Energetic spectra of relativistic reconnection at large scales using implicit PIC methods.

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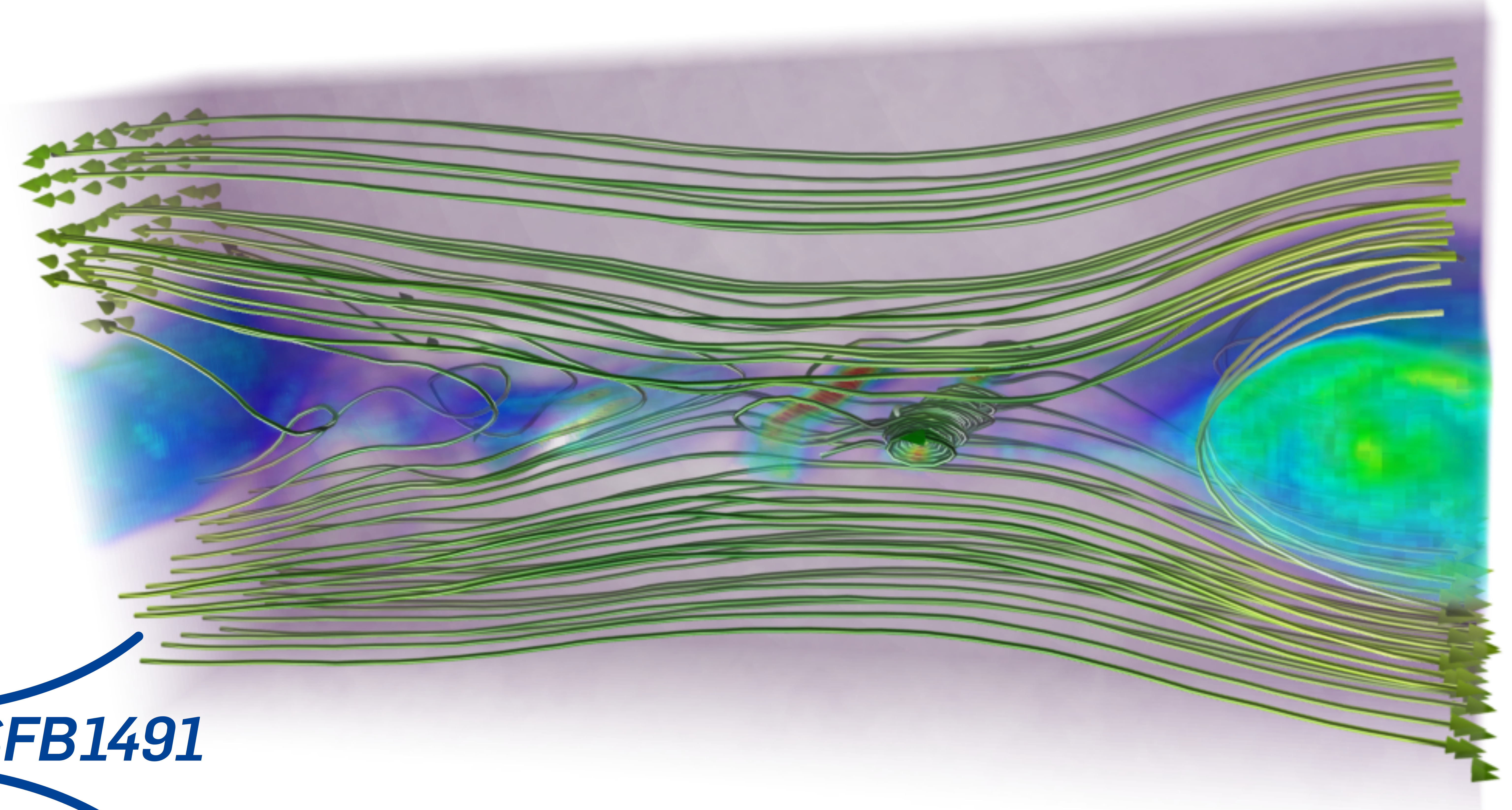

SFB1491

Energy spectra are important in astrophysics

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Observations imply energetic particle spectra

-Observations of neutrinos and cosmic rays from active galactic nuclei (AGN) e.g. NGC1068 and NGC7469

Detected by IceCube Collaboration between June 2019 and October 2023
Sommani et al. (**2024**) arXiv: 2403.03752, Cotton et al. (**2008**)

-requires an acceleration mechanism

-Could be produced by magnetic reconnection.

Sironi et al. (**2014**), Guo et al. (**2016**), Werner et al. (**2015**)

-Huge system sizes difficult to simulate.

AGN

Nature Astronomy 2018

Magnetic field strength (~ 10^4 G)

Scale length

$$L \approx 0.007\ \mathrm{pc} \approx 1 \times 10^{10}\ \mathrm{d_e}$$

Assuming

$$n = 0.3\ \mathrm{cm}^{-3}$$

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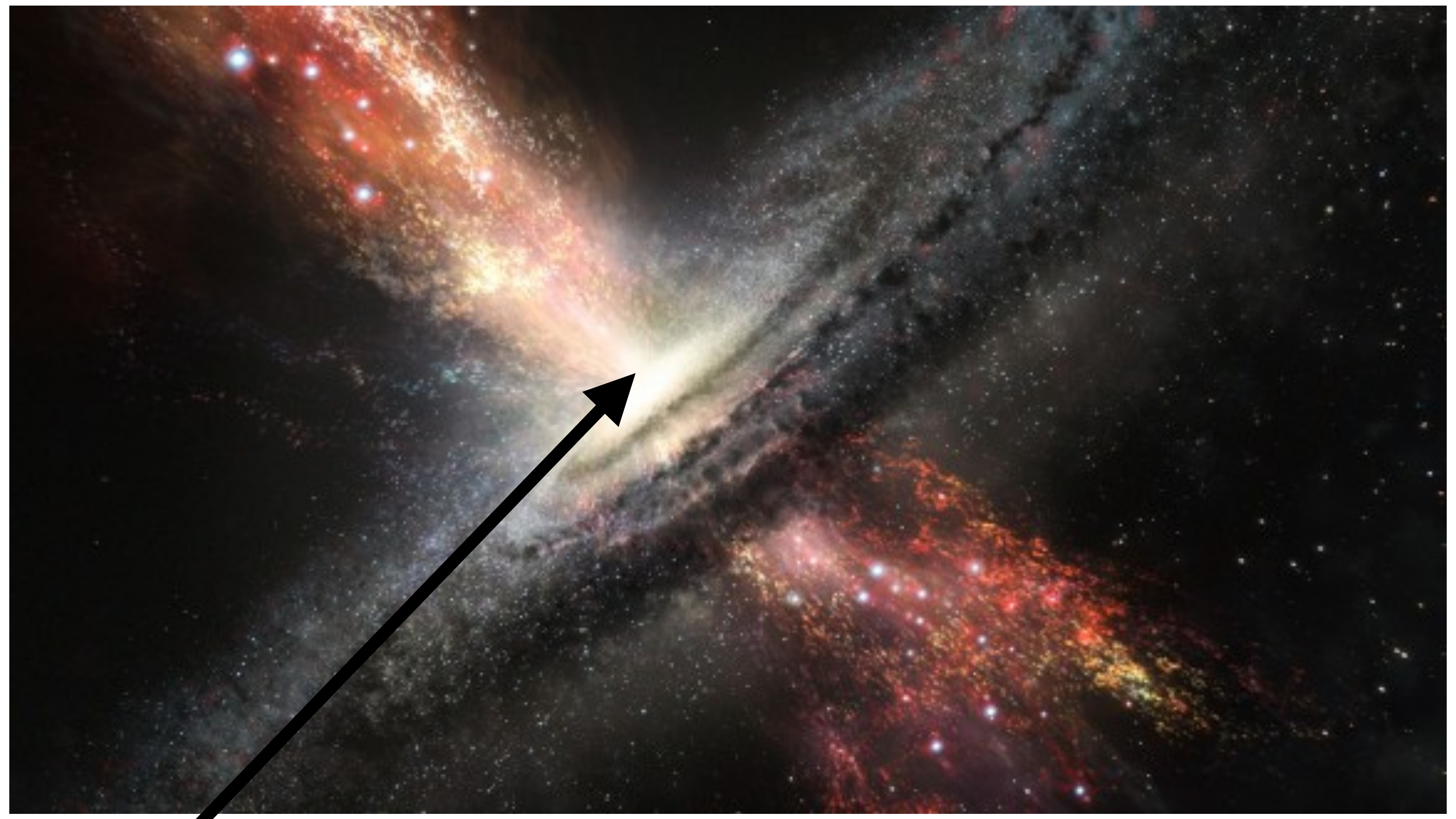

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Assuming

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A strongly relativistic regime

What is a relativistic plasma?

Relativistic plasma

-Relativistic Alfvén speed (high magnetization)

$$\sigma_{\alpha,c} \equiv \frac{B^2}{4\pi n m_\alpha c^2} > 1$$

-Relativistic temperatures

$$\frac{T_\alpha}{m_\alpha c^2} > 1$$

-At times, electron-positron (pair) dominant plasma.

High magnetization → free energy for energetic spectra

Hot magnetization

$$\sigma_{\alpha,h} \equiv \frac{B^2}{4\pi n h_\alpha} \approx \frac{B^2}{16\pi n T_\alpha} > 1$$

Outline

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Introduction

Tearing instability for pairs
Benchmark from explicit PIC simulations

Reconnection at large scales
Advantages of semi-implicit methods

Let’s consider a Harris equilibrium

Harris equilibrium

$$B_x = B_0 \tanh\left(\frac{y}{\lambda}\right)$$

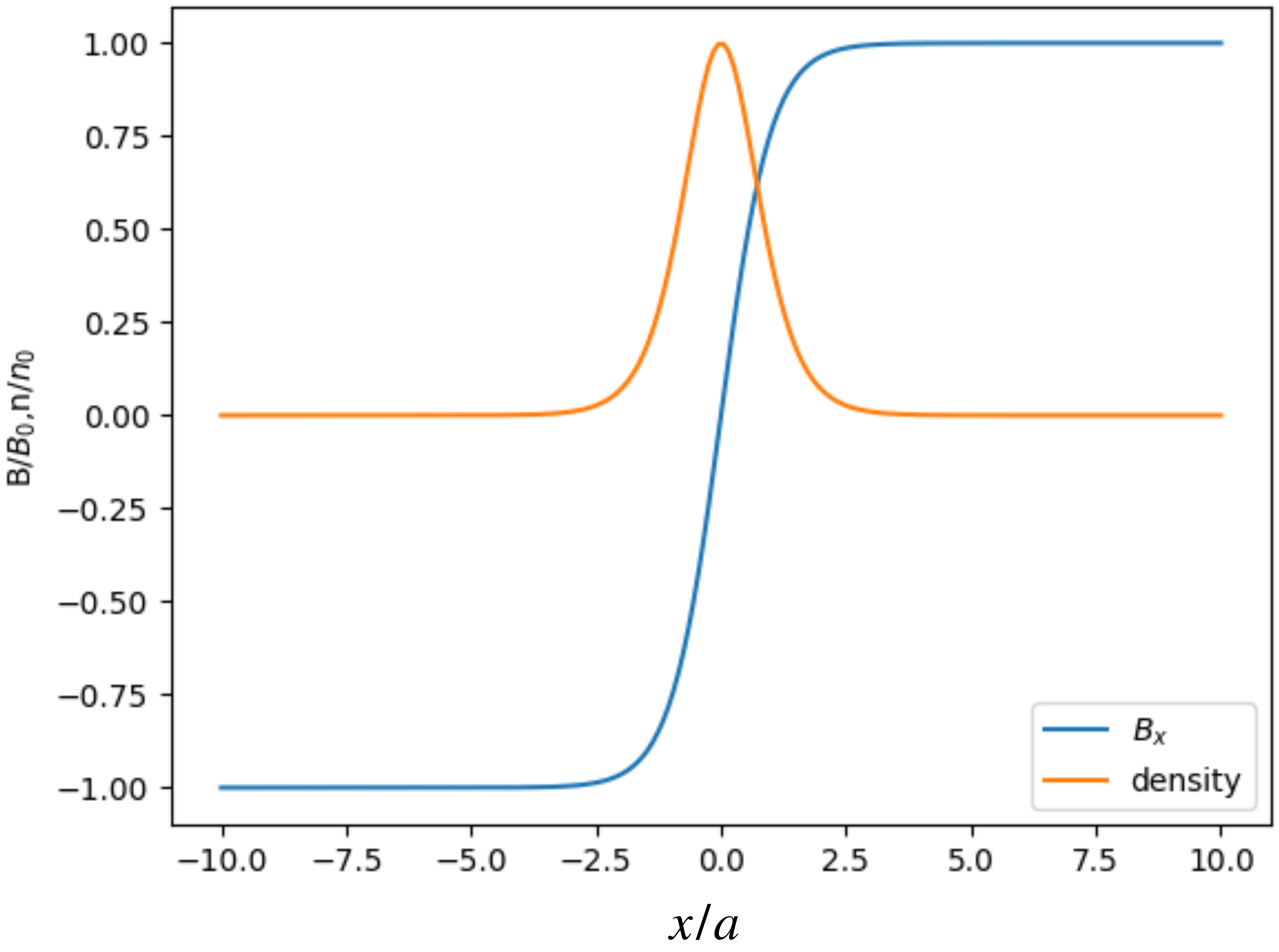
$$n = n_0 \ \mathrm{sech}^2\left(\frac{y}{\lambda}\right)$$

Constant and uniform
v_d **and** T

Not only in force balance

$$\frac{B_0^2}{8\pi} = 2n_0 T = n_0\left(T_e + T_i\right)$$

Is in kinetic equilibrium



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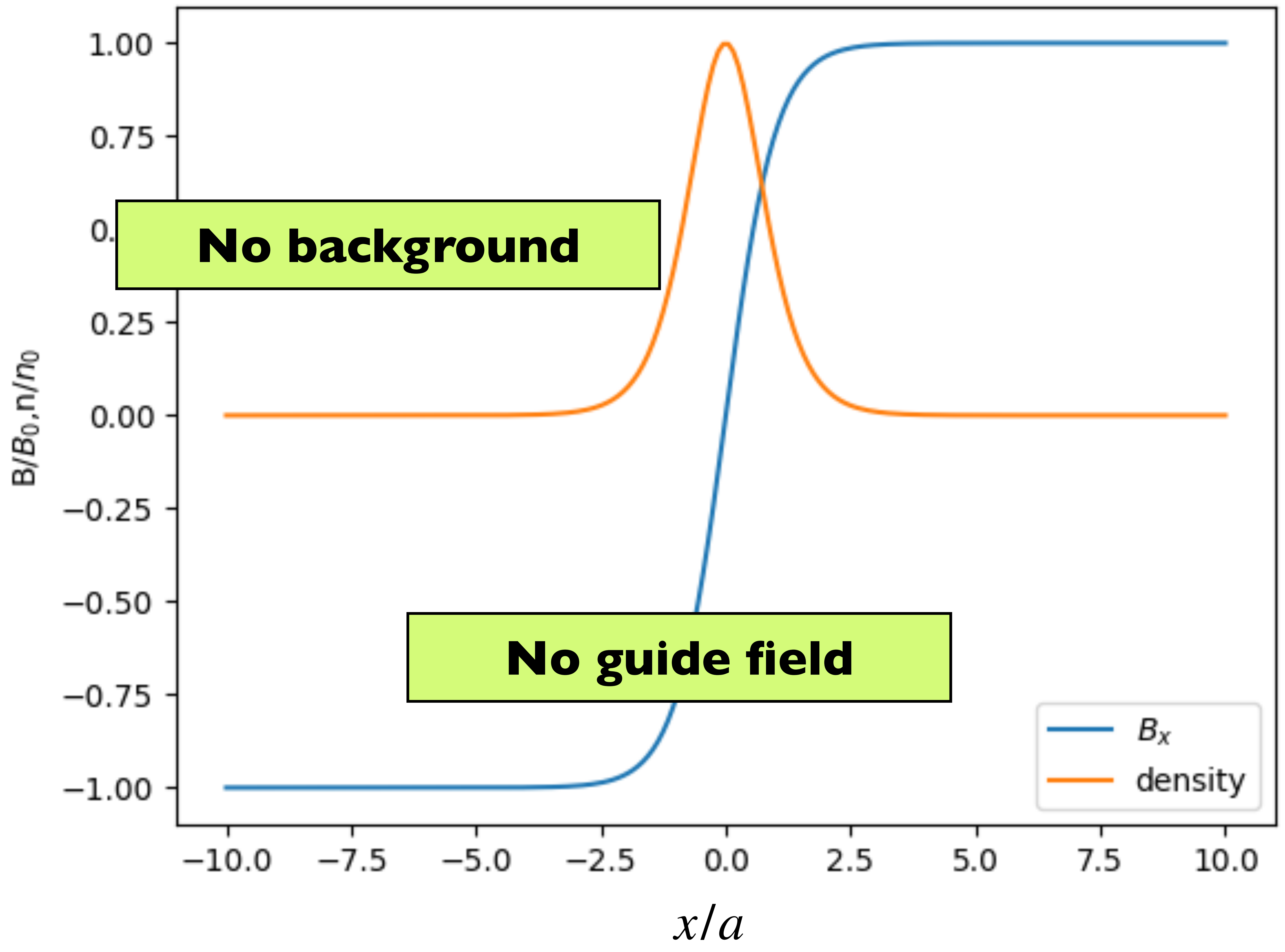

Zelenyi model corrected for relativistic drifts

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From Zelenyi 1979 + Hoshino 2020

Non-relativistic : $\frac{v_T}{c} \ll 1$

Relativistic : $\frac{T}{mc^2} \gg 1 \quad \left(\frac{v_T}{c} \sim 1\right)$

$$T_\alpha = \frac{m_\alpha v_T^2}{2}$$

$$\frac{\gamma a}{v_T} = C_1(ka)\frac{1}{\Gamma_d^{5/2}}\left(\frac{u_d}{v_T}\right)^{3/2}$$

$$\frac{\gamma a}{c} = C_2(ka)\frac{1}{\Gamma_d^{5/2}}\left(\frac{u_d}{c}\right)^{3/2}$$

$$u_d = \Gamma_d v_d$$

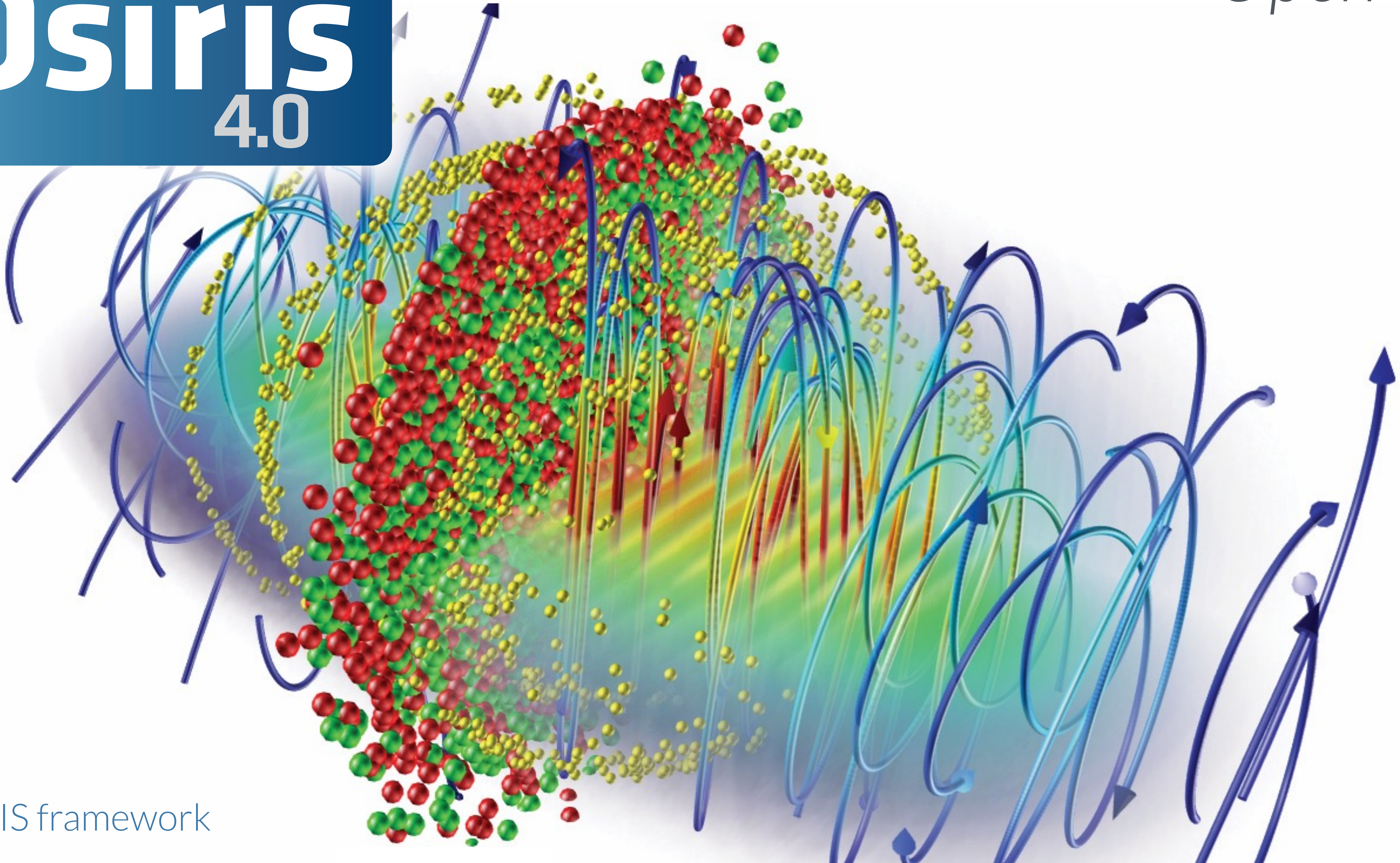
$$\Gamma_d = \sqrt{1 + \frac{u_d^2}{c^2}}$$

$$\frac{u_d}{v_T} = \frac{\rho_{L,C}}{a} = \frac{\sqrt{\Gamma_D} d_{e,C}}{a}$$

$$\frac{u_d}{c} = \frac{\rho_{L,R}}{a} = \frac{\sqrt{\Gamma_D} d_{e,R}}{a}$$

Osiris 4.0

Open-source version available



Open-access model

- 40+ research groups worldwide are using OSIRIS
- 400+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available
- Support for education and training

