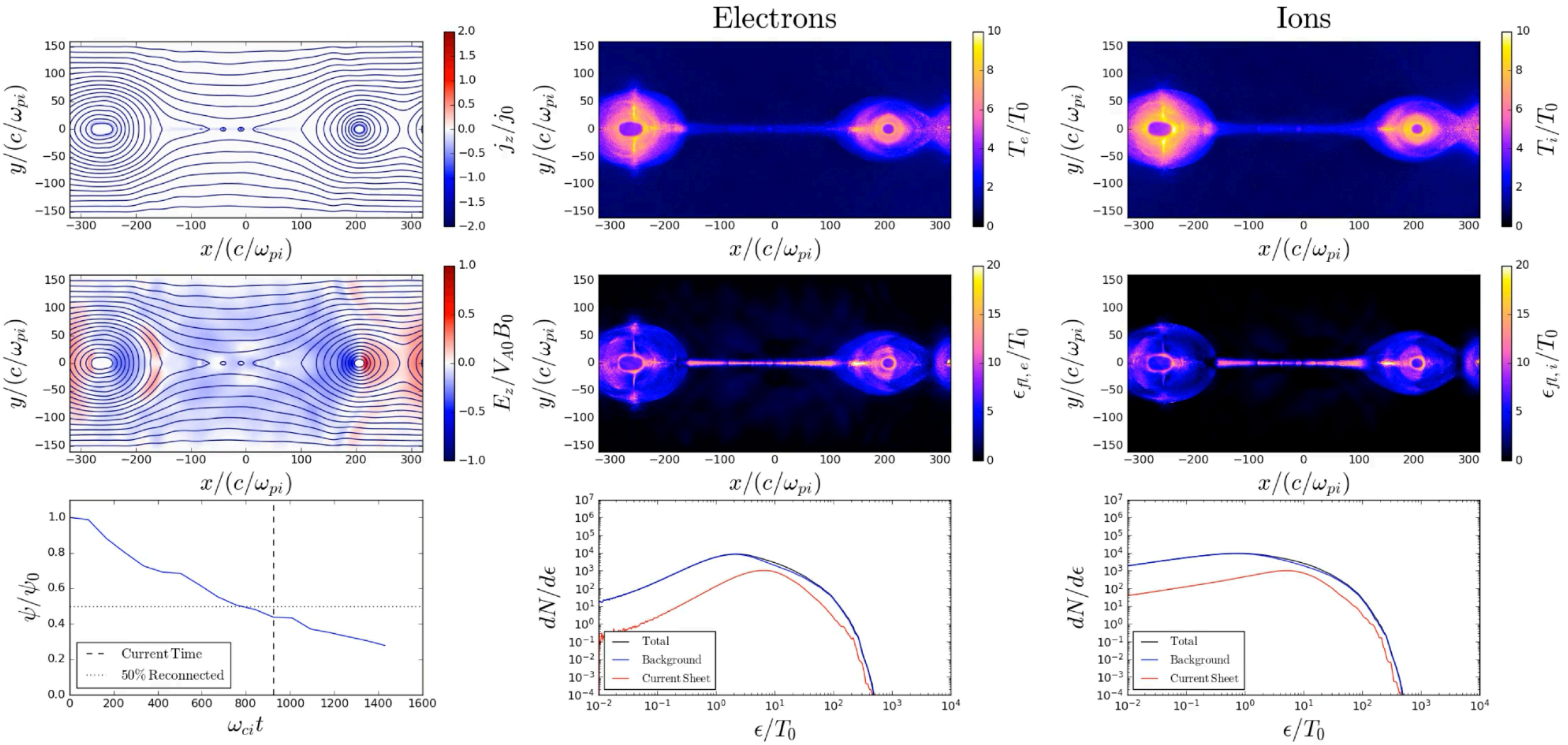


Future directions

- Study influence of out-of-plane guide field on nonthermal particle acceleration efficiency and partitioning