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Open-source version at:

https://osiris-code.github.io/

OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Support for advanced CPU / GPU architectures
- Extended physics/simulation models
- AI/ML surrogate models and data-driven discovery

visXD

UNIVERSITY OF MICHIGAN UCLA TÉCNICO LISBOA

Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

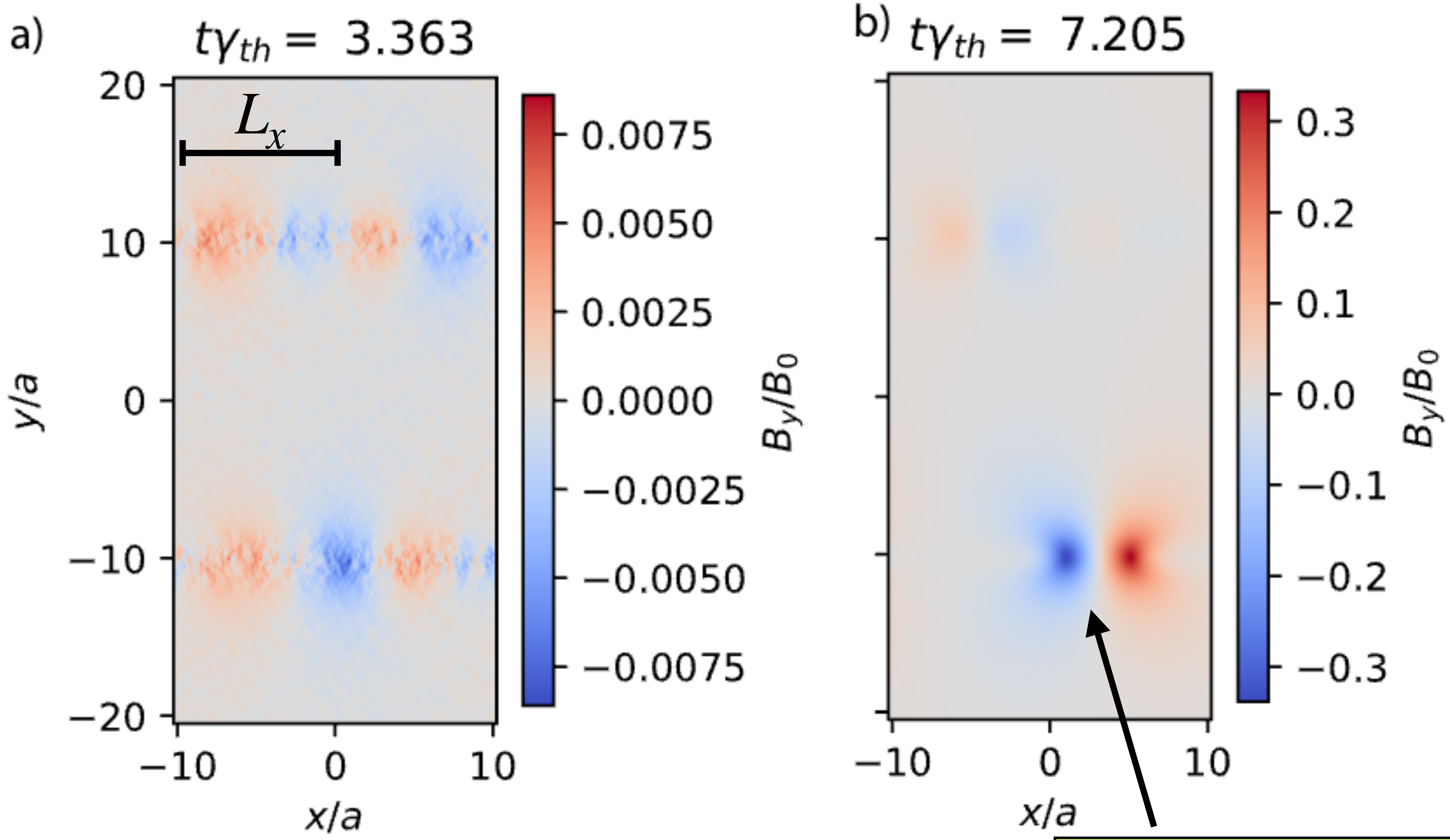
Linear grows at predicted wavelength

$$k_{max}a \sim \frac{1}{2}$$

$$ka \approx \frac{2\pi}{L_x/a} = \frac{2\pi}{10} \approx 0.63 \sim \frac{1}{2}$$

Simulation

$$\frac{a}{\rho_{L,C}} = 2.5 \qquad \frac{T}{m_e c^2} = 0.00125$$



Schoeffler et al. J.P.P 2025

Islands merge in nonlinear stage

Tearing eigenmodes

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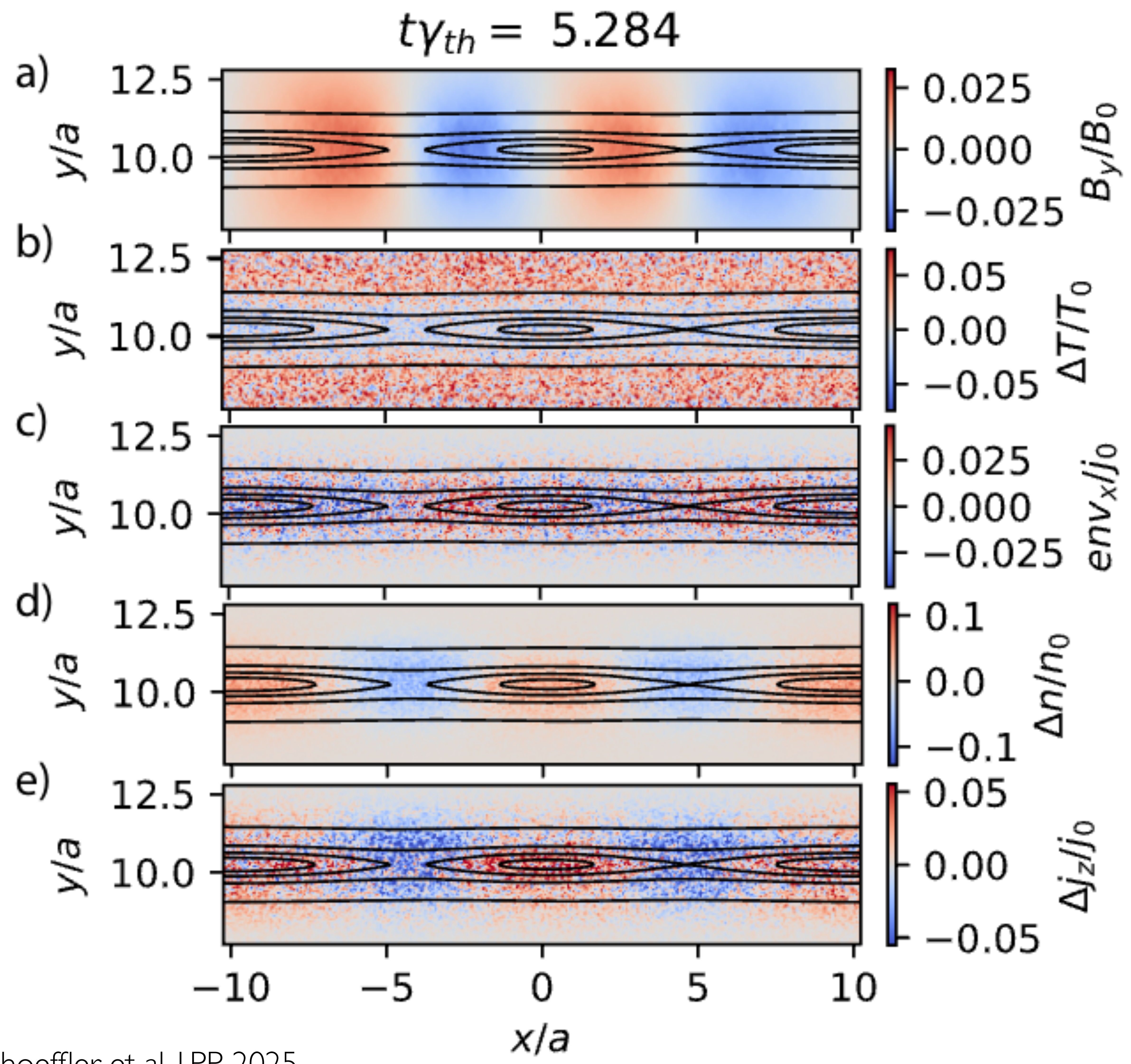
Tearing modes consist of ...

- **Heating (island centers)**
- **Flows away from x-line**
- **Density peaked at island centers**
- **Current also peaked at island centers**

Simulation

$$\frac{a}{\rho_{L,C}} = 2.5 \qquad \frac{T}{m_e c^2} = 0.00125$$



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Growth rates are measured from transverse field

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Magnetic field B_y grows as predicted linearly

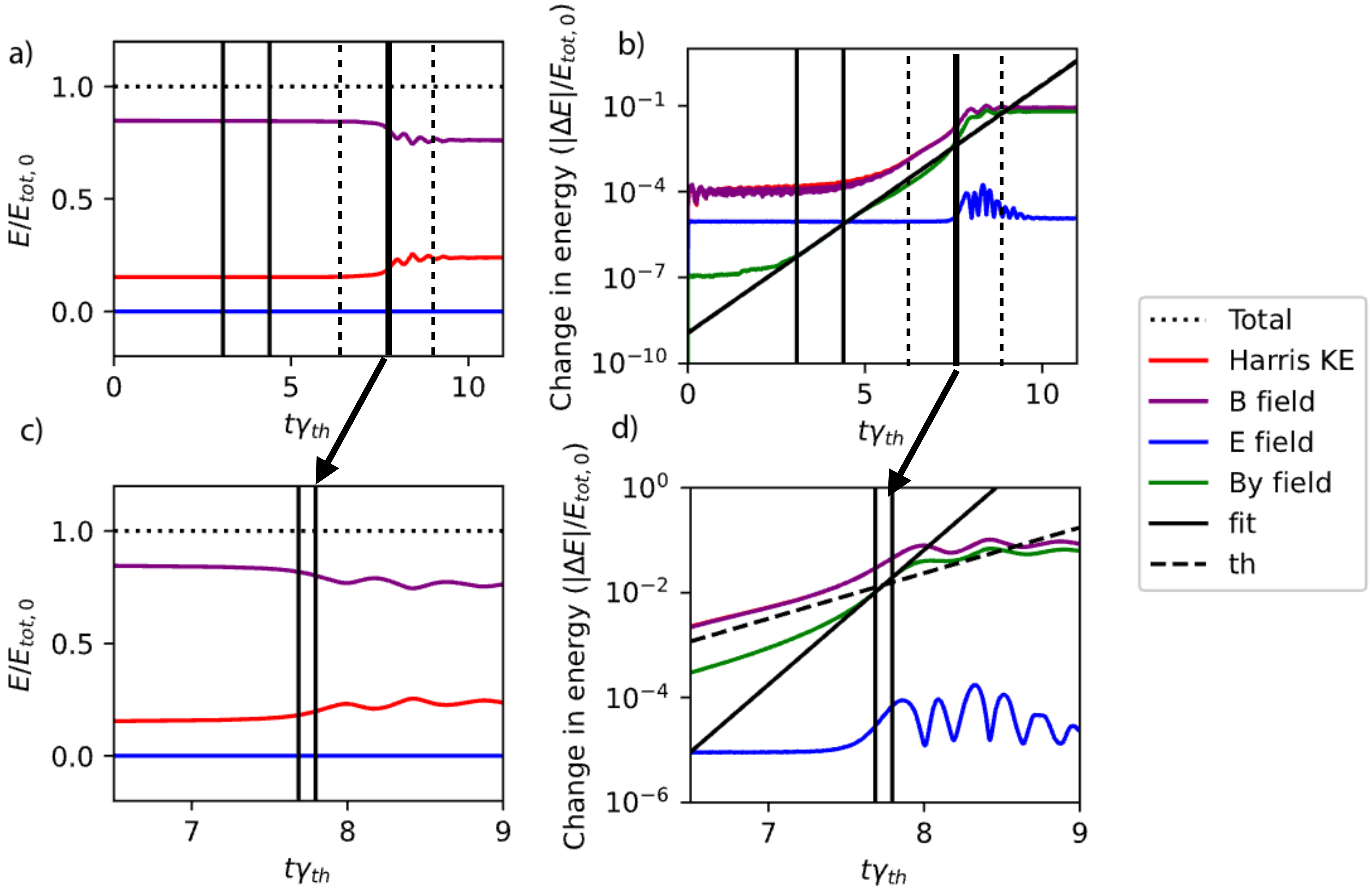
$$\frac{\gamma a}{v_T} = C_1(ka)\frac{1}{\Gamma_d^{5/2}}\left(\frac{\rho_{L,C}}{a}\right)^{3/2}$$

Nonlinear stage grows as if $a/\rho_{L,C} = 1$

$$\frac{\gamma a}{v_T} = C_1(ka)$$

Simulation

$$\frac{a}{\rho_{L,C}} = 2.5 \qquad \frac{T}{m_e c^2} = 0.00125$$



Schoeffler et al. J.P.P 2025

Simulations match Zelenyi (non-relativistic)

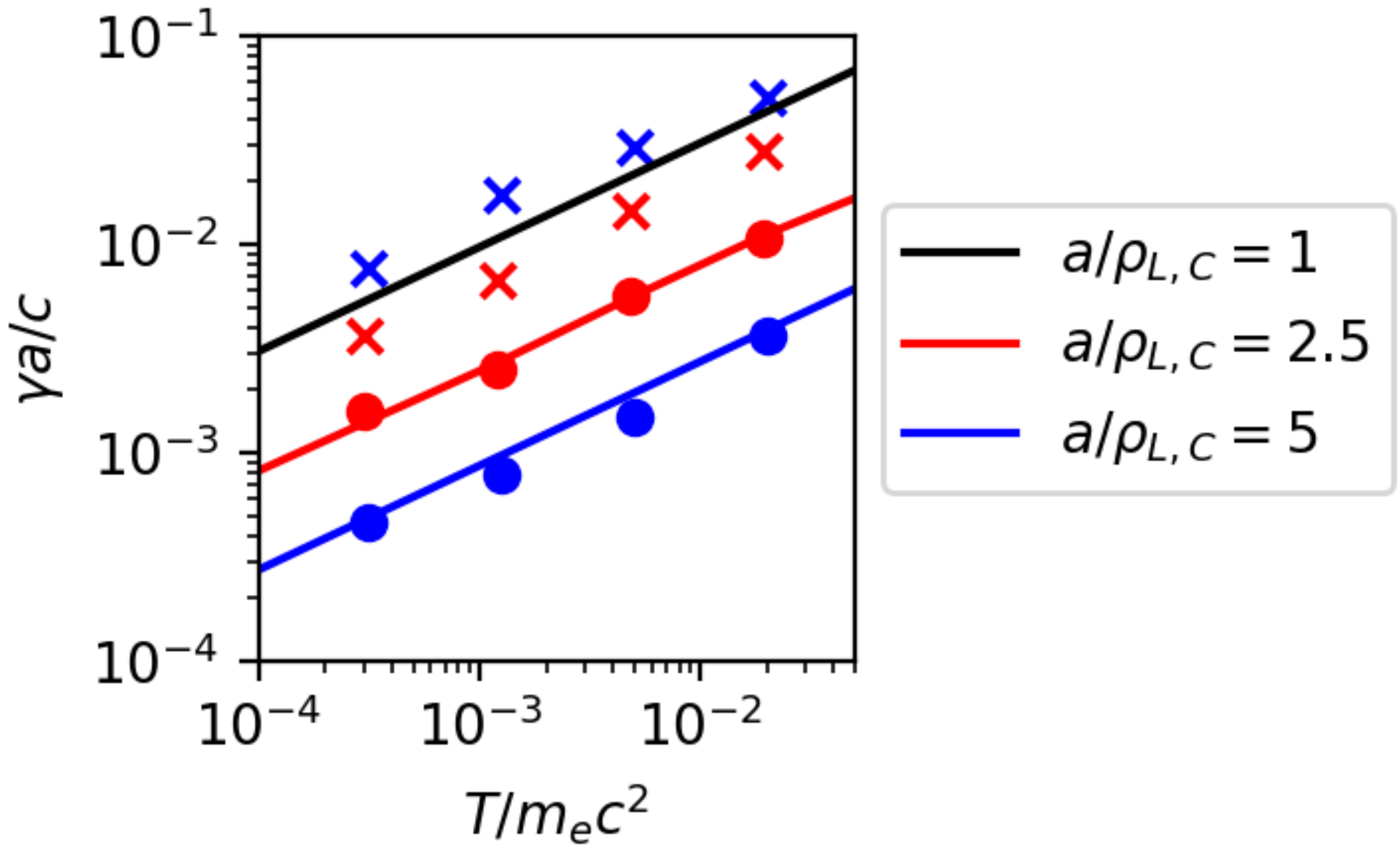
From Zelenyi 1979

$$\frac{\gamma a}{v_T} = C_1(ka)\frac{1}{\Gamma_d^{5/2}}\left(\frac{\rho_{L,C}}{a}\right)^{3/2}$$

Non-relativistic : $\frac{v_T}{c} \ll 1$

Good fit, holding $\frac{a}{\rho_{L,C}}$ **constant**

and $\frac{L_x}{a} = 10$, $\frac{L_y}{a} = 20$



Schoeffler et al. J.P.P 2025

Simulations match Zelenyi (relativistic)

From Zelenyi 1979 + Hoshino 2020

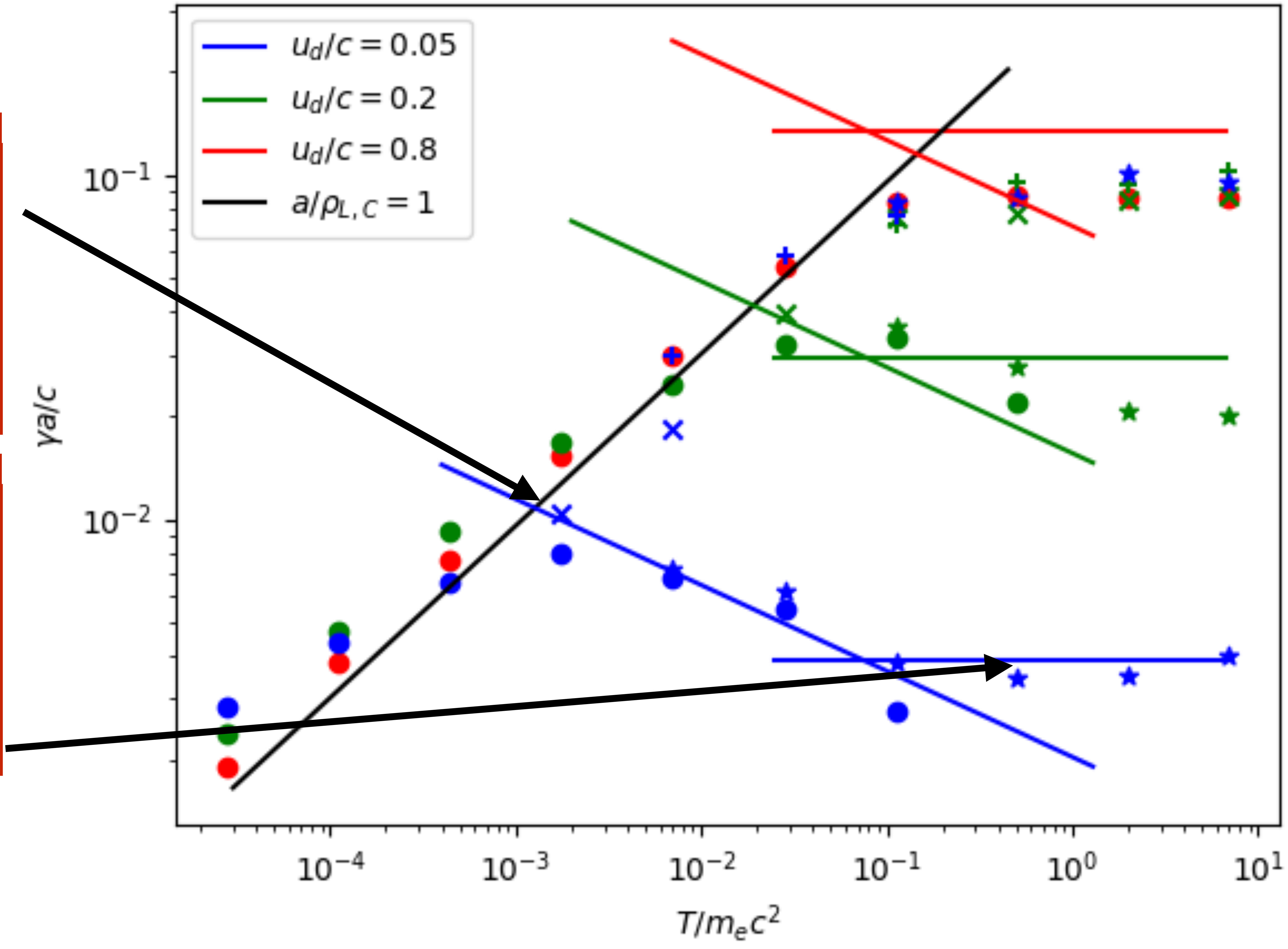
Non-relativistic

$$\frac{\gamma a}{v_T} = C_1(ka)\frac{1}{\Gamma_d^{5/2}}\left(\frac{u_d}{v_T}\right)^{3/2}$$

Relativistic

$$\frac{\gamma a}{c} = C_2(ka)\frac{1}{\Gamma_d^{5/2}}\left(\frac{u_d}{c}\right)^{3/2}$$