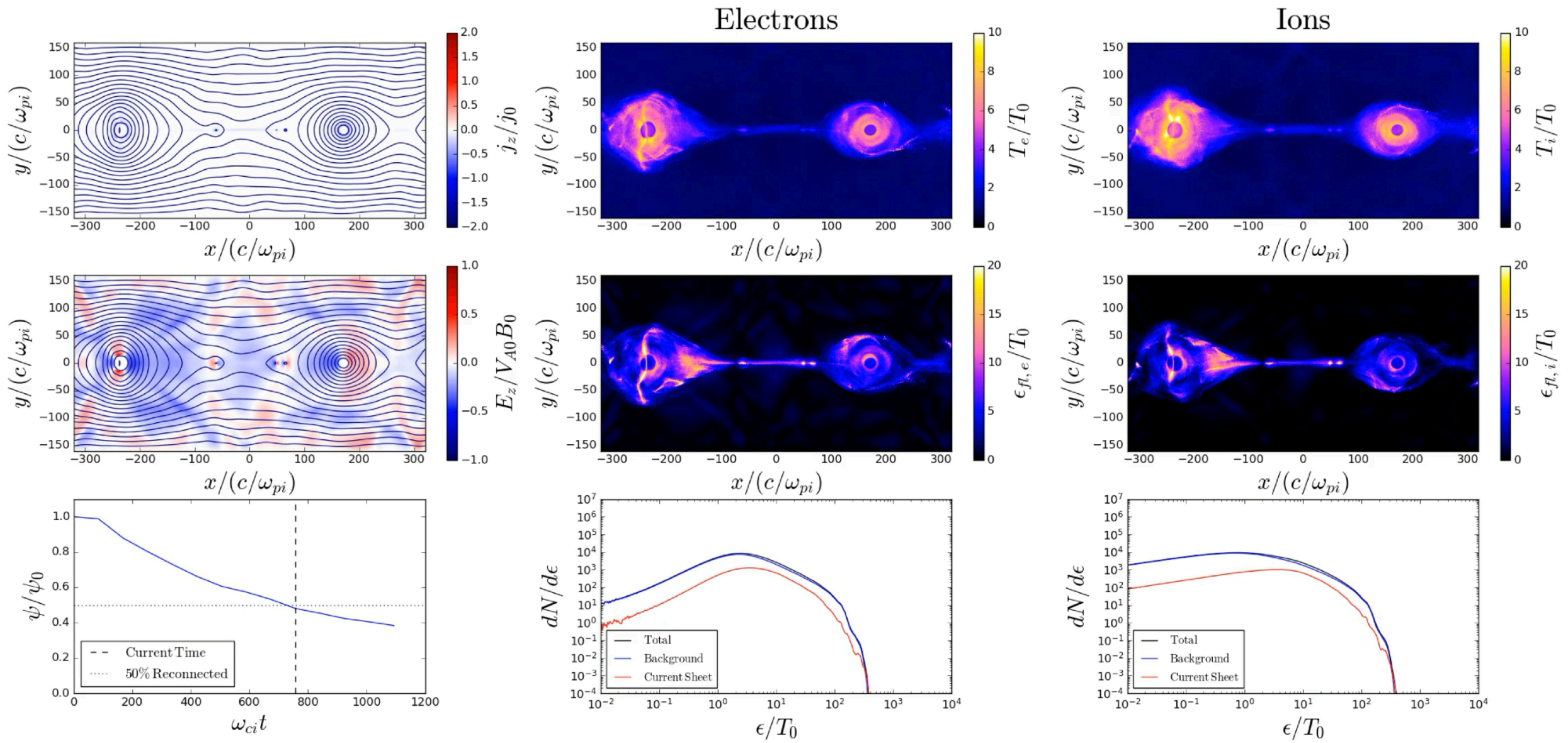
- Three-dimensional simulations to investigate the influence of the drift-kink instability on partitioning and dependence on guide field

- Connect results to observations in space physics and astrophysics



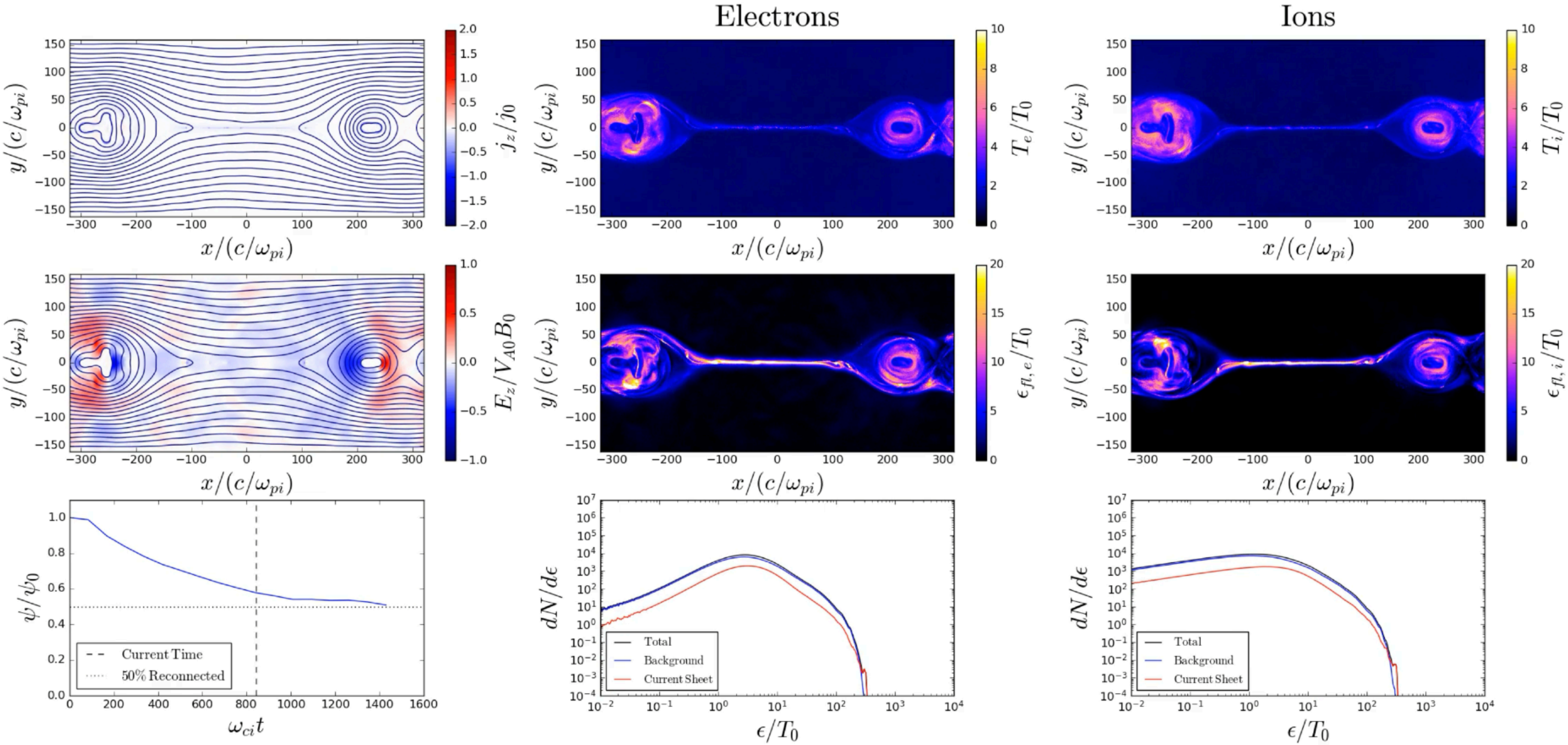
$$B_G/B_0 = 0$$

$$m_i/m_e = 100 \quad T_0/m_ec^2 = 32$$



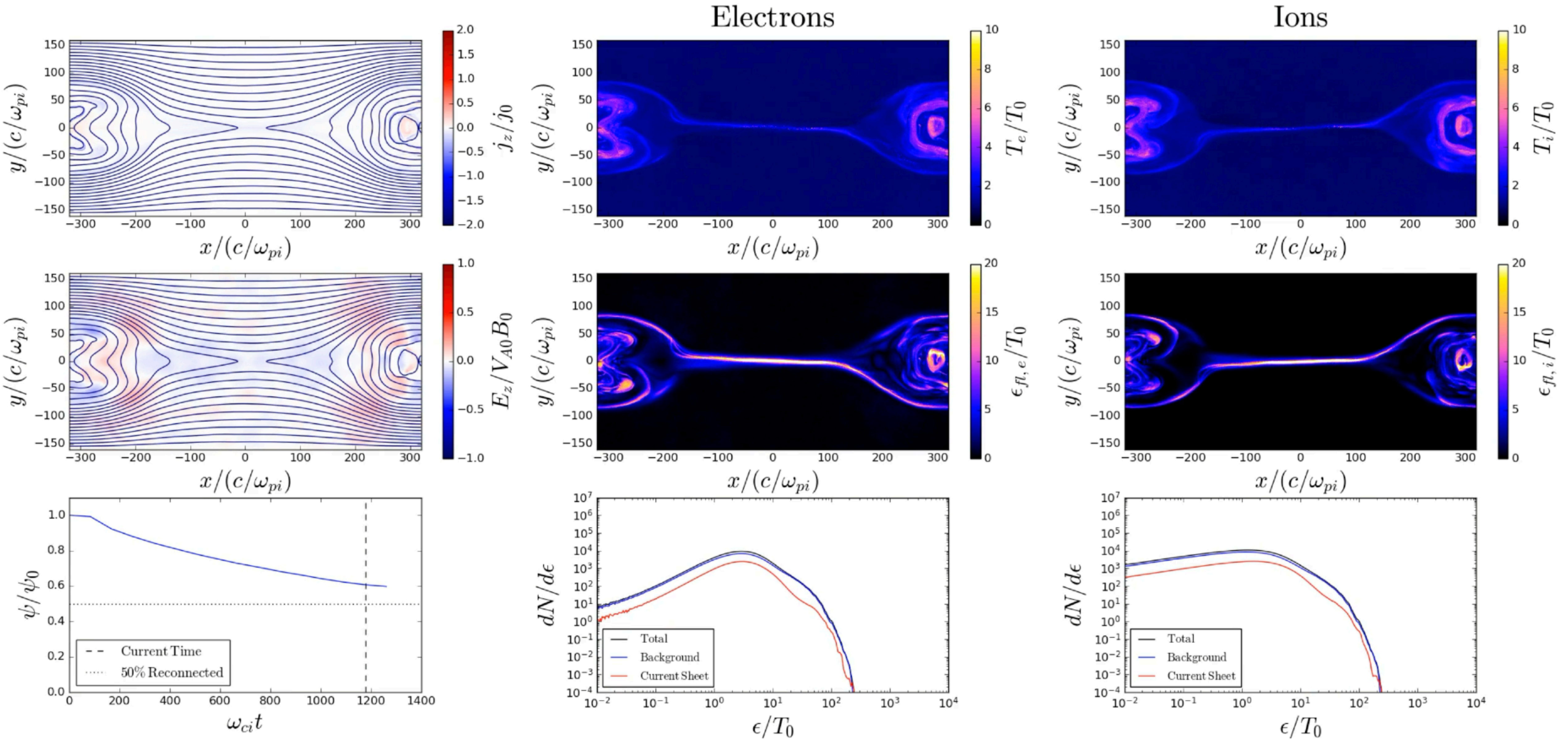