Good fit, holding $\frac{\rho_{L,R}}{a} = \frac{u_d}{c}$ **constant**



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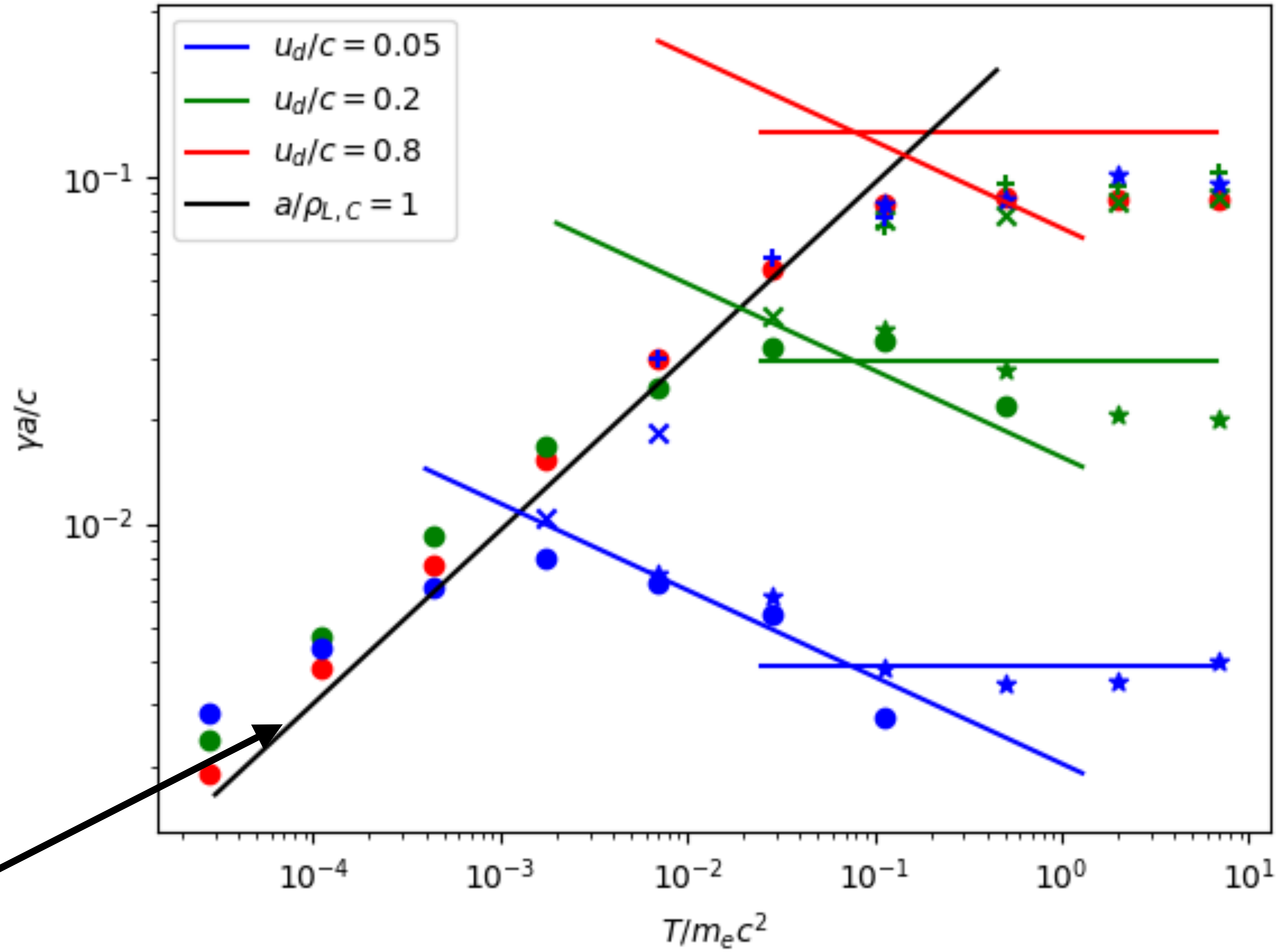
Simulations match Zelenyi (relativistic)

For constant u_D ,
as T_e decreases so does $\frac{a}{\rho_{L,C}}$

When $\frac{a}{\rho_{L,C}} < 1$ **growth rate follows**



$$\frac{\gamma a}{v_T} = C_1(ka)\frac{1}{\Gamma_d^{5/2}}\left(\frac{\rho_{L,C}}{a}\right)^{3/2}$$

Assuming $\frac{a}{\rho_{L,C}} = 1$

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Tearing for pair-plasmas

Prediction follow model

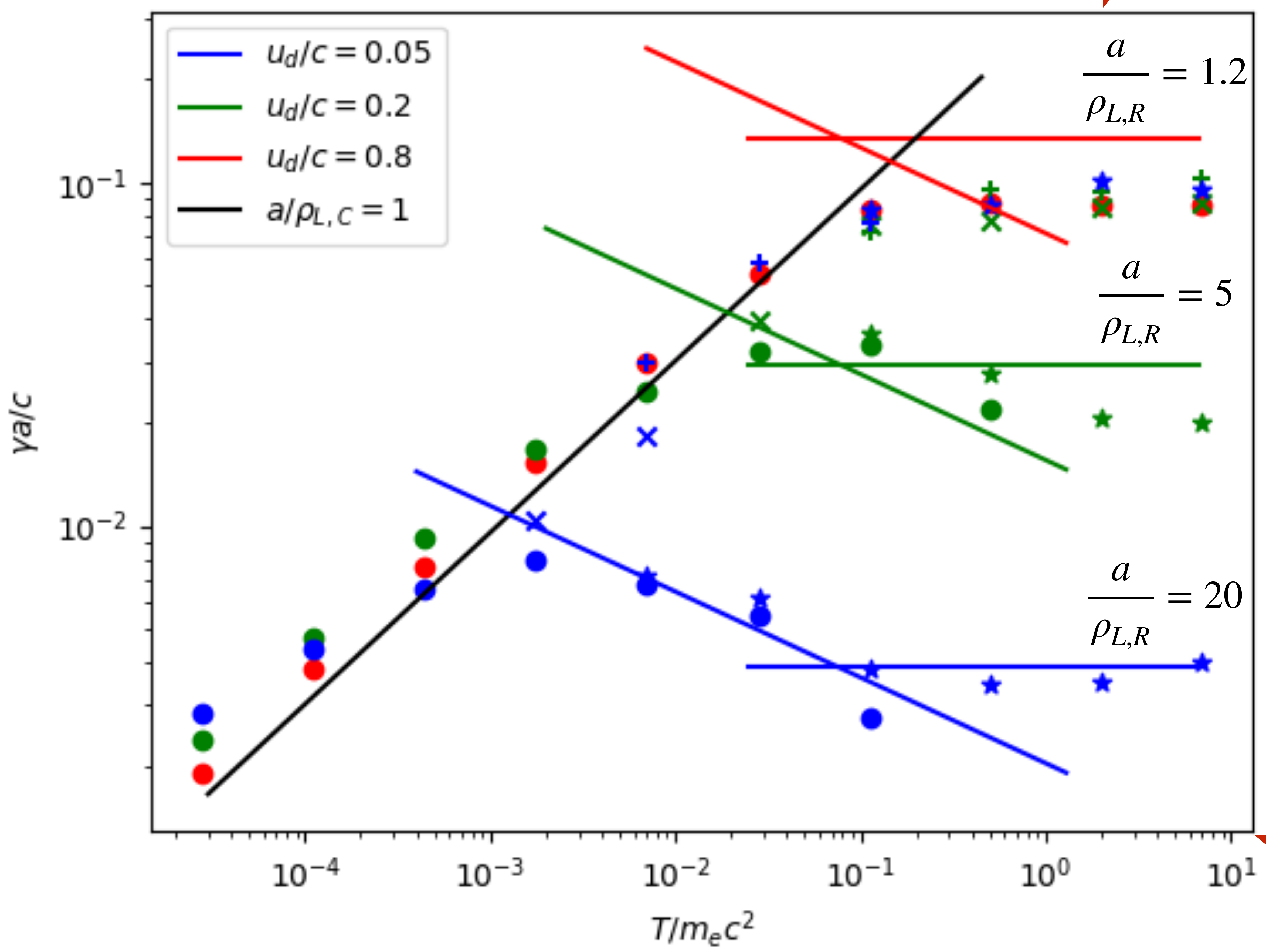
-Zelenyi model matches PIC simulations

Zelenyi and Krasnosel'skikh (1979)

-Extrapolations to large $\frac{a}{\rho_{L,R}} \gg 1$ can give estimate for tearing rate in thick current sheets.

-Electron-positron (pair) dominant plasma assumed, but growth rate is modified by only a factor ~ 1 .

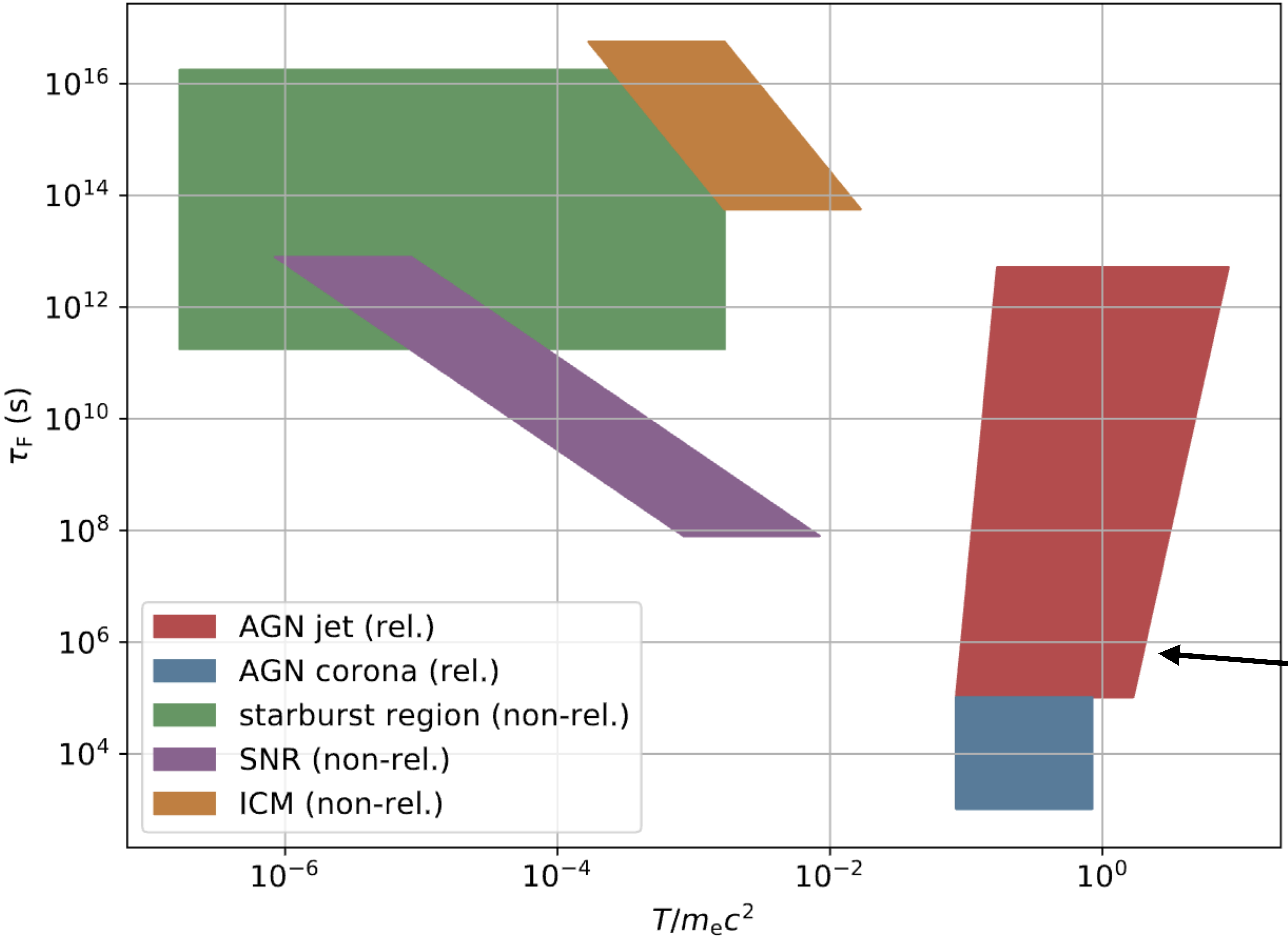
More relativistic



Current thickness a

Schoeffler et al. J.P.P 2025

Estimated formation times for astrophysical objects



Potential tearing unstable current sheet can be generated on a timescale.

$$\tau_F \sim \frac{L}{v_A}$$

Ratio of system size and Alfvén speed.

Relativistic regimes have faster time scales

Schoeffler et al. J.P.P 2025

Critical thickness before tearing

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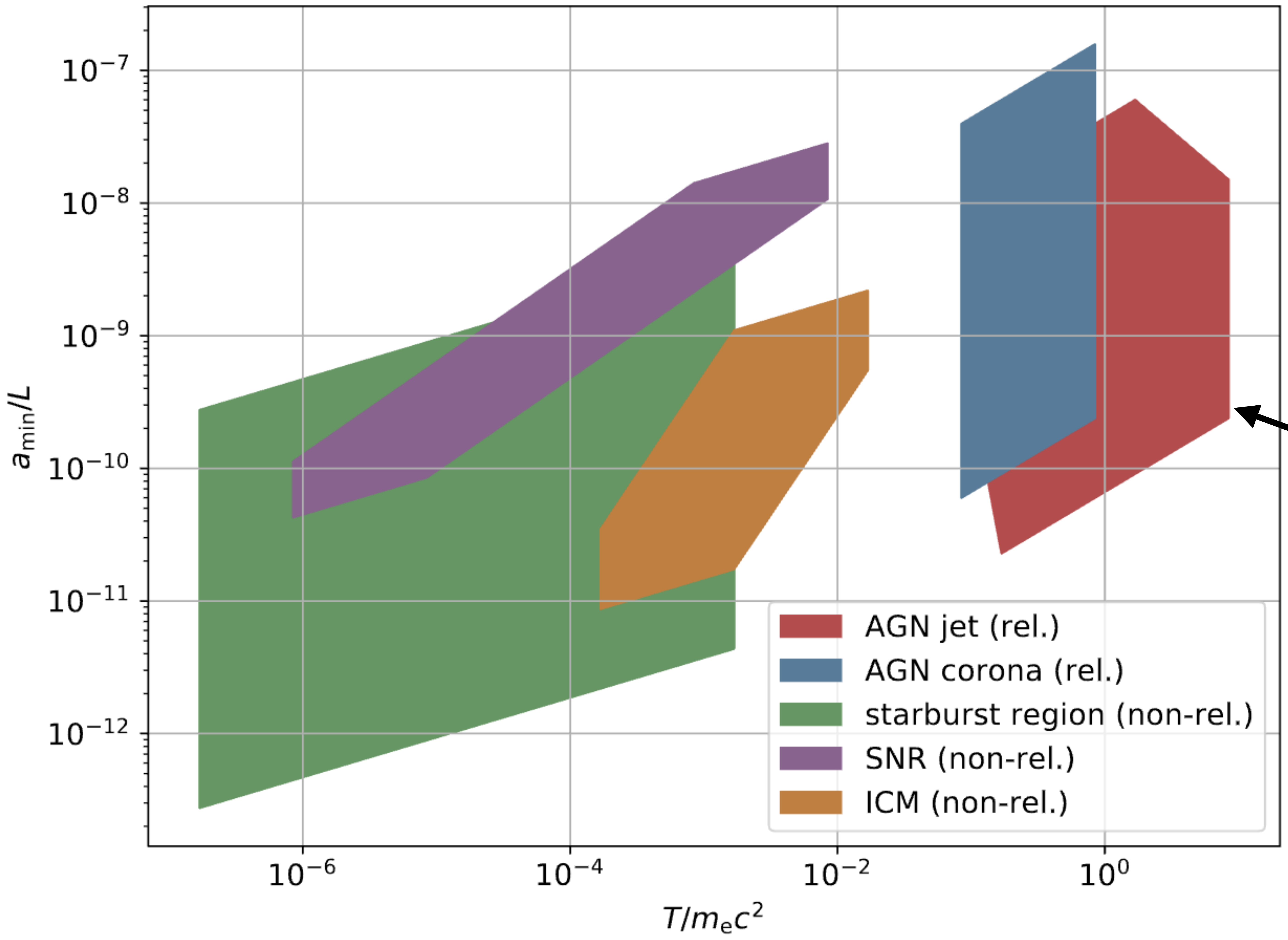

Thickness of current sheet must thin to extreme values before tearing is fast enough.

$$\gamma\tau_F > 1$$

Relativistic regimes can reach critical thickness a_{min} easier

Schoeffler et al. J.P.P 2025

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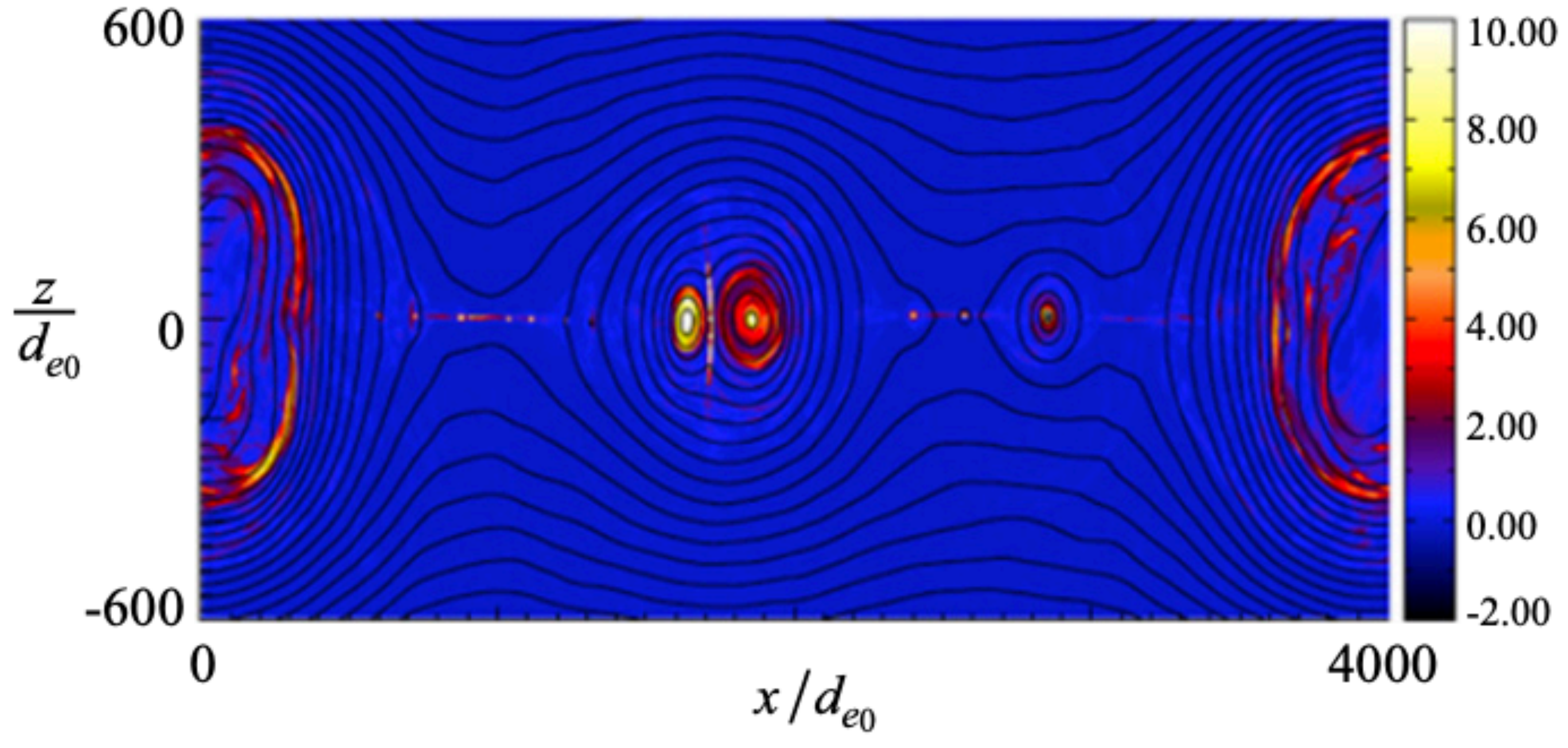
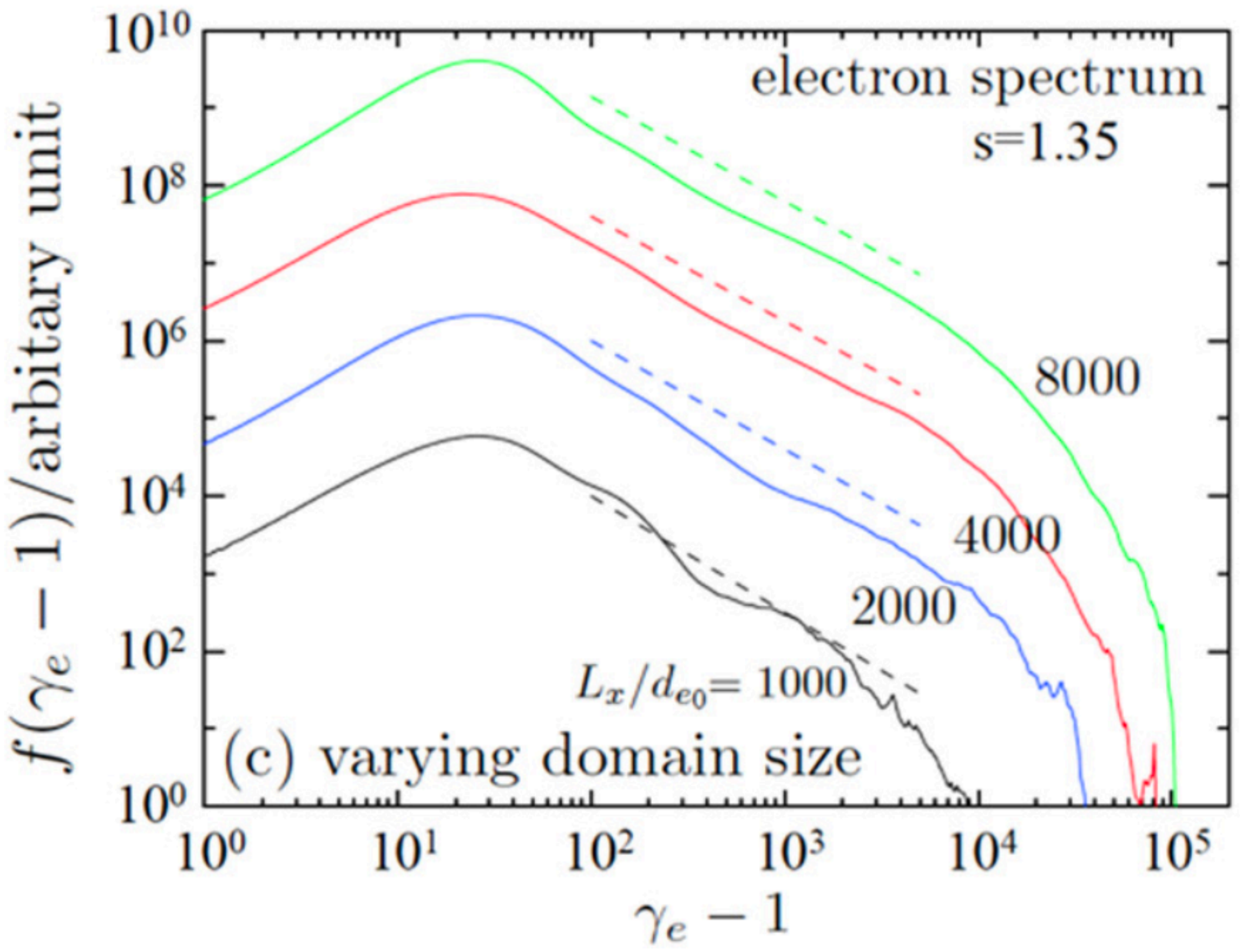
Energetic spectra found in explicit PIC simulations

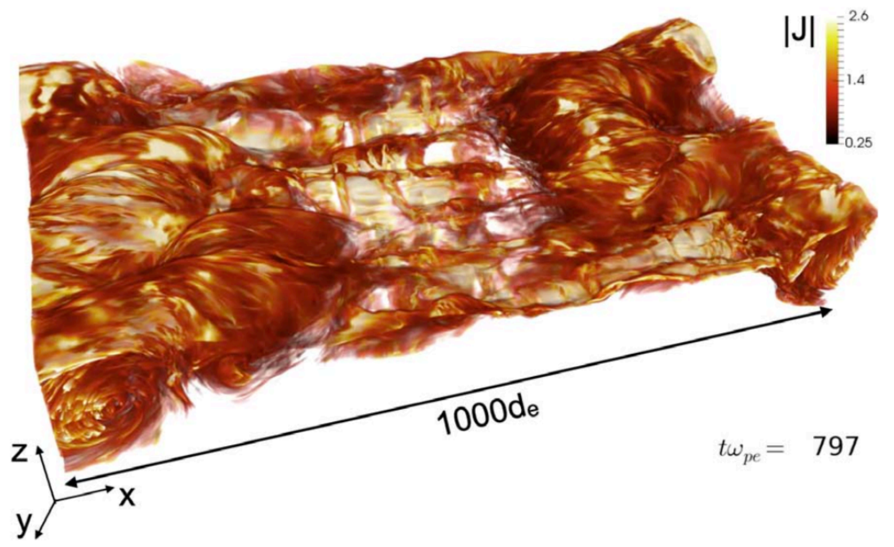




Guo et al. (**2016**)

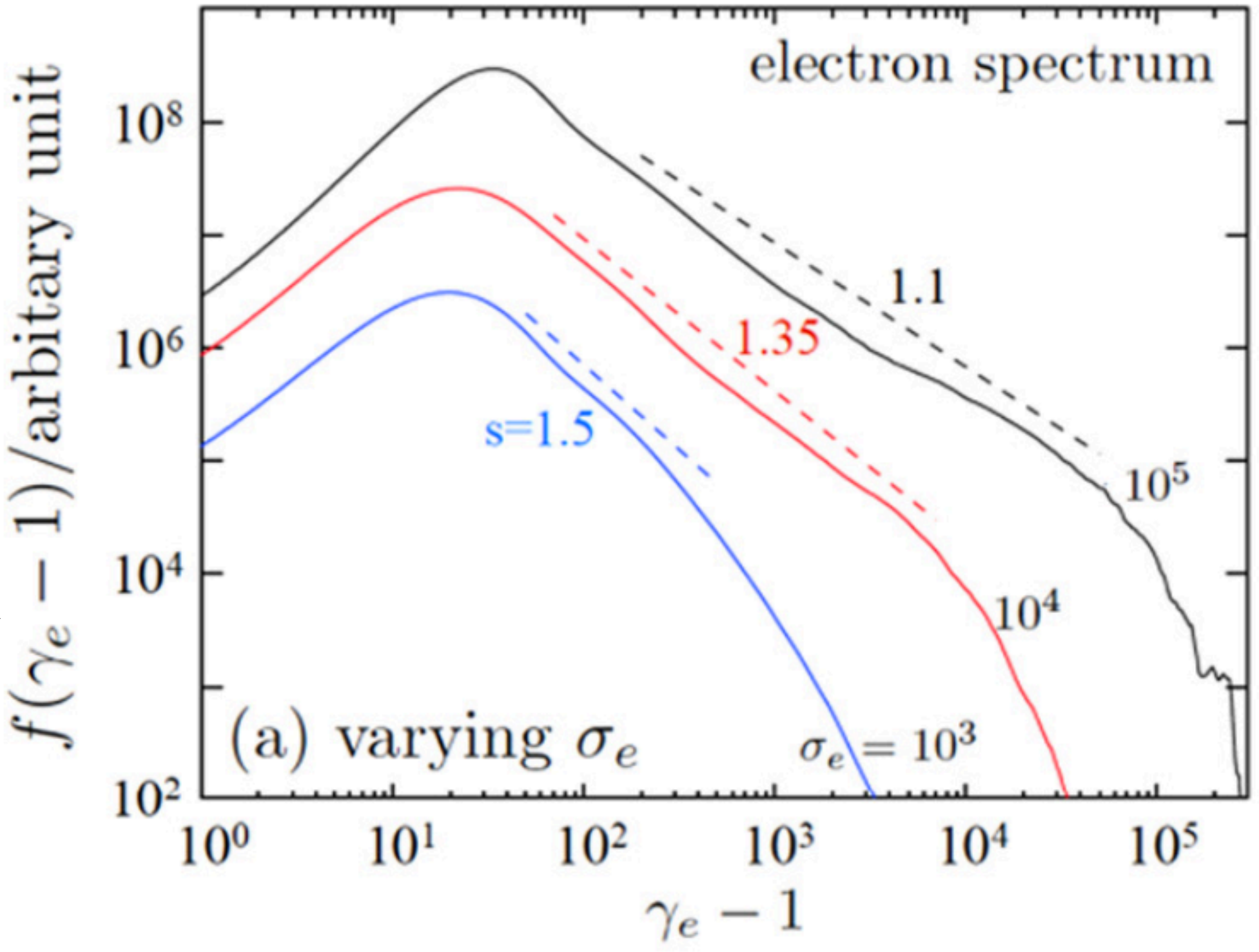
Simulations done here in 2D, also reproduced spectra in 3D.

Guo et al. (**2021**)

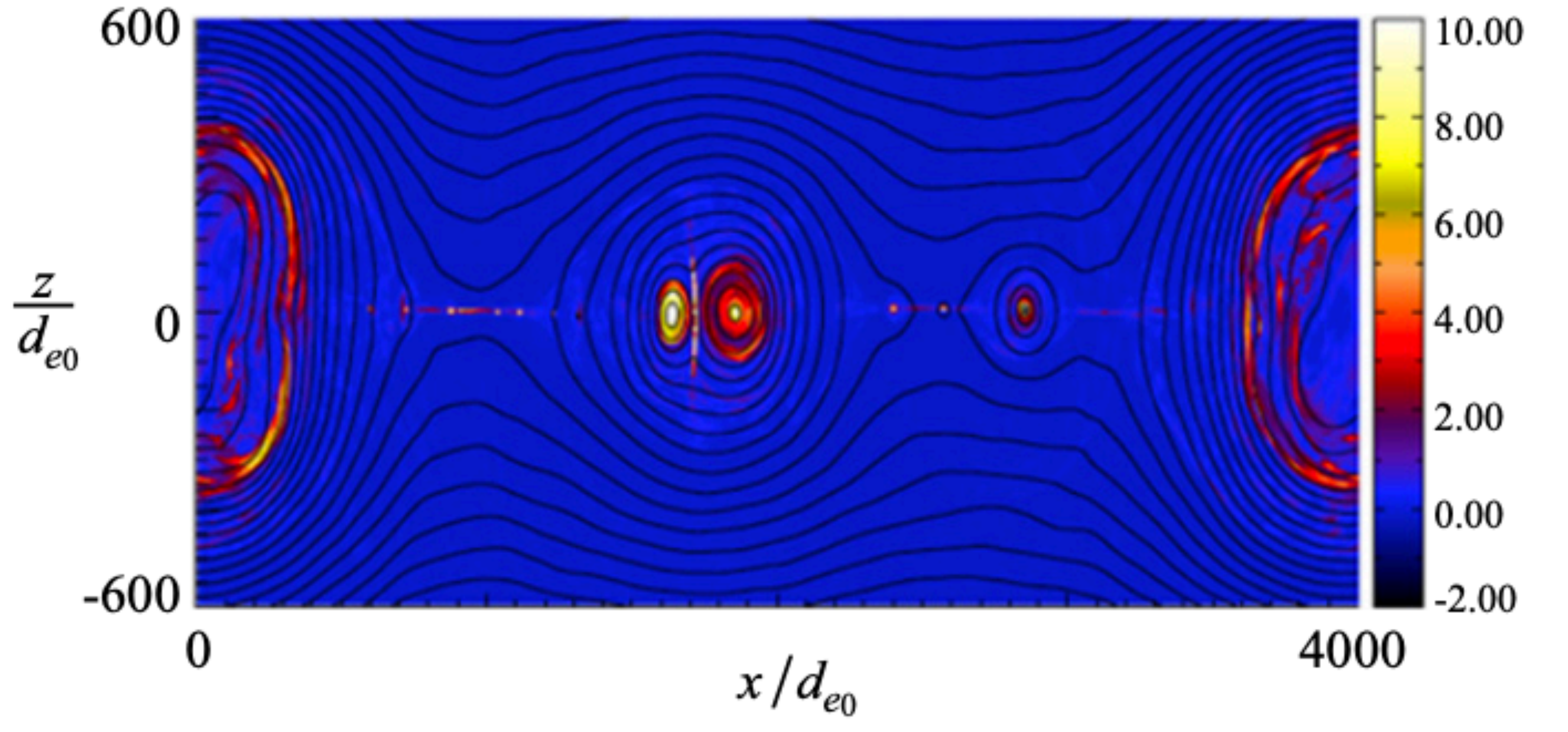


Spectral index depends on magnetization

Hard spectra independent of system size



Energetic spectra found in explicit PIC simulations



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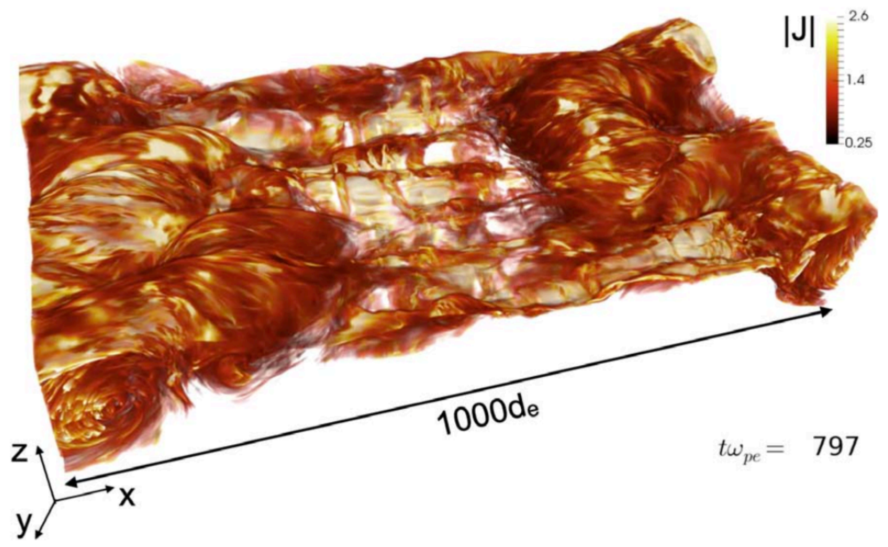
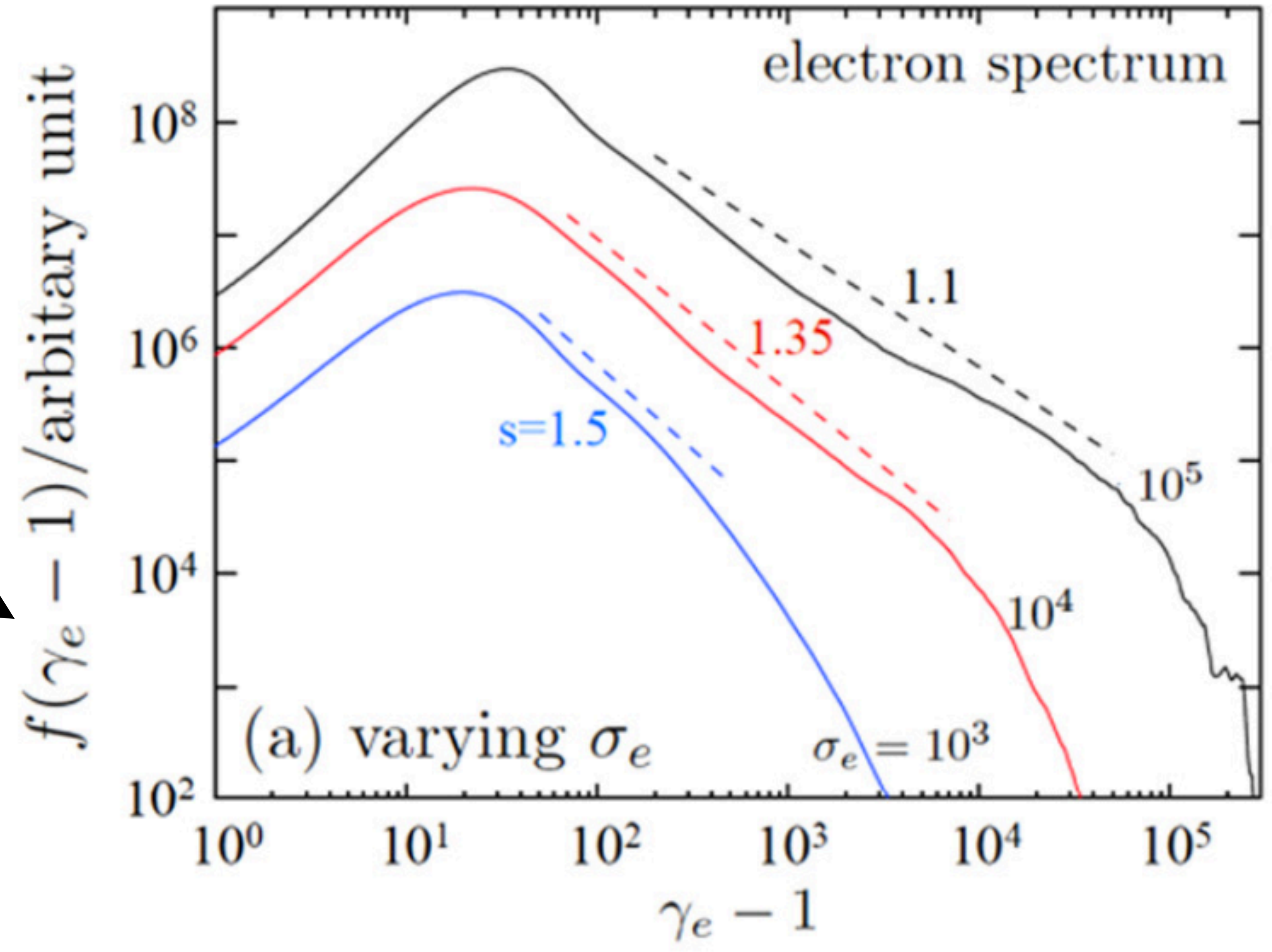
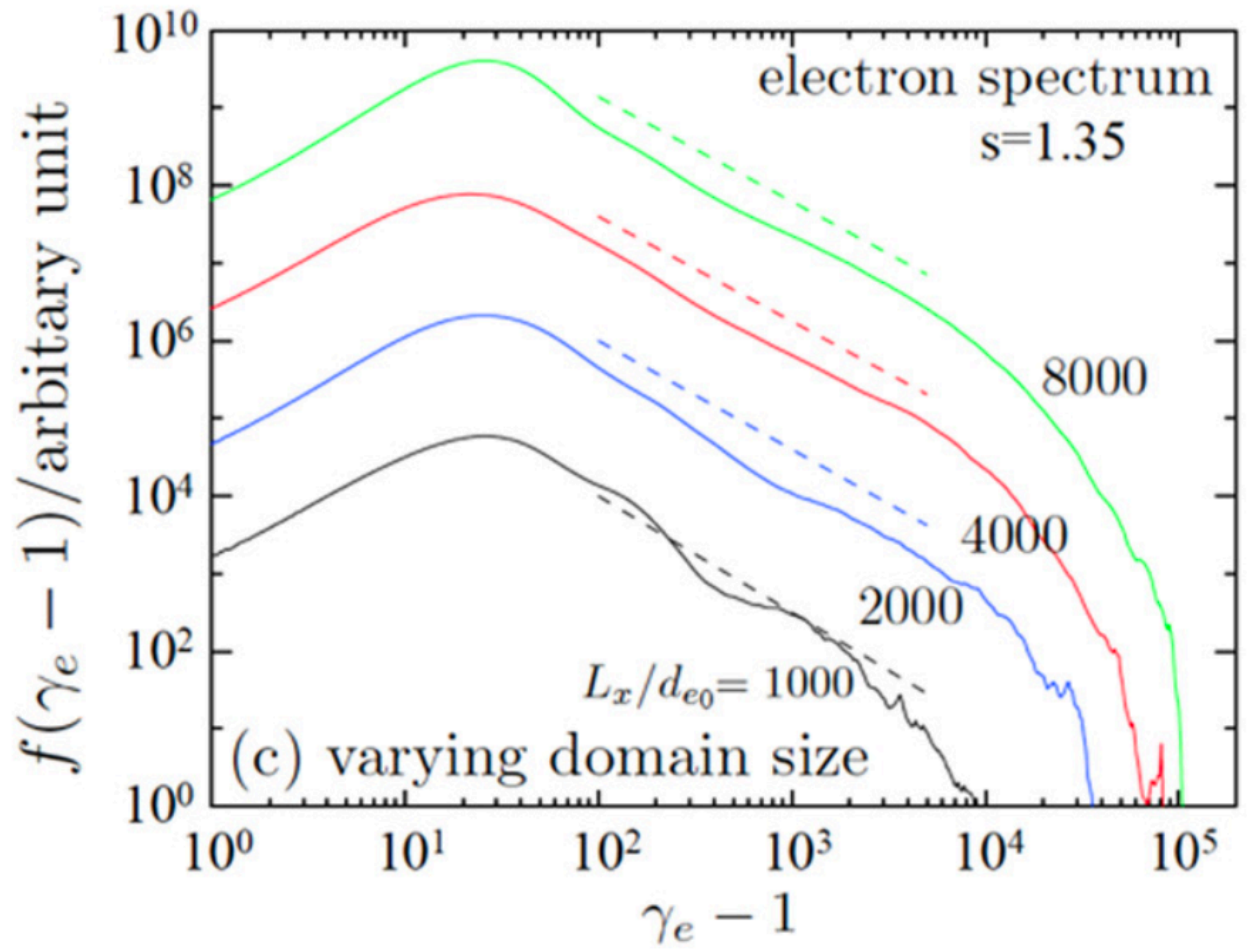


Guo et al. (**2021**)

Can we go to larger system sizes with new numerical methods?

depends on magnetization





Hard spectra independent of system size

Guo et al. (**2016**)

What is an explicit particle-in-cell (PIC) code?

$$\frac{\partial u_i}{\partial t} = \frac{q}{mc}\left(E + \frac{v_i \times B}{c}\right)$$

$$v_i = \frac{u_i}{\gamma_i}$$

$u_{i,n+1}$ and E_{n+1} are based on the fields E_n and momenta $u_{i,n}$ from the previous time step

Deposit current

Interpolate fields

$$j = \sum_i q_i n_i v_i$$

Leads to instabilities if time steps and spaces are not fully resolved

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

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

What is an implicit particle-in-cell (PIC) code?

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

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

Interpolate fields

Deposit current

All equations are solved self-consistently in terms of $u_{i,n}$, E_n, $u_{i,n+1}$, and E_{n+1} usually by iteration

Avoids instabilities, allowing for under-resolution of time and space

What is an semi-implicit particle-in-cell (PIC) code?

Stays explicit

$$\boxed{\frac{\partial u_i}{\partial t} = \frac{q}{mc}\left(E + \frac{v_i \times B}{c}\right)}$$

Interpolate fields

Deposit current

$$j = \sum_i q_i n_i v_i \qquad v_i = \frac{u_i}{\gamma_i}$$

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

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

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Avoids instabilities, allowing for under-resolution of time and space

Must resolve in explicit codes

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We need to resolve the Debye scales

Under resolution leads to numerical heating or numerical instabilities

Spatial resolution

$$\lambda_D/dx > 1$$

$$d_e/dx > 1$$

$$d_i/dx > 1$$

$$\lambda_D^2 = \frac{T}{4\pi mne^2} \qquad d_e^2 = \frac{m_e c^2}{4\pi mne^2} \qquad d_i^2 = \frac{m_i c^2}{4\pi mne^2}$$

$$\lambda_D = \frac{v_T}{c} d_e = \frac{v_T}{c}\sqrt{\frac{m_e}{m_i}} d_i$$

We can under-resolve in implicit/ semi-implicit codes

We don’t need to resolve the Debye scales

If we are mainly interested in ion scales, we can under-resolve the electron scales

Spatial resolution

$\cancel{\lambda_D/dx > 1}$

$\cancel{d_e/dx > 1}$

$d_i/dx > 1$

$$\lambda_D^2 = \frac{T}{4\pi mne^2} \qquad d_e^2 = \frac{m_e c^2}{4\pi mne^2} \qquad d_i^2 = \frac{m_i c^2}{4\pi mne^2}$$

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$\cancel{\lambda_D/dx > 1}$

$\cancel{d_e/dx > 1}$

$d_i/dx > 1$

semi-implicit schemes tend to be $\sim 10\times$ slower

But,

Factor of $\sqrt{m_i/m_e}c/v_T$ faster for each space direction

Most benefit in 3D

$$\lambda_D^2 = \frac{T}{4\pi mne^2} \qquad d_e^2 = \frac{m_e c^2}{4\pi mne^2} \qquad d_i^2 = \frac{m_i c^2}{4\pi mne^2}$$

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We can under-resolve in implicit/ semi-implicit codes

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We don't need to resolve the Debye scales

If we are mainly interested in ion scales, we can under-resolve the electron scales