$$B_G/B_0 = 0.1$$

$$m_i/m_e = 100 \quad T_0/m_ec^2 = 32$$



$$B_G/B_0 = 0.5$$

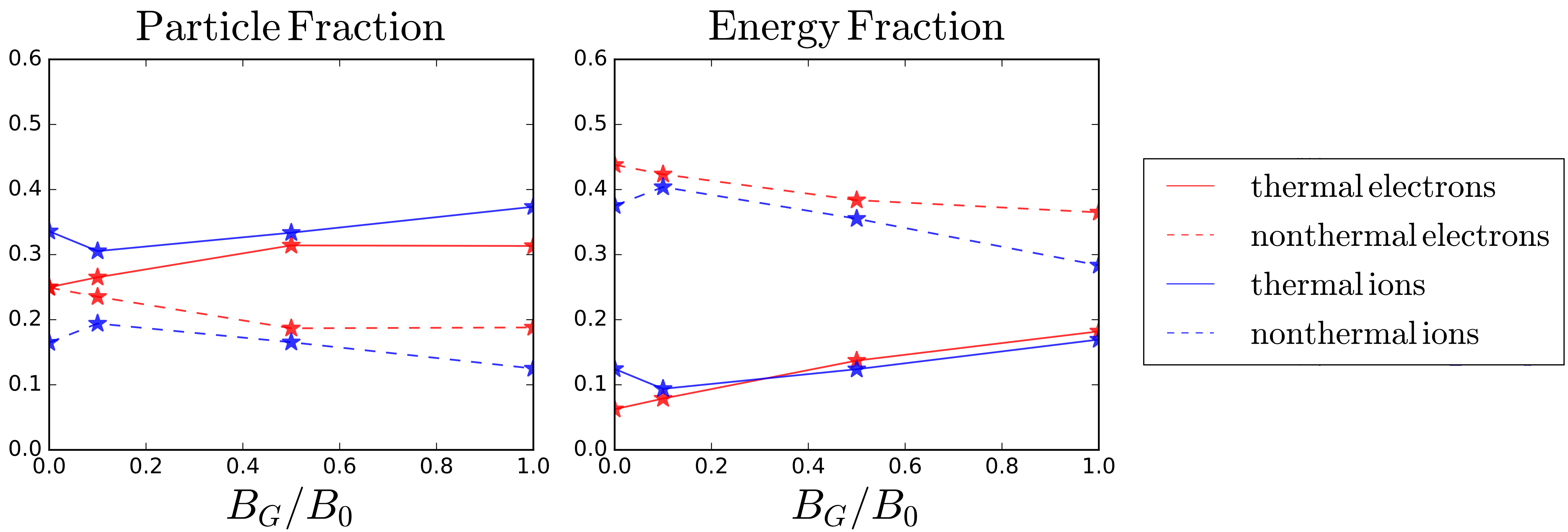
$$m_i/m_e = 100 \quad T_0/m_ec^2 = 32$$



$B_G/B_0 = 1$

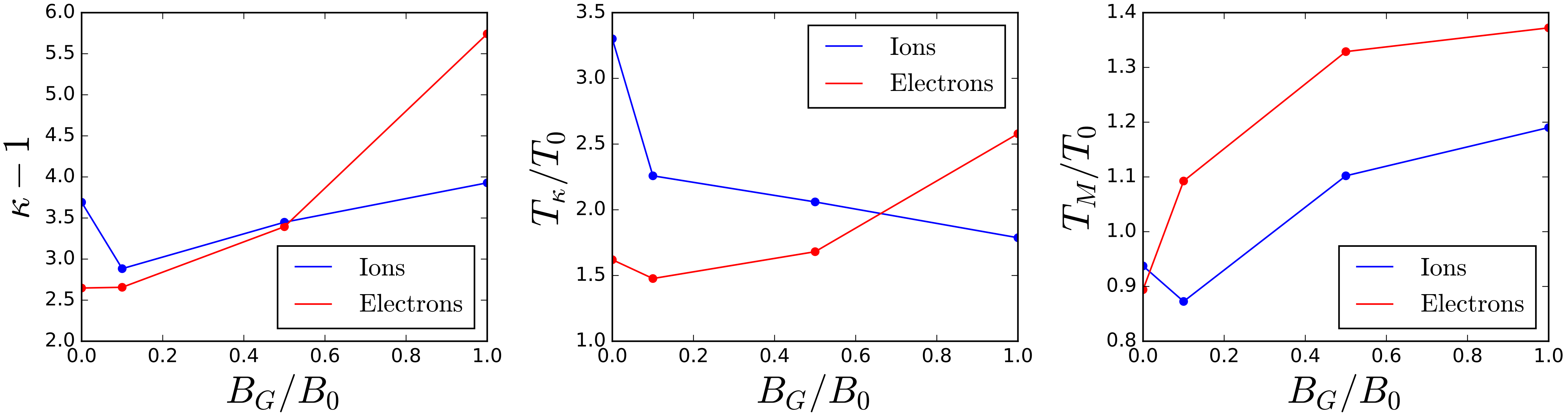