Spatial resolution

$\cancel{\lambda_D/dx > 1}$

$\cancel{d_e/dx > 1}$

$d_i/dx > 1$

$$\lambda_D^2 = \frac{T}{4\pi m n e^2} \qquad d_e^2 = \frac{m_e c^2}{4\pi m n e^2} \qquad d_i^2 = \frac{m_i c^2}{4\pi m n e^2}$$

$$\lambda_D = \frac{v_T}{c} d_e = \frac{v_T}{c}\sqrt{\frac{m_e}{m_i}} d_i$$

semi-implicit schemes tend to be $\sim 10\times$ **slower**

But,

Factor of $\sqrt{m_i/m_e}c/v_T$ **faster for each space direction**

Most benefit in 3D

Time resolution

$\cancel{dx/dt > c}$

$dx/dt > v_T$

RelSIM

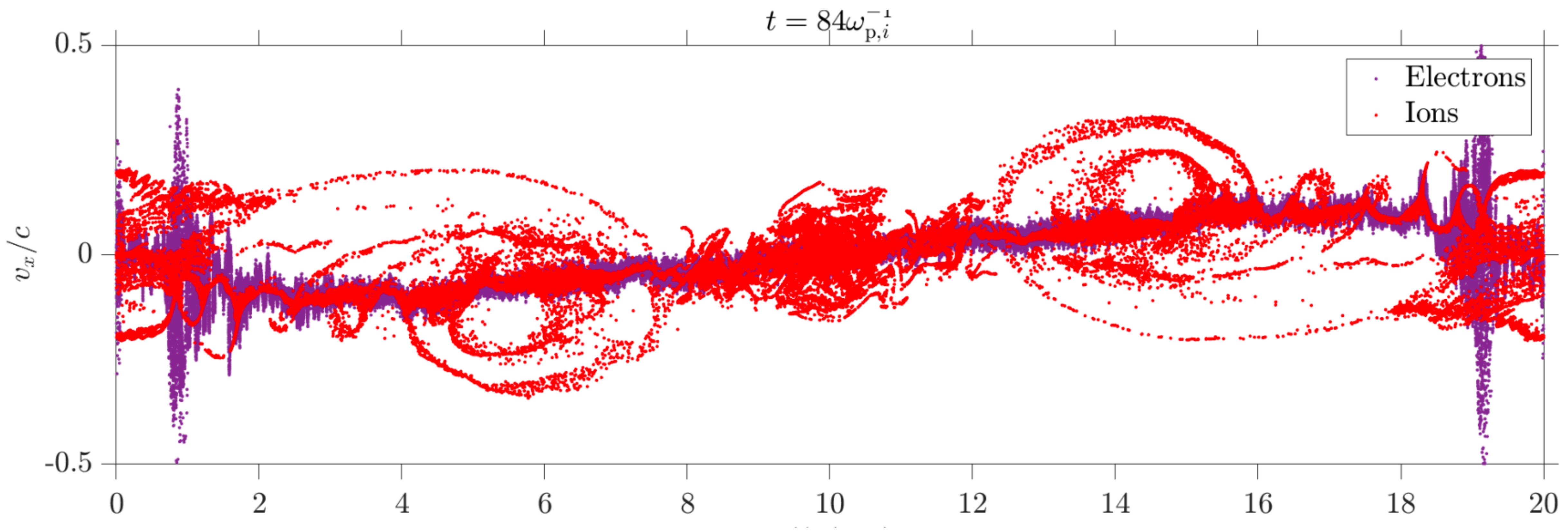
Relativistic Semi-Implicit code RelSIM

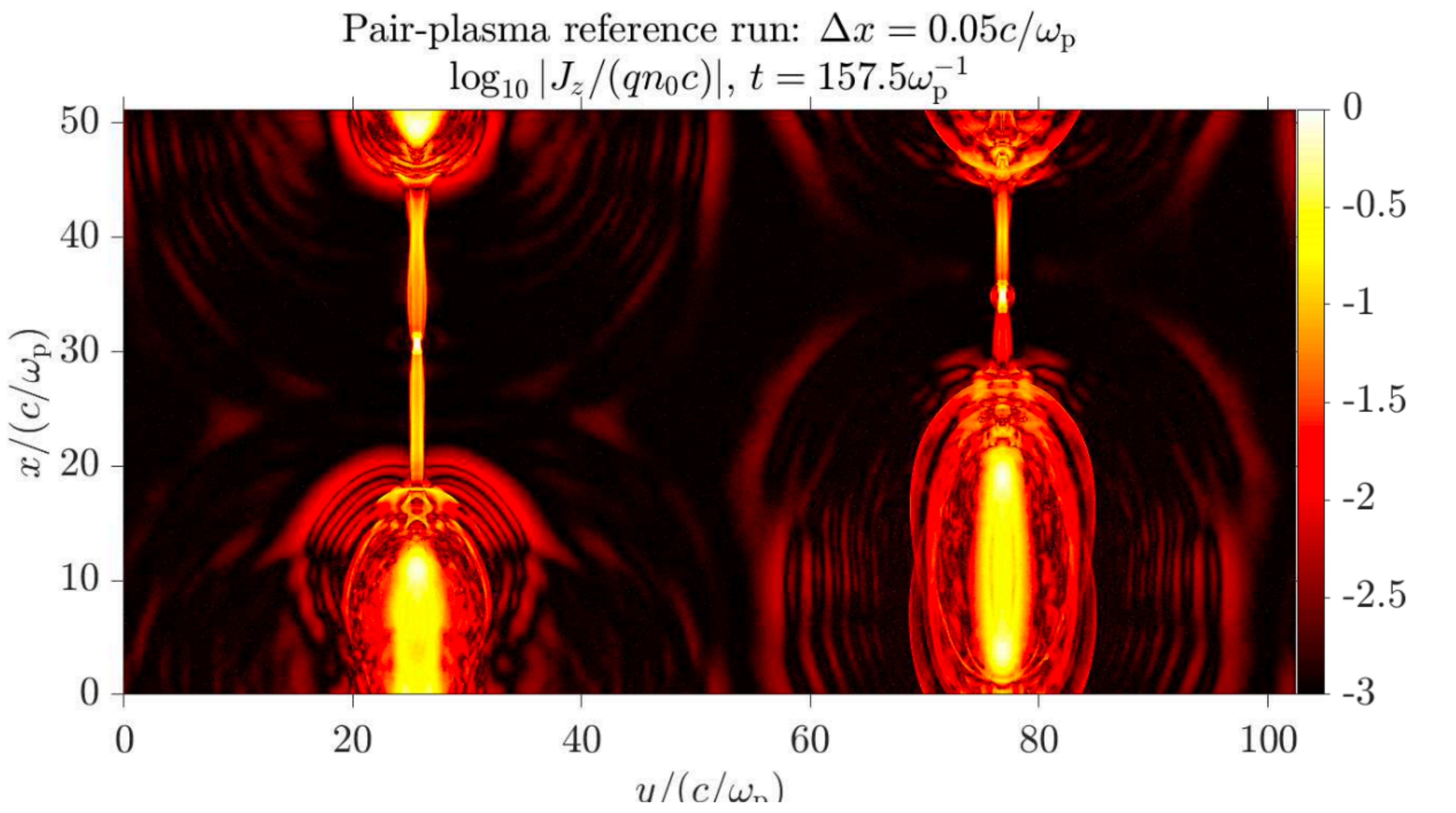
Bacchini 2023 [https://doi.org/10.48550/arXiv.2306.04685]

RelSIM is EcSIM (Lapenta 2017): modified such that it can do simulations of relativistic plasmas.

Tested relativistic two-stream

Tested relativistic shock evolution





Tested relativistic pair reconnection

Setup to simulate tearing

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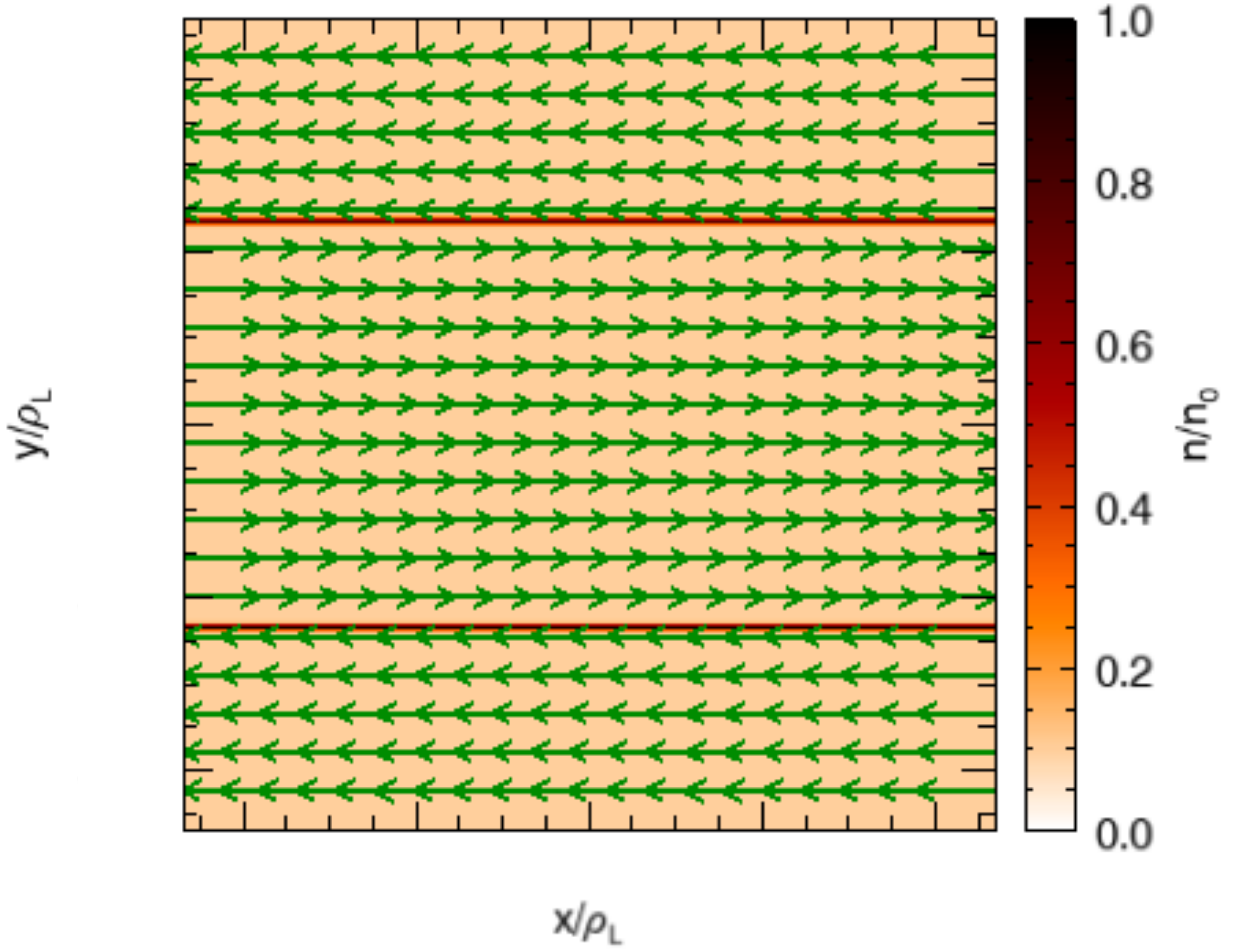
$$\frac{L_x}{\rho_{Le,R}} = 250$$



No background

$$n_b = 0$$

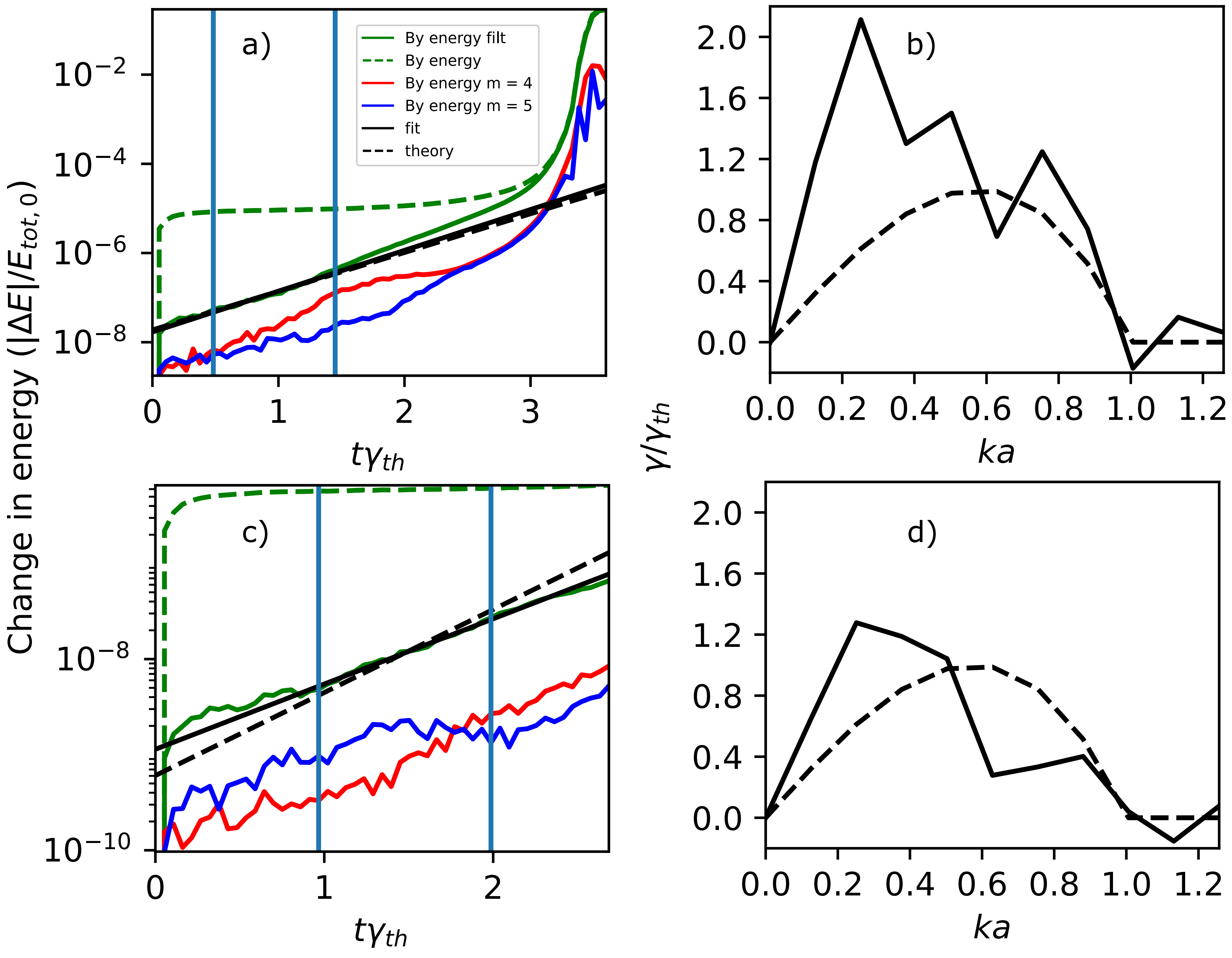
Double Harris Sheet configuration

$$\frac{T_{e,H}}{m_e c^2} = \frac{T_{i,H}}{m_e c^2} = 10 \qquad \frac{a}{d_i} = 8.94 \qquad n = \frac{n_0}{2}\mathrm{sech}^2\left(\frac{y \mp L_y/2}{a}\right)$$

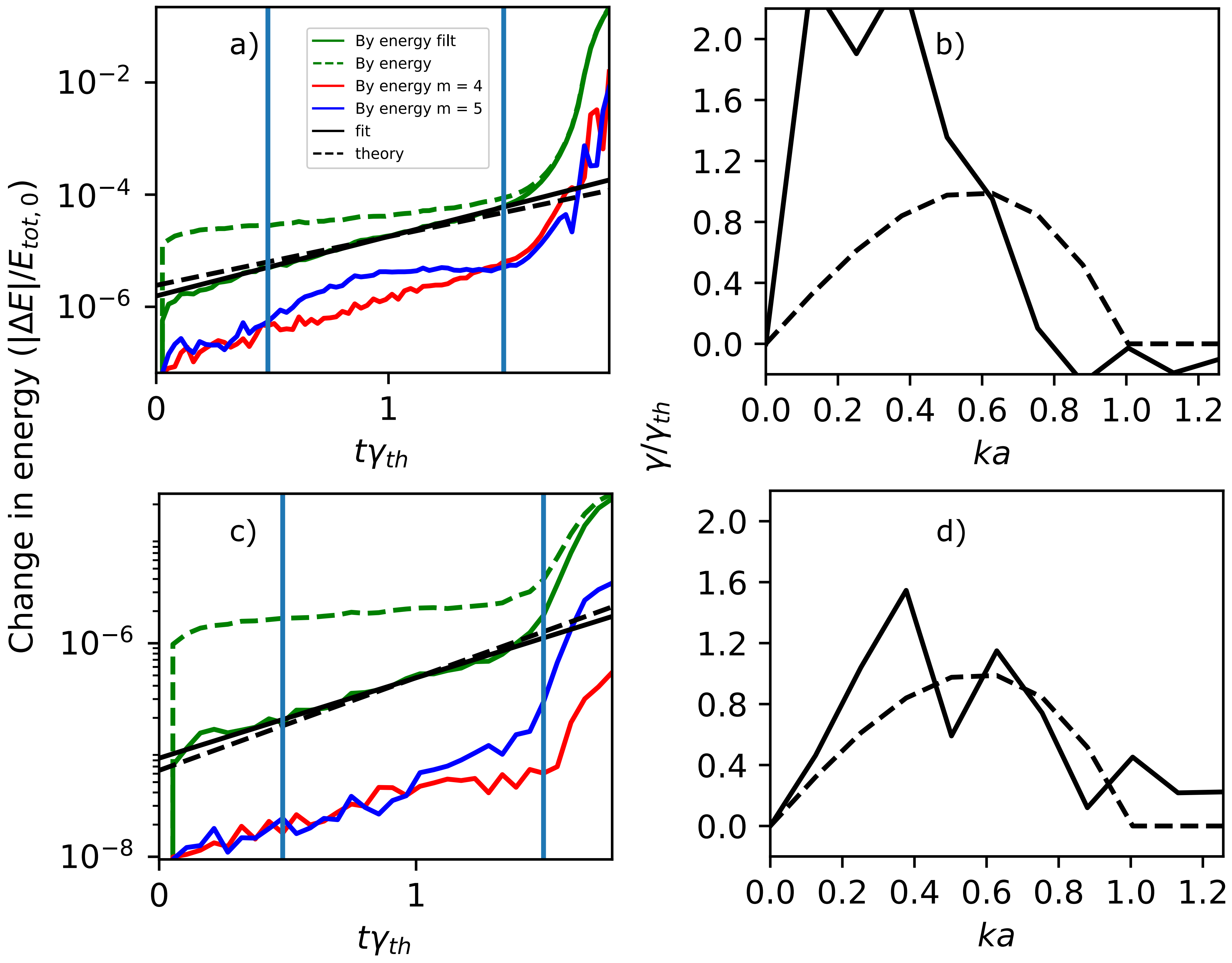
$$\frac{u_d}{c} = 0.05 \qquad B_x = B_0\left[1 - \tanh\left(\frac{y - L_y/2}{a}\right) + \tanh\left(\frac{y + L_y/2}{a}\right)\right]$$

Tearing fits theory with RelSIM and OSIRIS

Explicit OSIRIS simulation



Implicit RelSIM simulation



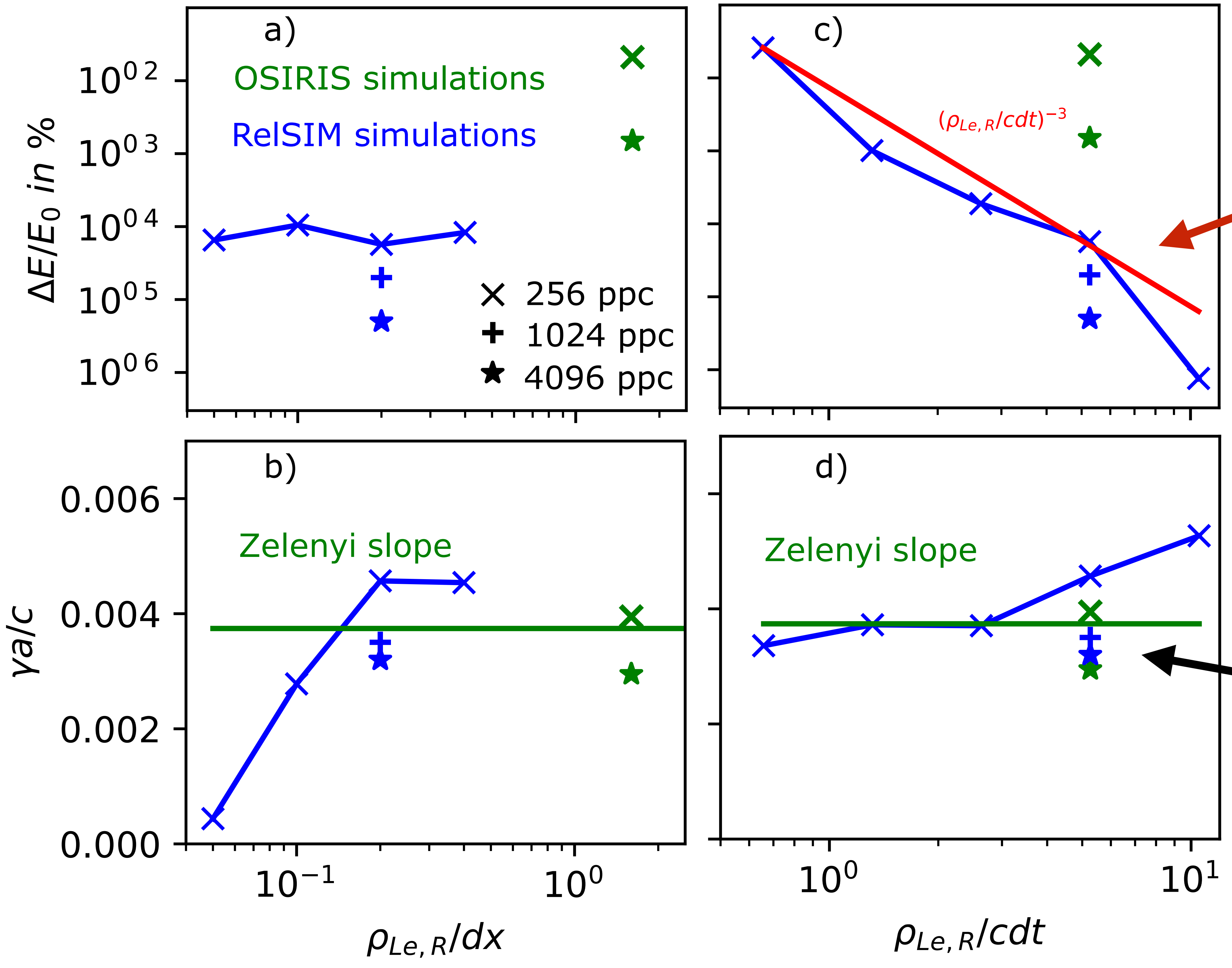
256 particles per cell

4096 particles per cell

1/4 the resolution

Schoeffler et al. (**2025**) in review

One can get away with less resolution with RelSIM

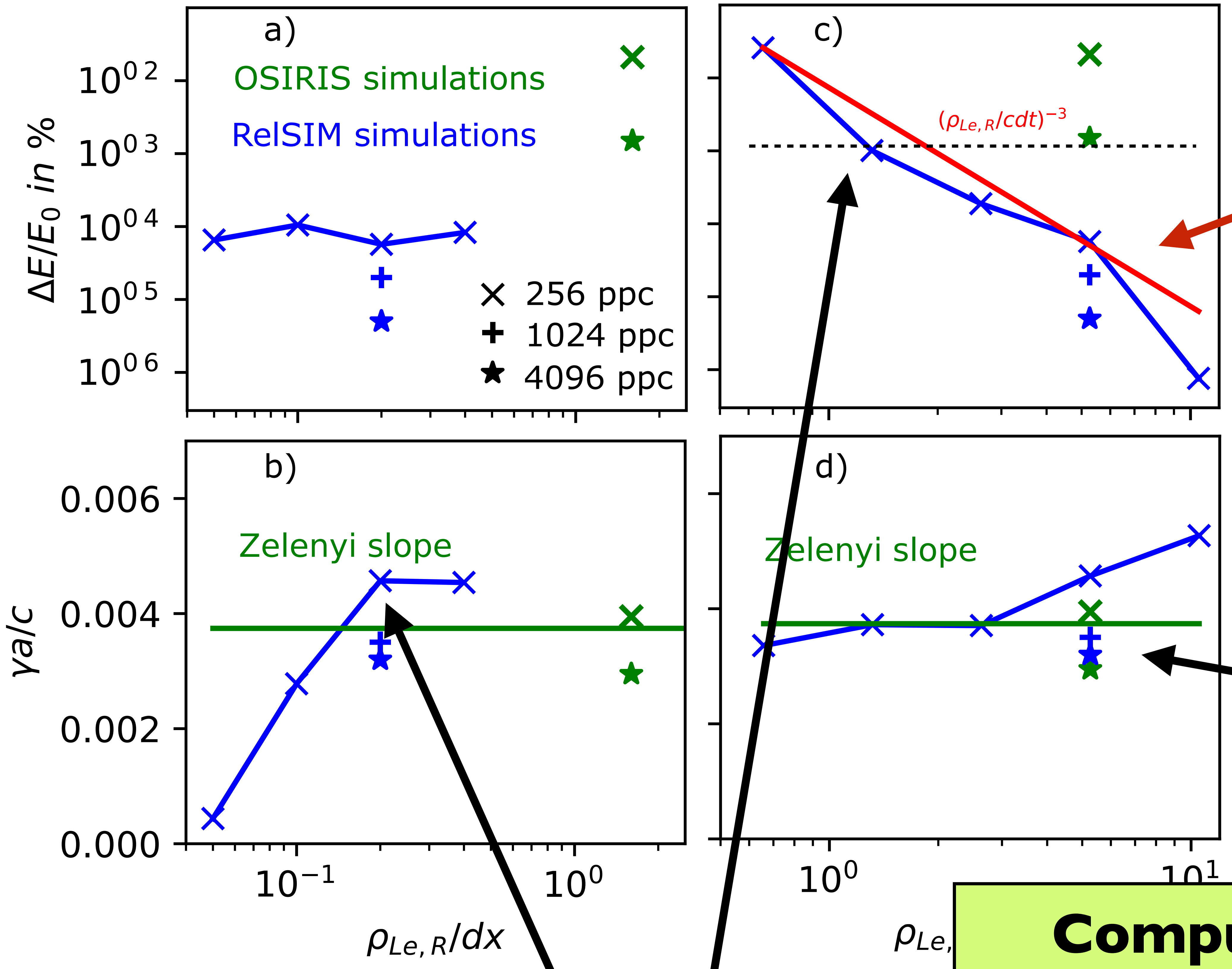


Energy conservation depends on time resolution

Fits theory with enough particles per cell

Schoeffler et al. (**2025**) in review

One can get away with less resolution with RelSIM



Energy conservation depends on time resolution

Fits theory with enough particles per cell

$\rho_{Le,R}/dx \approx 0.2 \quad dt\omega_{pe0} \approx 3$

Computational savings of a factor 256

Setup to simulate nonlinear reconnection

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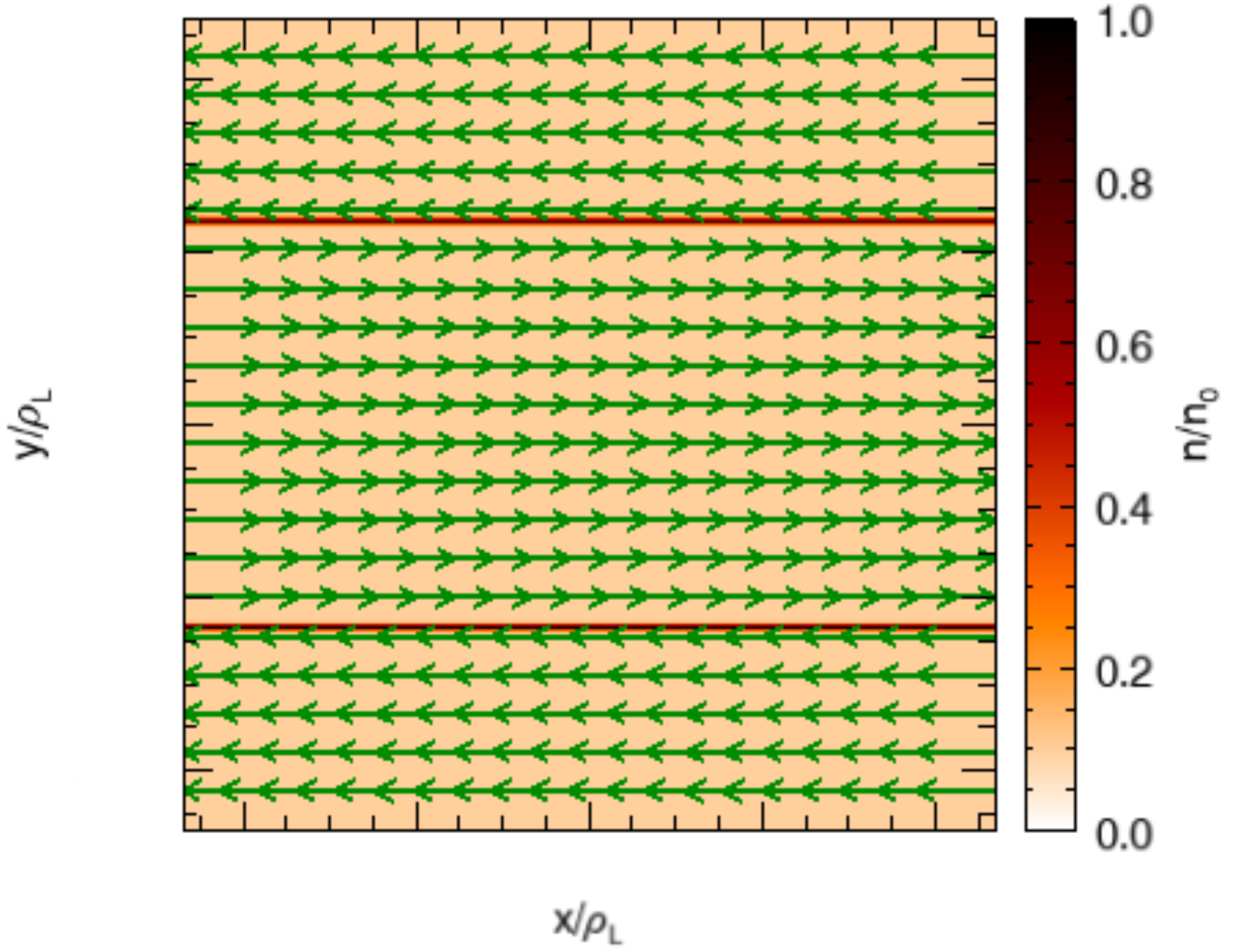
$$\frac{L_x}{d_{i,C}} = 50$$



Background parameters

$\sigma_{i,c} = 100$ $\qquad \frac{T_i}{T_e} = 1$

$\frac{T_{e,b}}{m_e c^2} = 10$ $\qquad \frac{m_i}{m_e} = 100$

Double Harris Sheet configuration

$\frac{T_{e,H}}{m_e c^2} = 10$ $\qquad \frac{a}{d_i} = 0.5$

$$n = \frac{n_0}{2}\mathrm{sech}^2\left(\frac{y \mp L_y/2}{a}\right)$$

$\frac{u_d}{c} = 0.4$ $\qquad \frac{n_0}{n_b} = 269$

$$B_x = B_0\left[1 - \tanh\left(\frac{y - L_y/2}{a}\right) + \tanh\left(\frac{y + L_y/2}{a}\right)\right]$$

Previous results reproduced with OSIRIS

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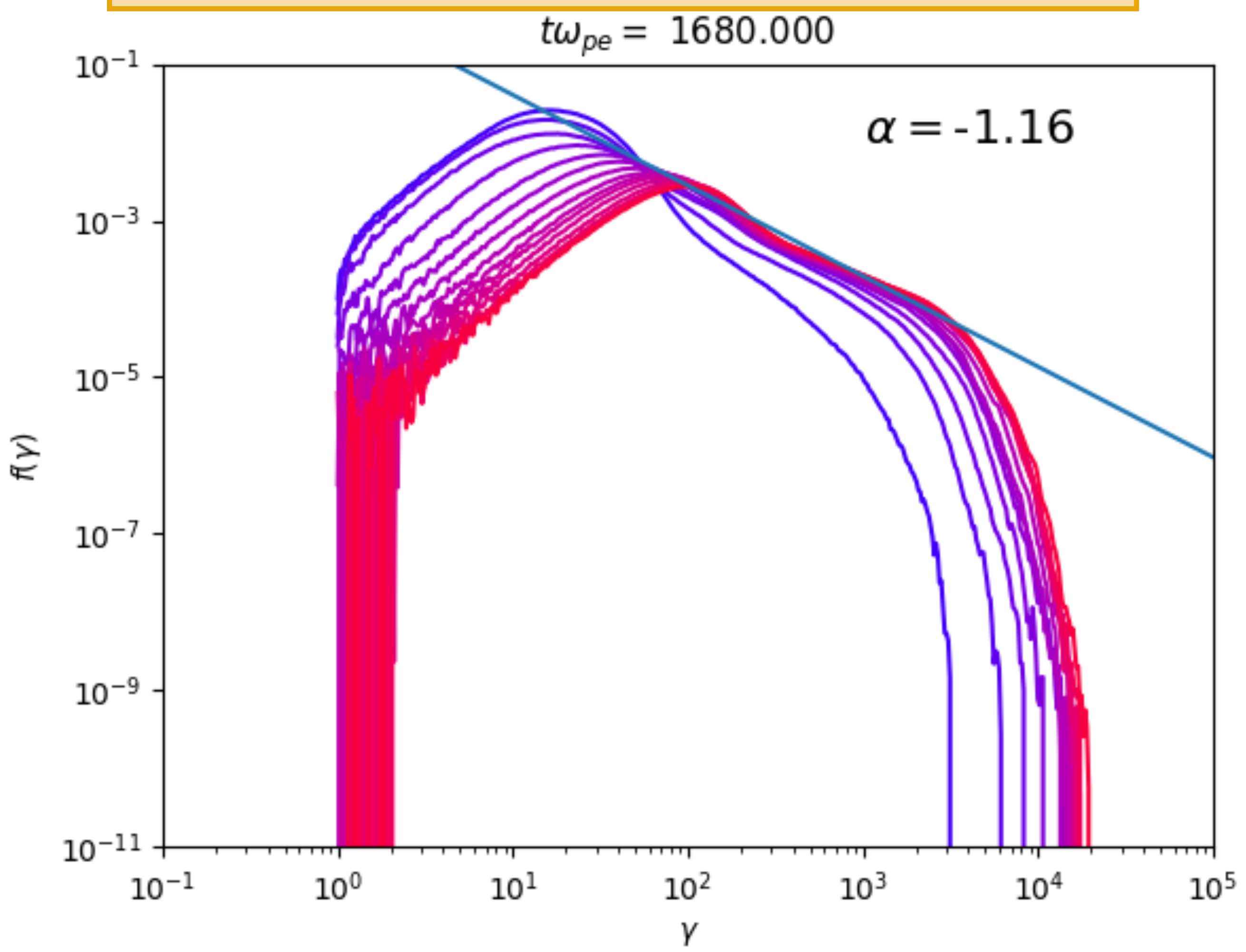
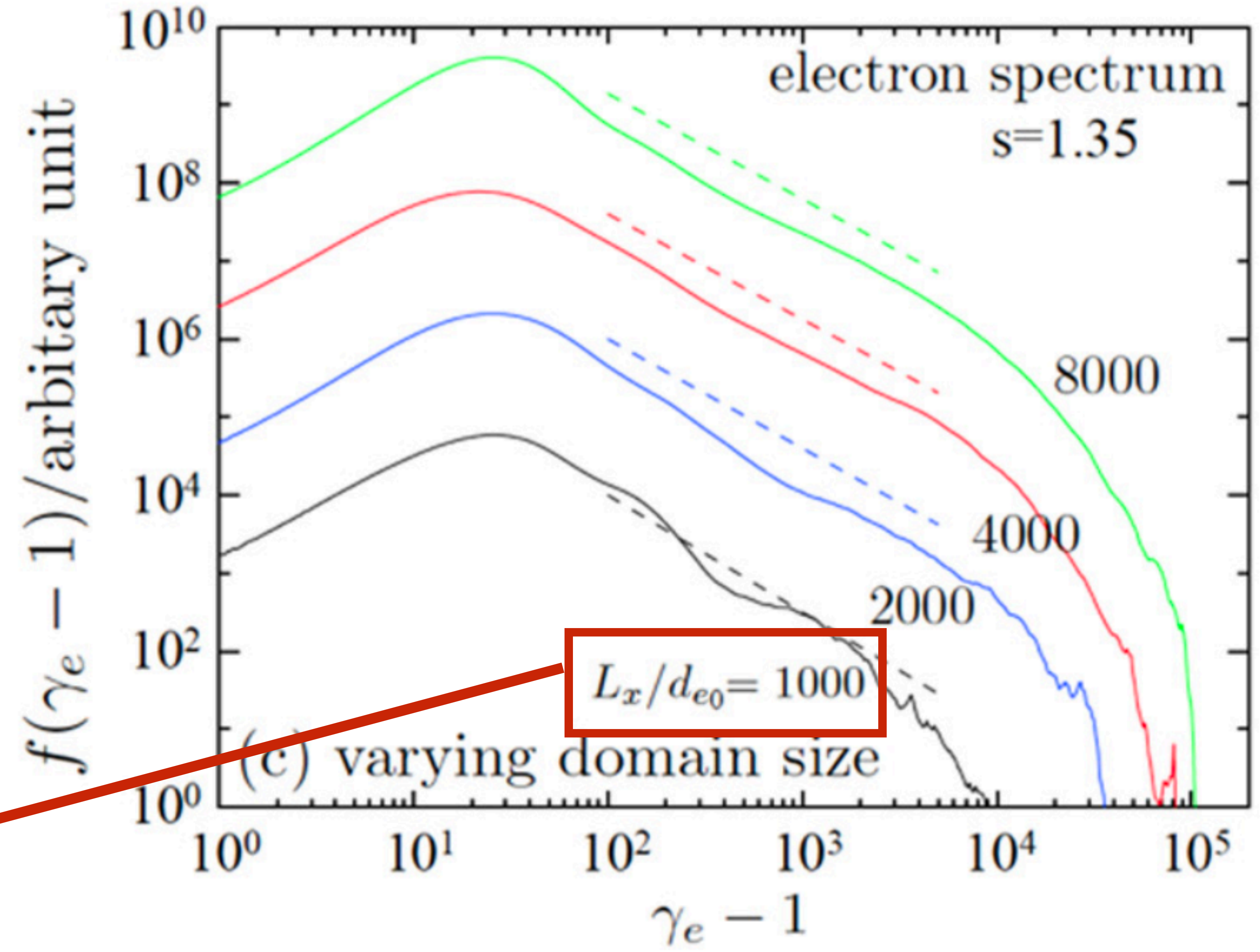
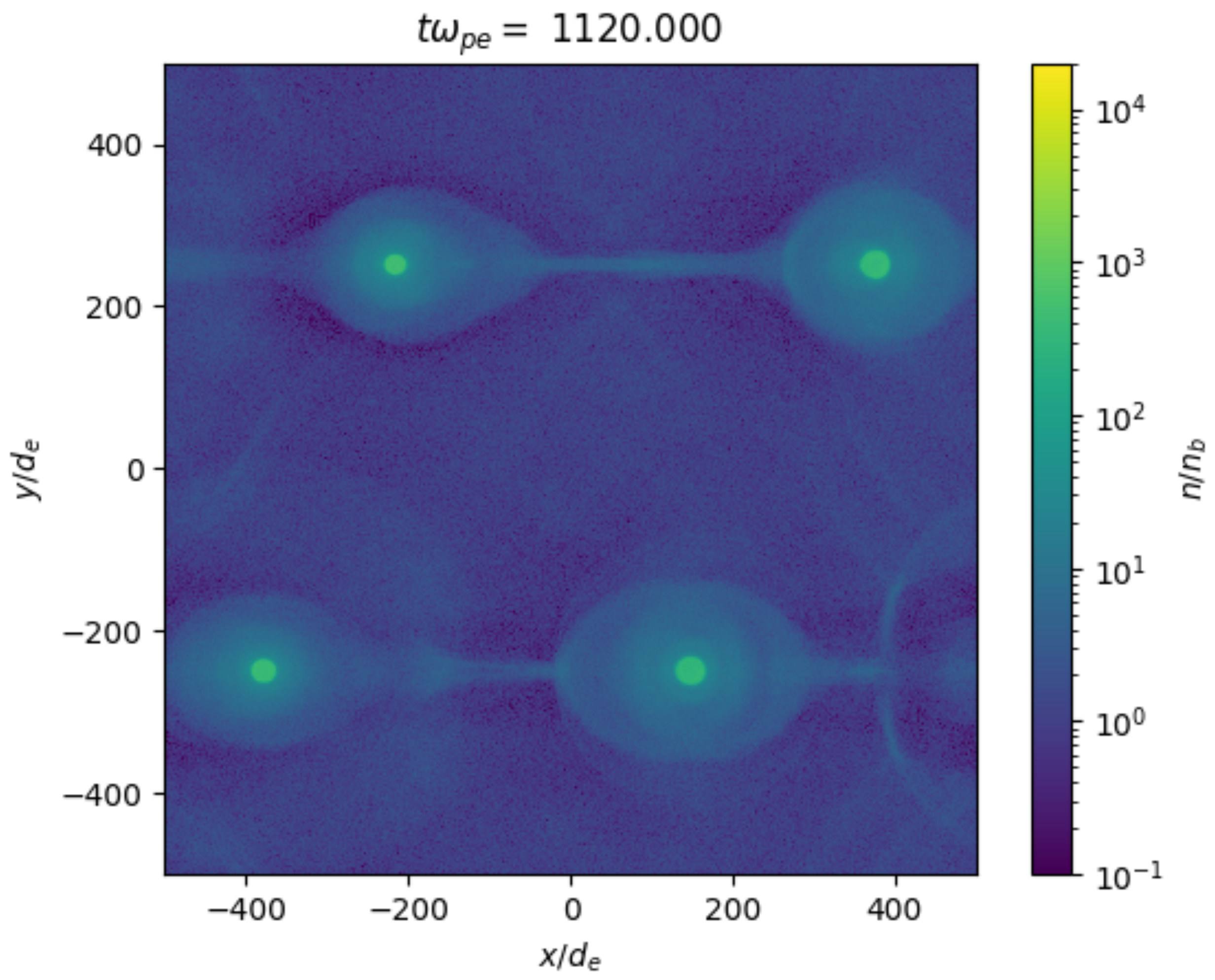
OSIRIS simulation

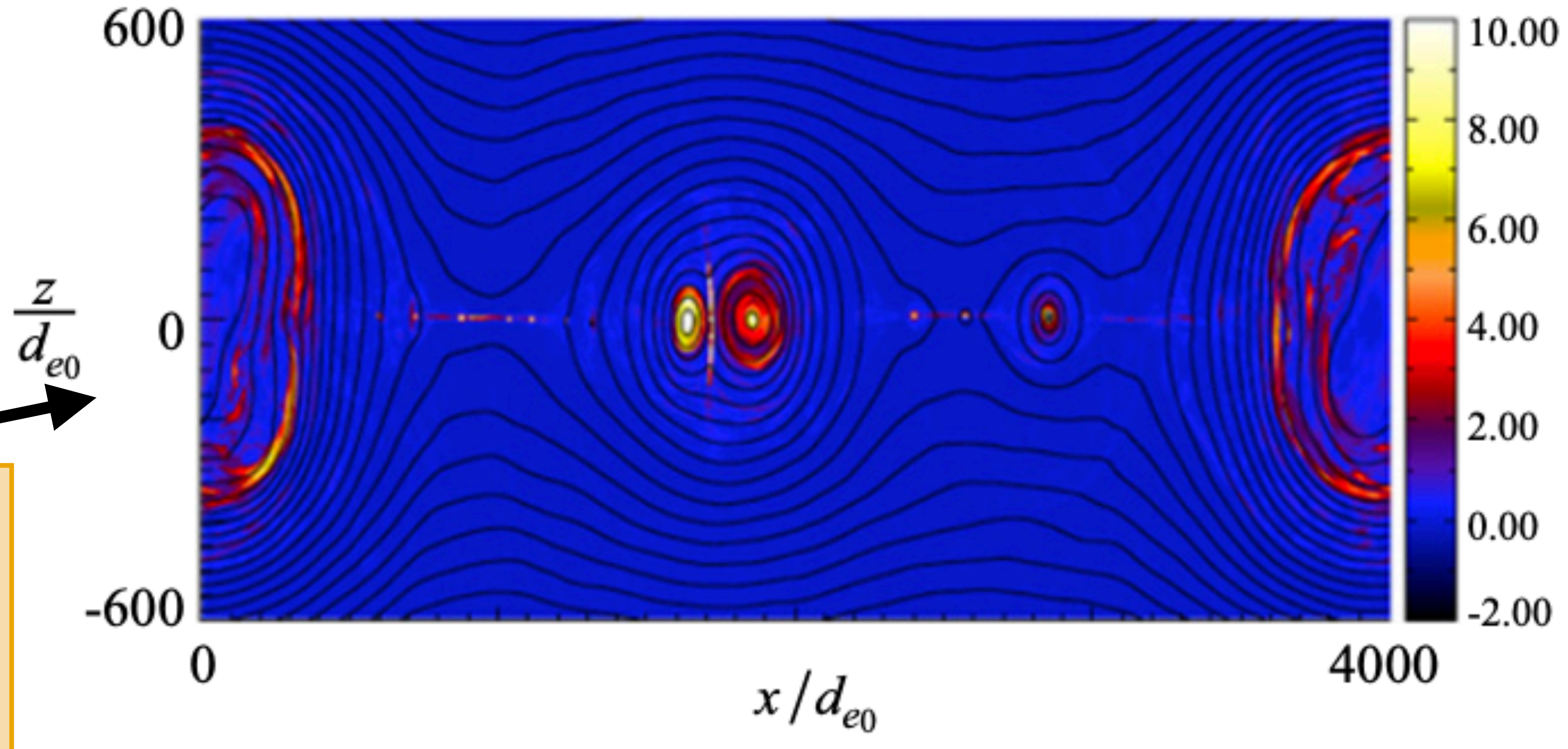






Different initial conditions:

Starts from reconnecting current sheet, with force free current sheet.