$m_i/m_e = 100 \quad T_0/m_ec^2 = 32$

Partitioning for varied guide field



$$m_i/m_e = 100 \quad T_0/m_e c^2 = 32$$

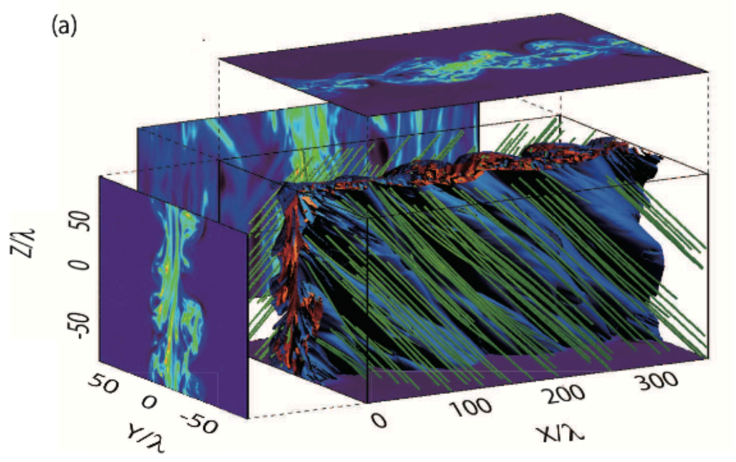
Fitting parameters for varied guide field