Guo et al. (**2016**)

Explicit results reproduced with implicit method

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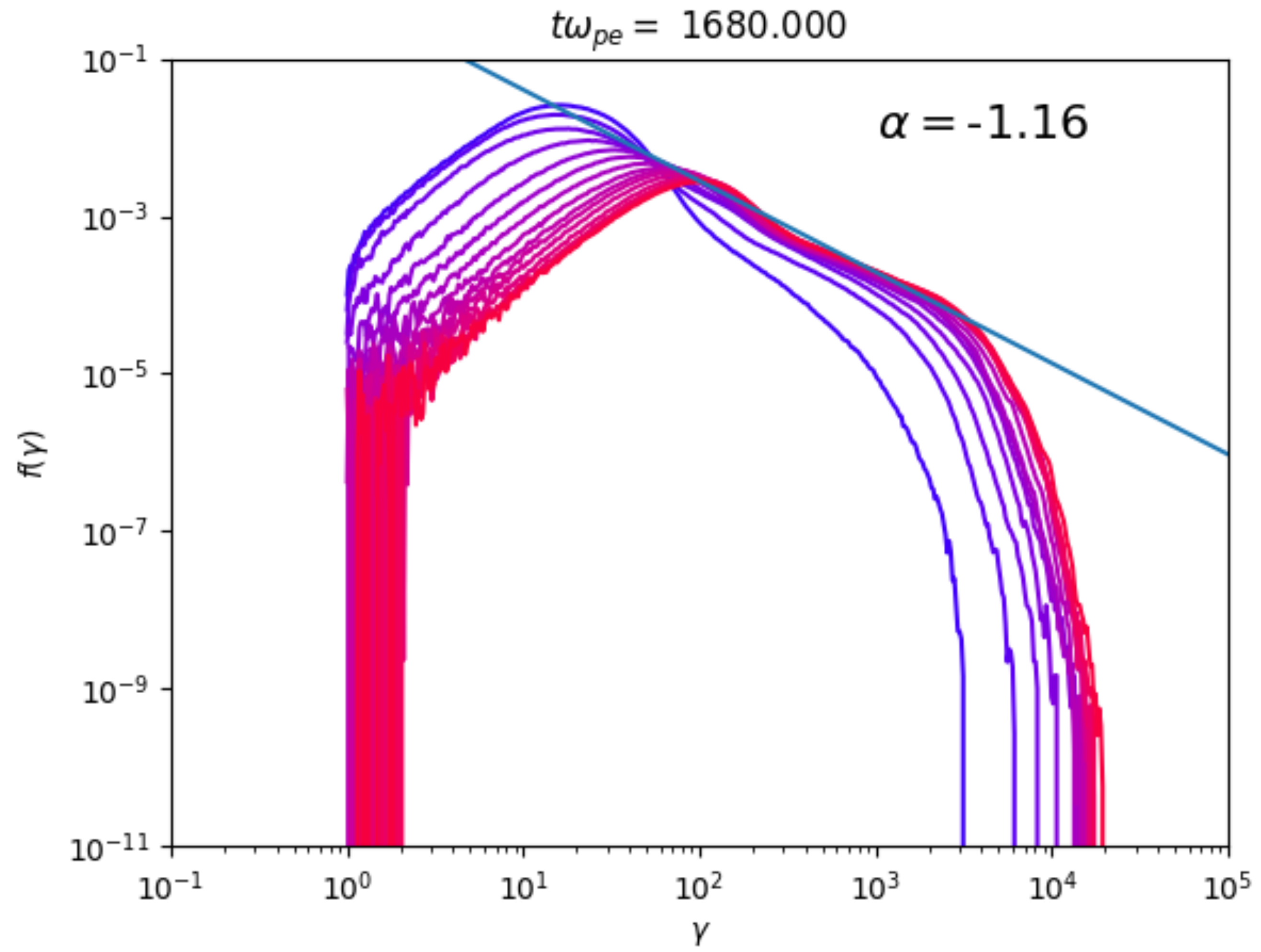
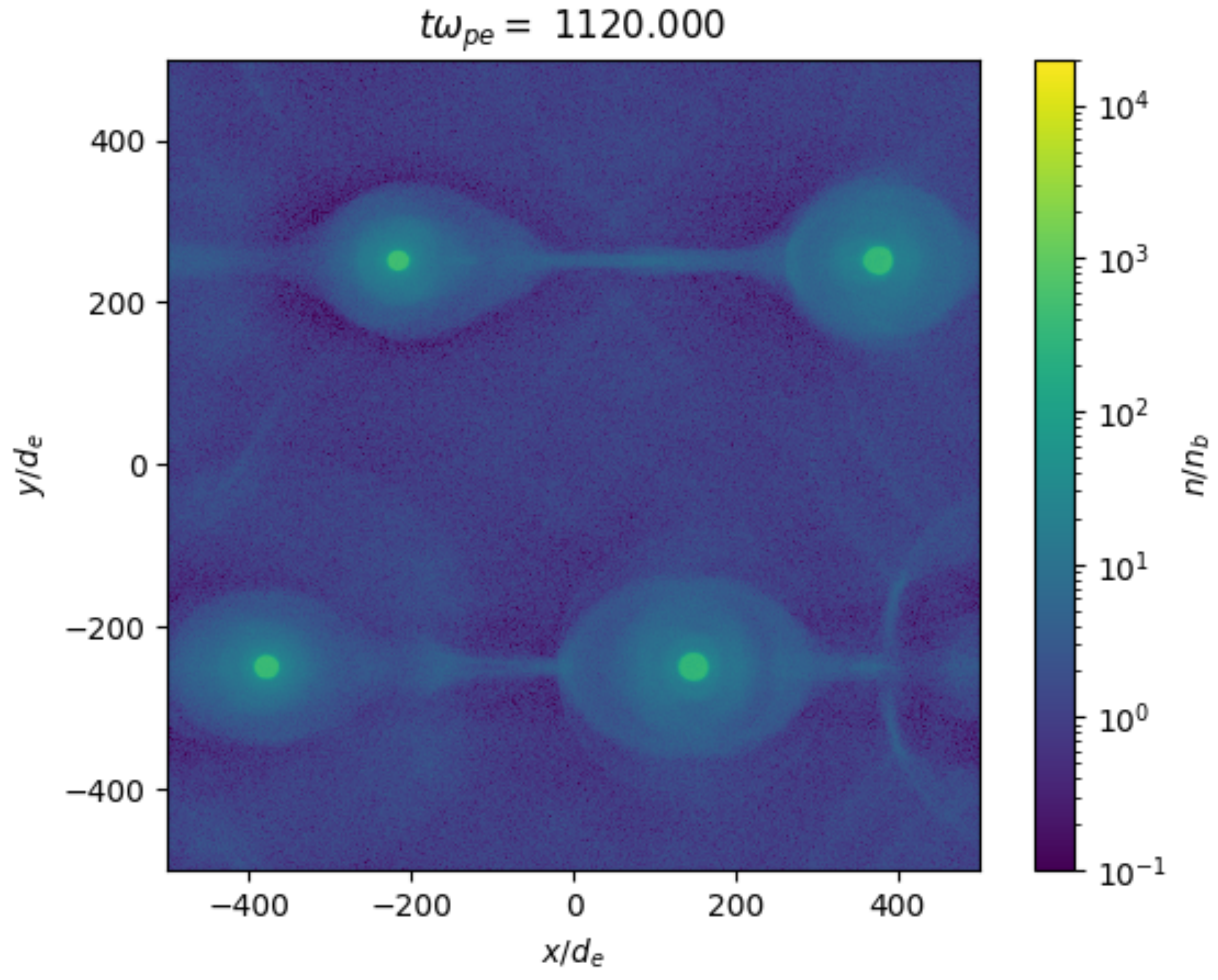
Explicit OSIRIS simulation





Length scales

$$d_e = \frac{c}{\omega_{pe}} = \sqrt{\frac{m_e c^2}{4\pi\, n_b\, e^2}}$$

$$\rho_0 = \frac{c}{\Omega_c} = \frac{m_e c^2}{eB_0}$$

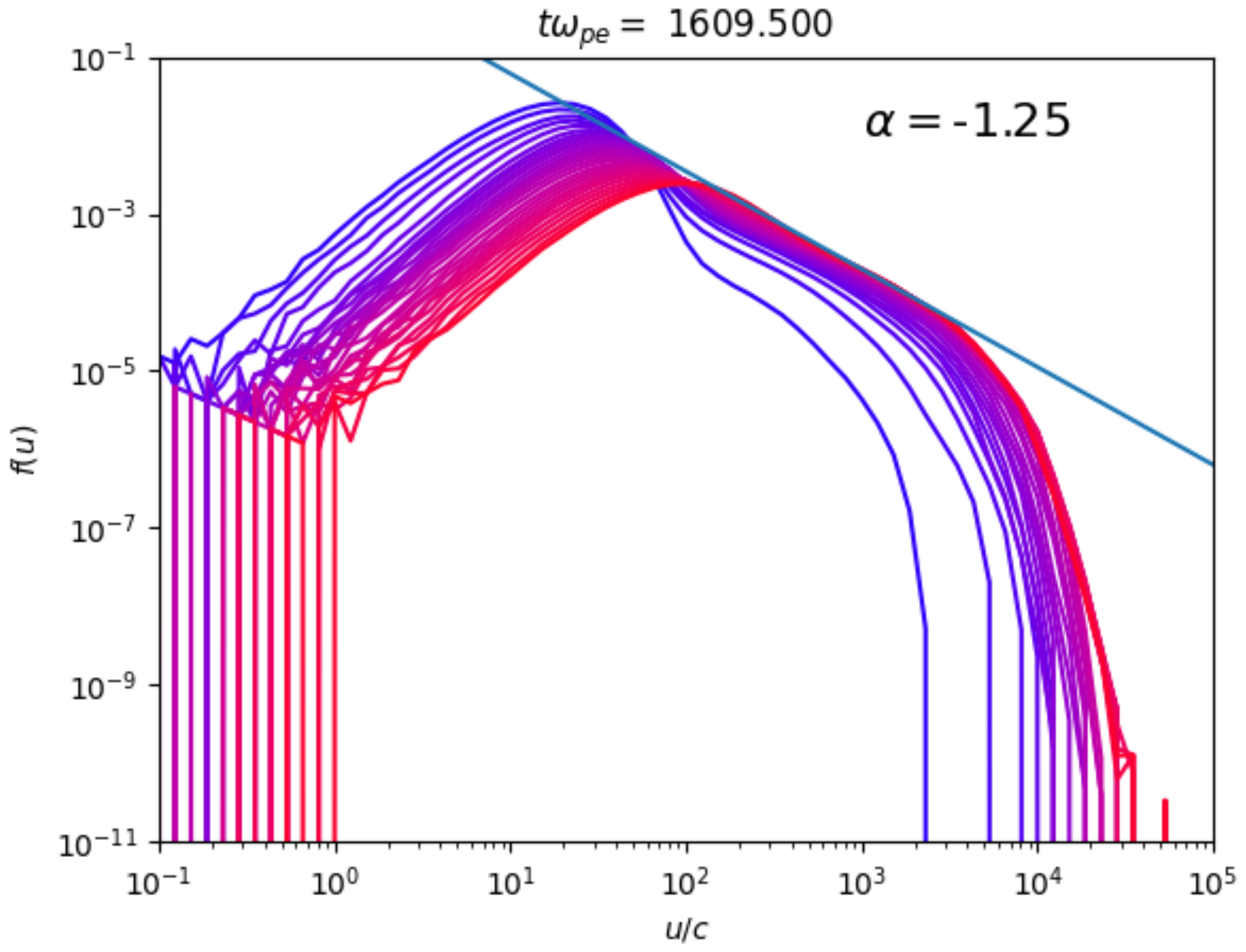
$$\rho_{Le,R} = \gamma_T \rho_0 = \frac{2T}{m_e c}\rho_0$$

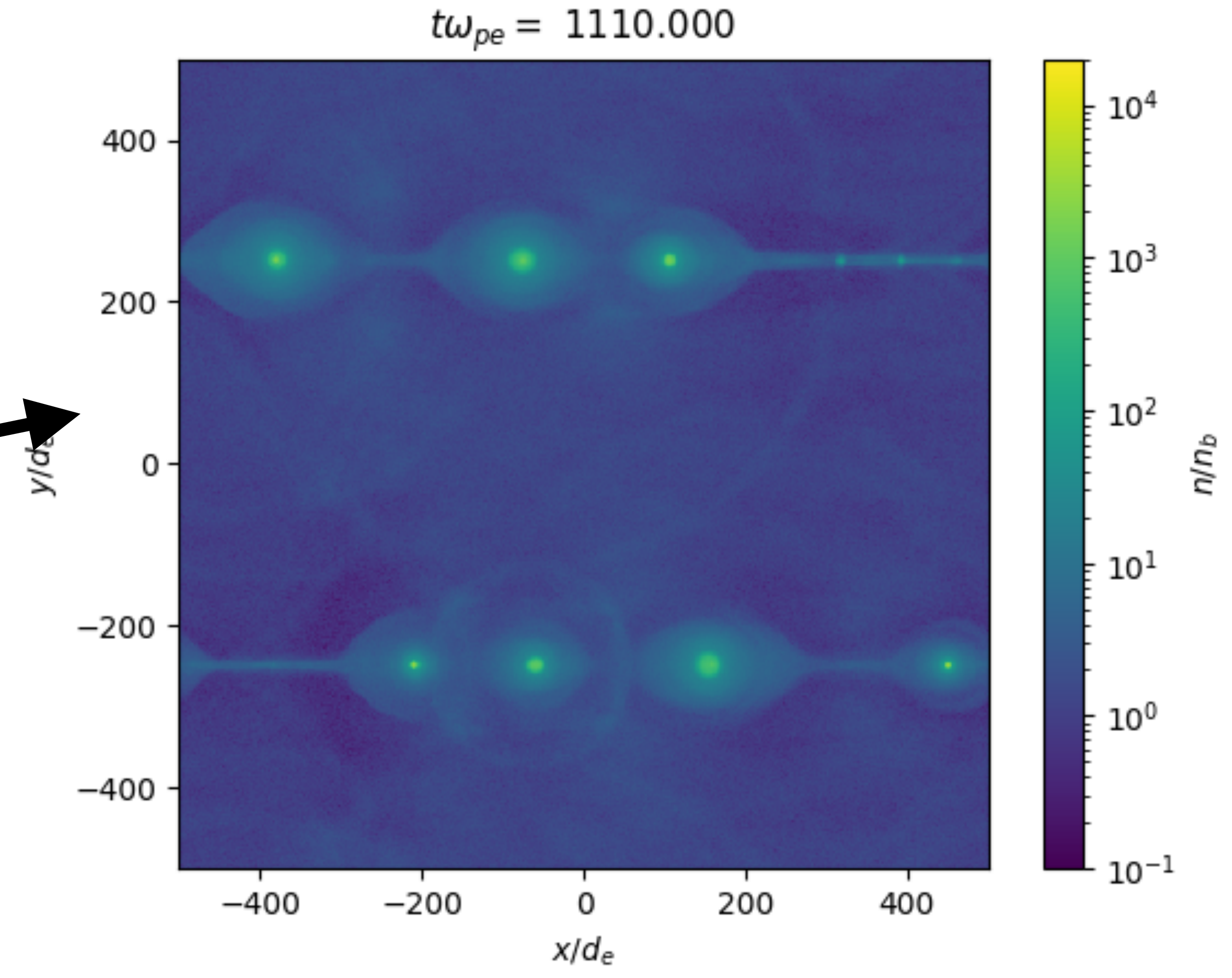
$$dx = 0.418 d_e = 1.86\rho_0 = 0.093\rho_{Le,R}$$

$$dx = 1.67 d_e = 7.45\rho_0 = 0.37\rho_{Le,R}$$

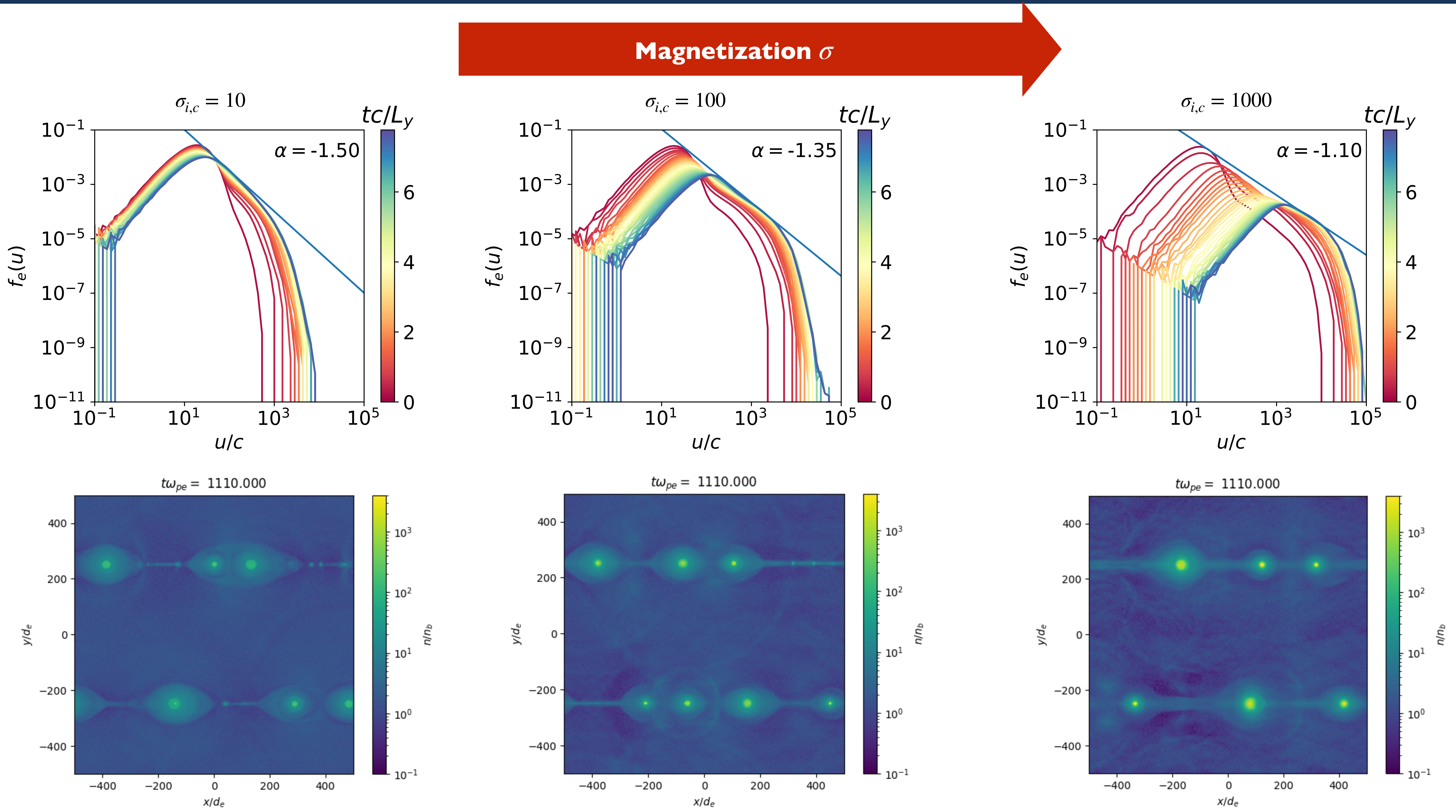
1/4 the resolution

Semi-implicit RelSIM simulation



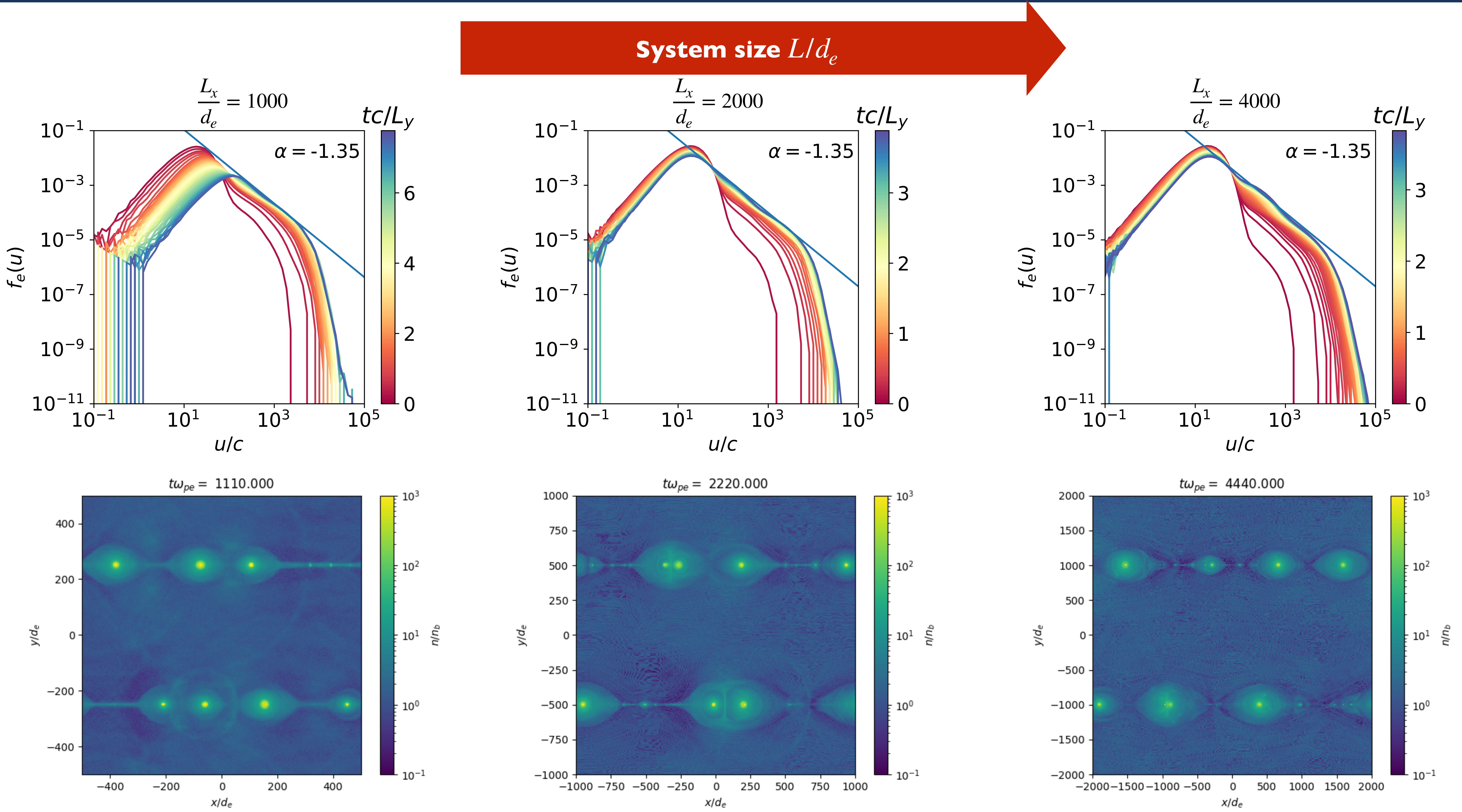


Magnetization dependence of spectra confirmed



Schoeffler et al. (**2025**) in review

System size dependence of spectra confirmed



Schoeffler et al. (**2025**) in review

Fluid codes are another strategy

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Simulation done with relativistic 5-moment fluid simulation MuPhyII, with test particles.