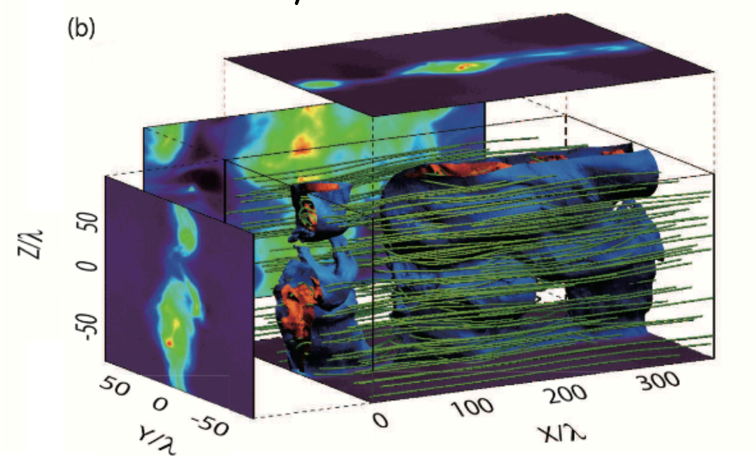
$$m_i/m_e = 100 \quad T_0/m_ec^2 = 32$$

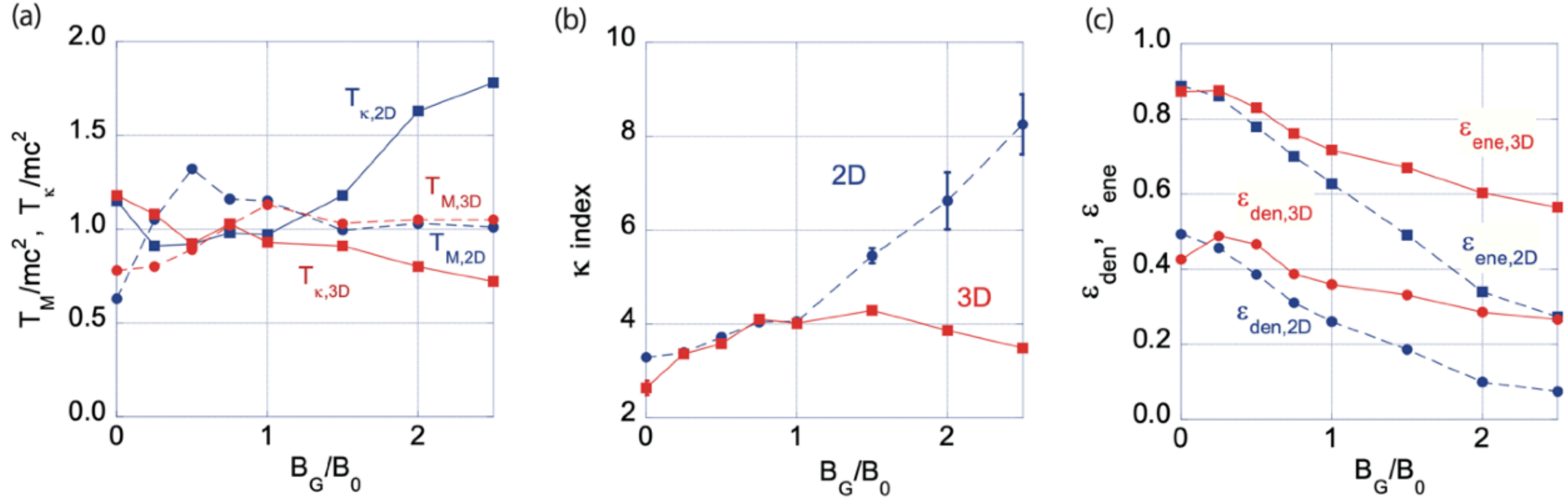
Three-dimensional effects on partitioning in electron-positron pair plasmas (Hoshino 2024)

$$B_G/B_0 = 1$$



$$B_G/B_0 = 0$$





- 3D reconnection is capable of maintaining a hard nonthermal energy spectrum even in the presence of a strong guide magnetic field

Conclusions

- Particle energy spectra in electron-ion reconnection can be fit to the sum of a Maxwellian and a Kappa distribution
- Model fitting procedure allows a quantification of the partitioning of dissipated magnetic energy into thermal and nonthermal electrons and ions
- At nonrelativistic temperatures, ions are preferentially heated
- As the temperature approaches the rest mass energy of a species of particles, a sharp increase in nonthermal particle acceleration efficiency occurs for that species
- Future work will investigate partitioning for varied guide fields and in three dimensions