2-fluid equations:

$$\partial_t \begin{pmatrix} \gamma_s \rho_s \\ \frac{w_s}{c^2}\gamma_s \mathbf{u}_s \\ w_s \gamma_s^2 - p_s \end{pmatrix} + \nabla \cdot \begin{pmatrix} \rho_s \mathbf{u}_s \\ \frac{w_s}{c^2} \mathbf{u}_s \otimes \mathbf{u}_s + p_s \mathbb{1} \\ w_s \gamma_s \mathbf{u}_s \end{pmatrix} = \begin{pmatrix} 0 \\ \mu_s \gamma_s \rho_s (\mathbf{E} + \frac{\mathbf{u}_s}{\gamma_s} \times \mathbf{B}) \\ \mu_s \rho_s \mathbf{u}_s \cdot \mathbf{E} \end{pmatrix}$$

Maxwell:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \epsilon_0 \partial_t \mathbf{E}, \quad \nabla \times \mathbf{E} = -\partial_t \mathbf{B}, \quad \nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0}\rho_c, \quad \nabla \cdot \mathbf{B} = 0$$

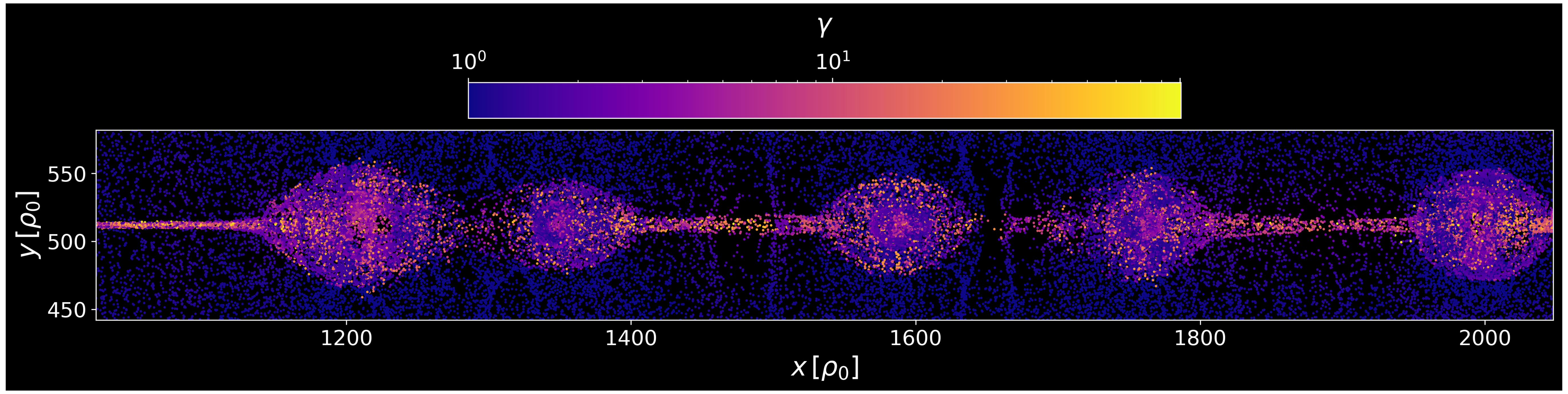
$$\rho_c = \sum_s \mu_s \gamma_s \rho_s, \quad \mathbf{j} = \sum_s \mu_s \rho_s \mathbf{u}_s$$

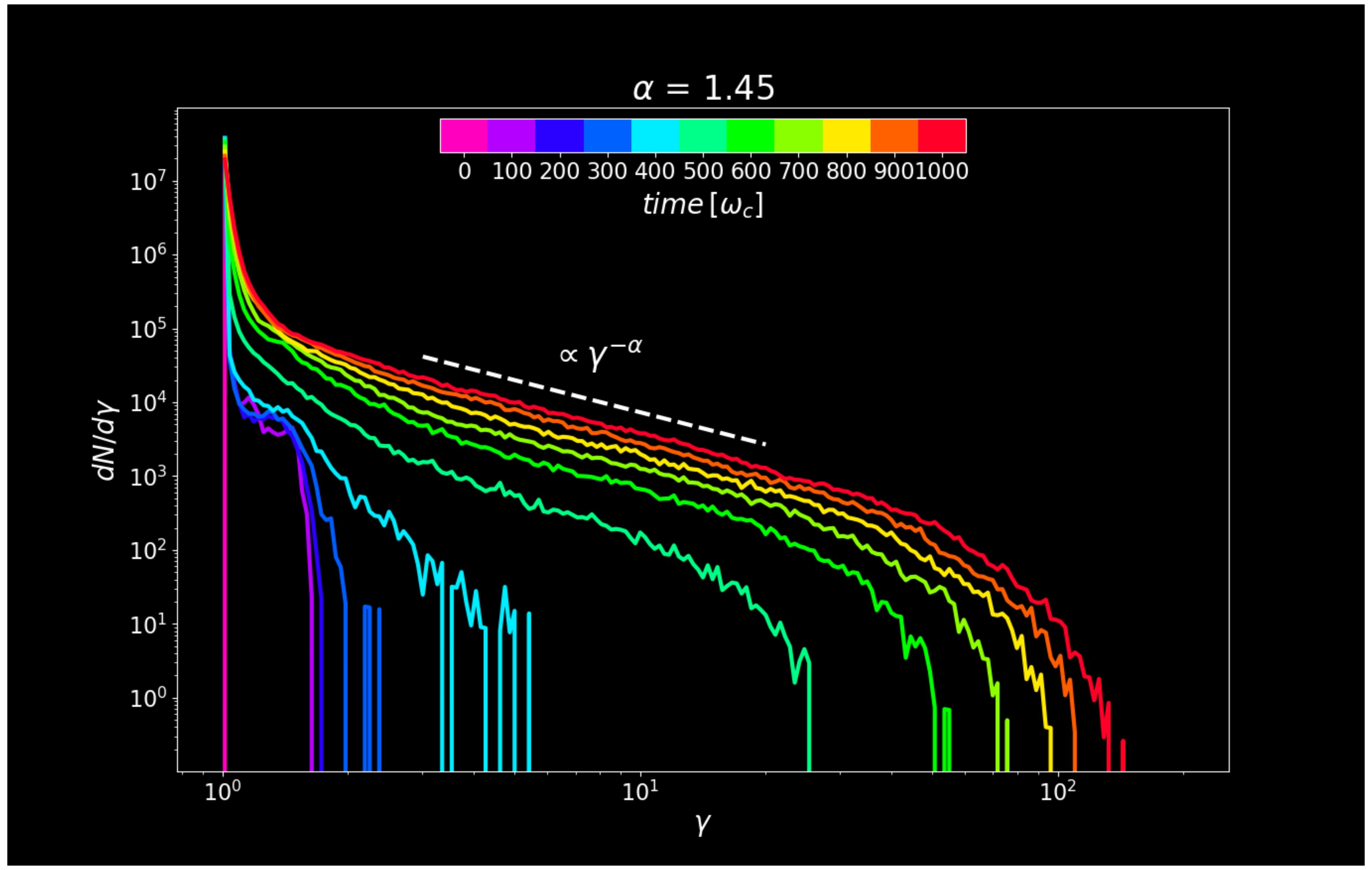
Simulation parameters

$$\sigma_{e,c} = 30 \qquad \frac{u_d}{c} = 0.6$$

$$L = 2048\,\rho_0 \approx 68\,\sigma\rho_0 \qquad \frac{n_0}{n_b} = 10$$

Parameters from Werner et al. (**2015**)





Wilbert et al. (**in preparation**)

Fluid codes are another strategy

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2-fluid equations:

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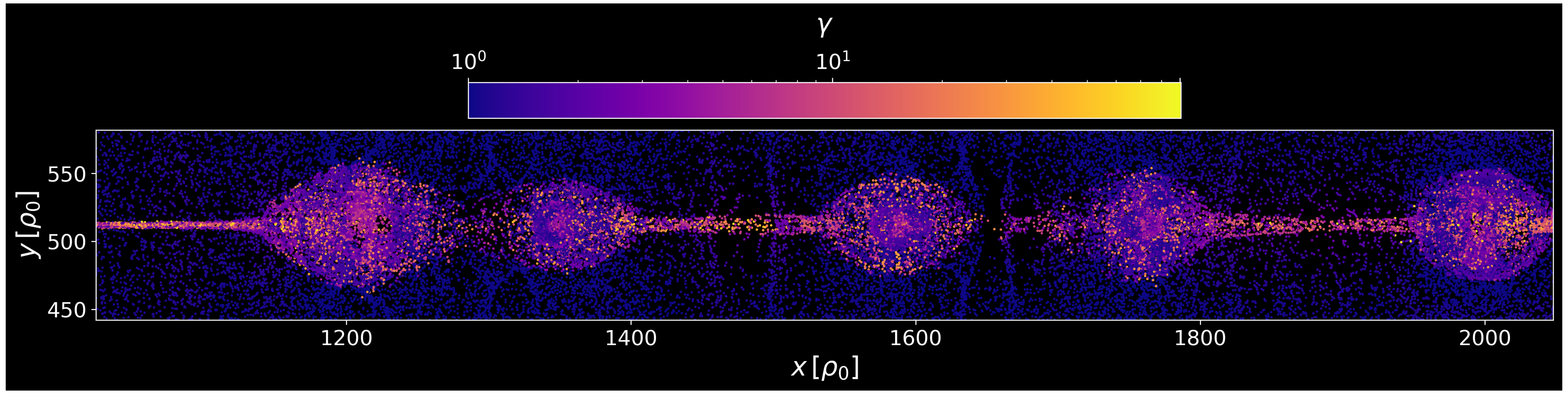

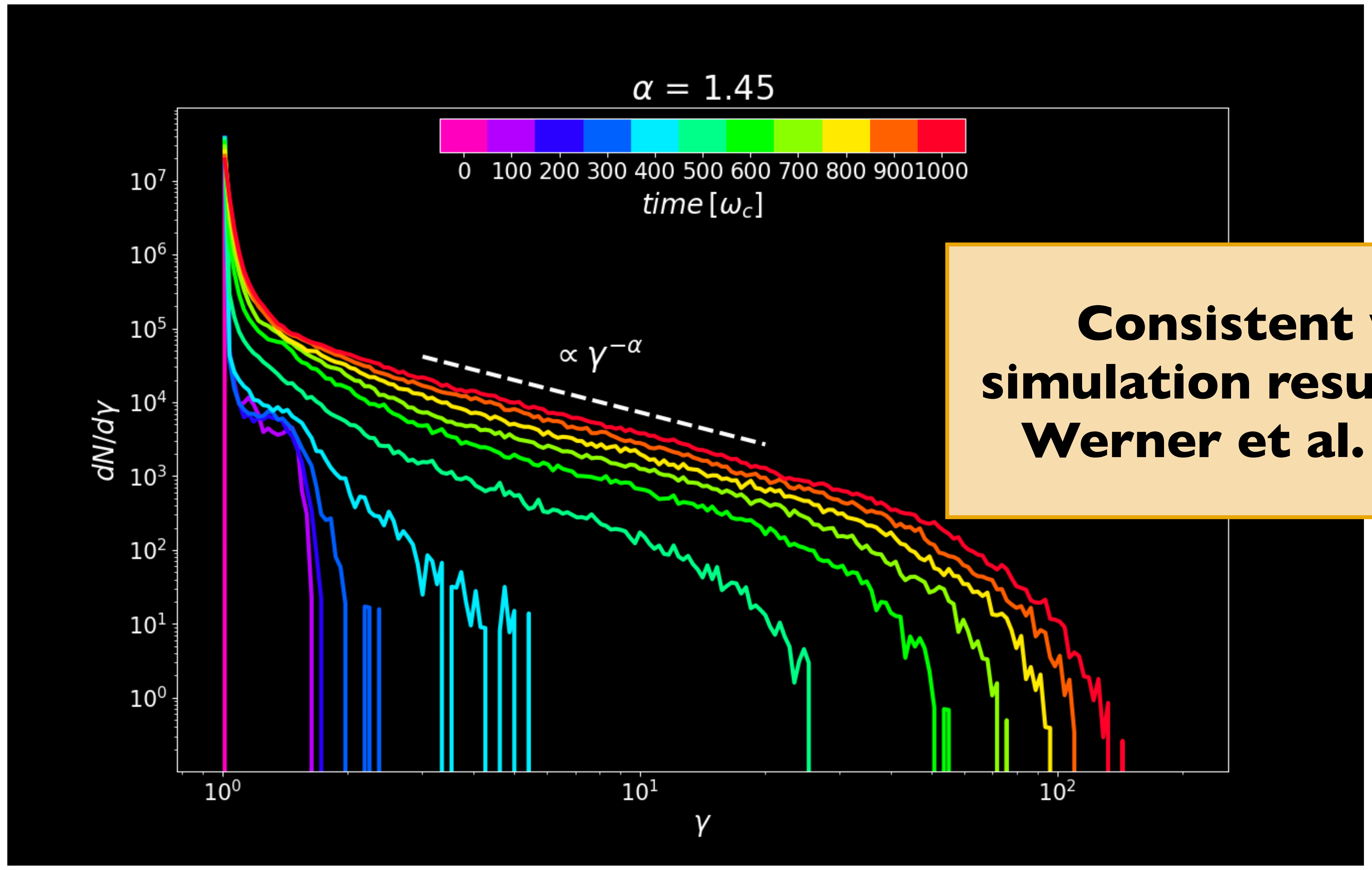

Consistent with simulation results from Werner et al. (2015)

Wilbert et al. (**in preparation**)

Fluid codes are another strategy

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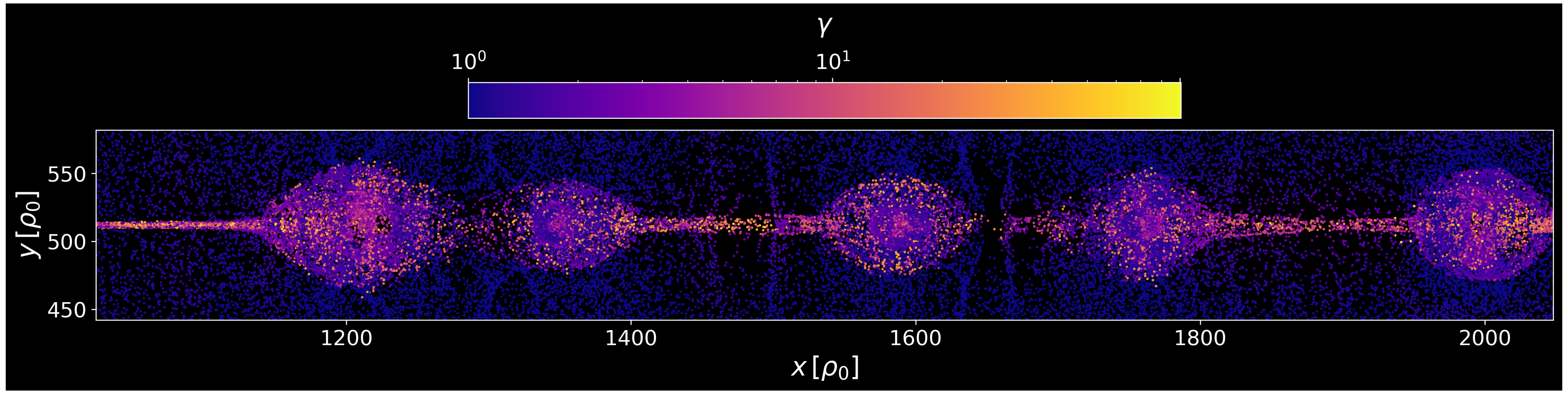

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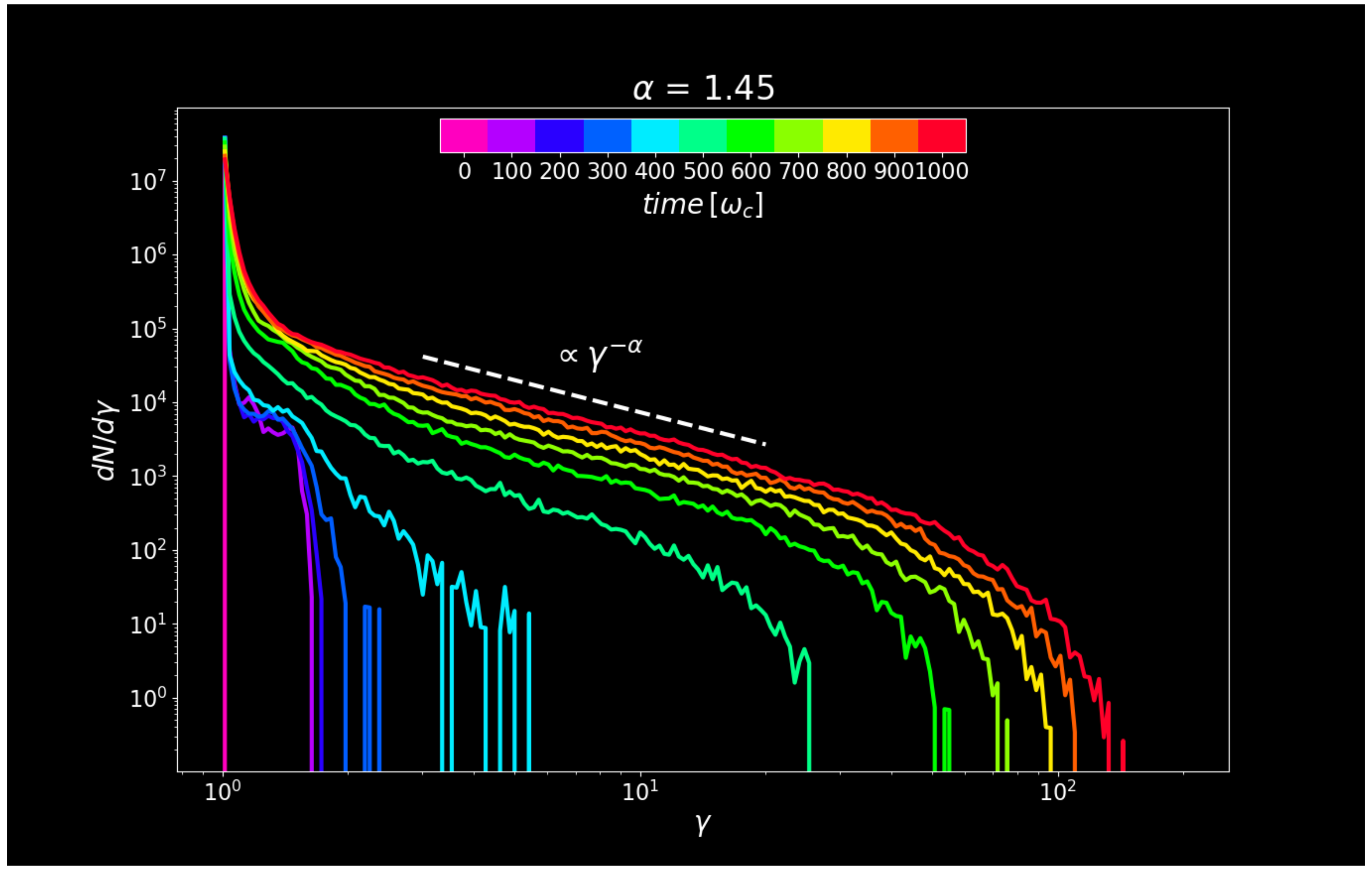

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Parameters from W

Is it also effective in 3D?

Wilbert et al. (**in preparation**)

3D simulations with RelSIM

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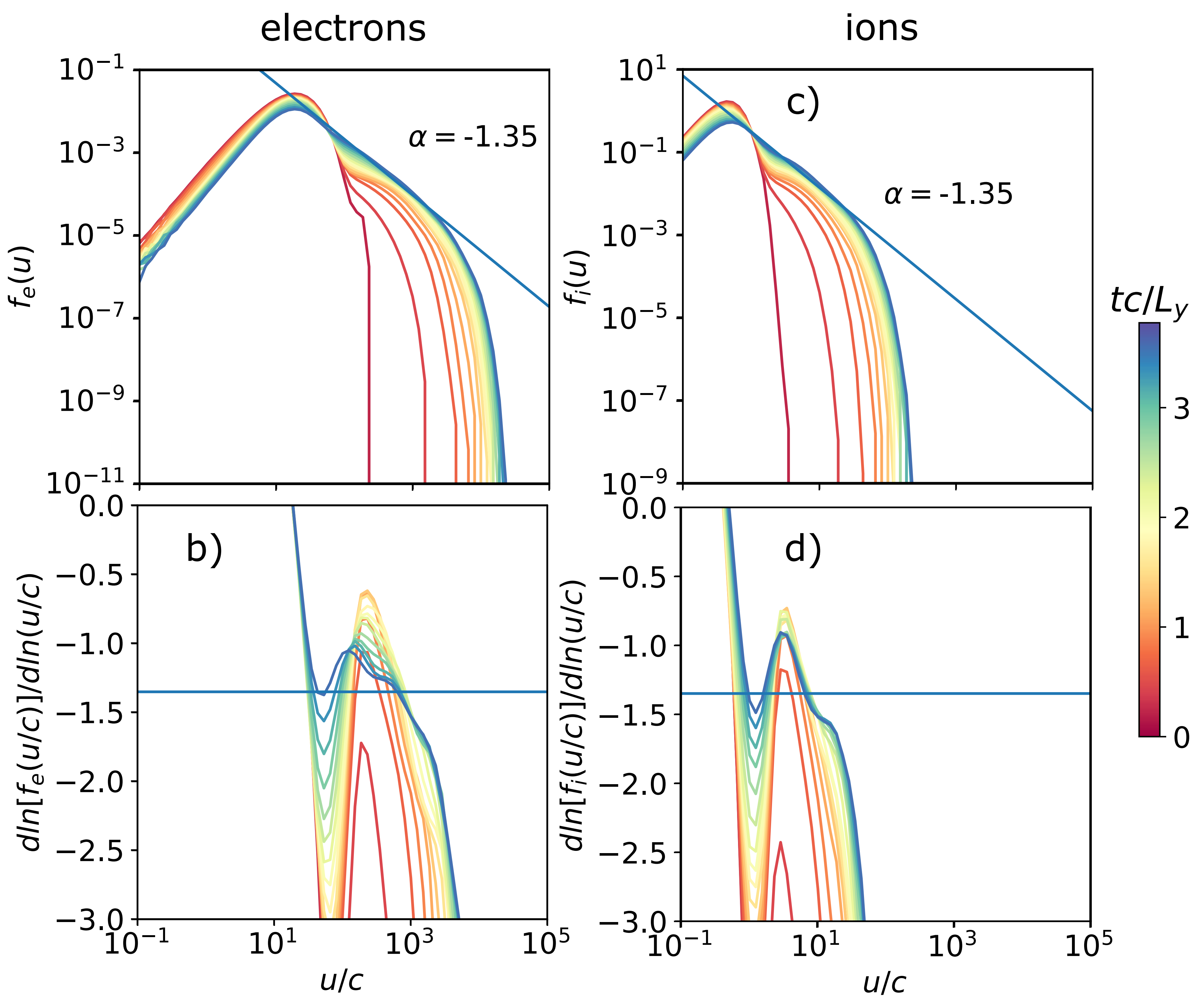
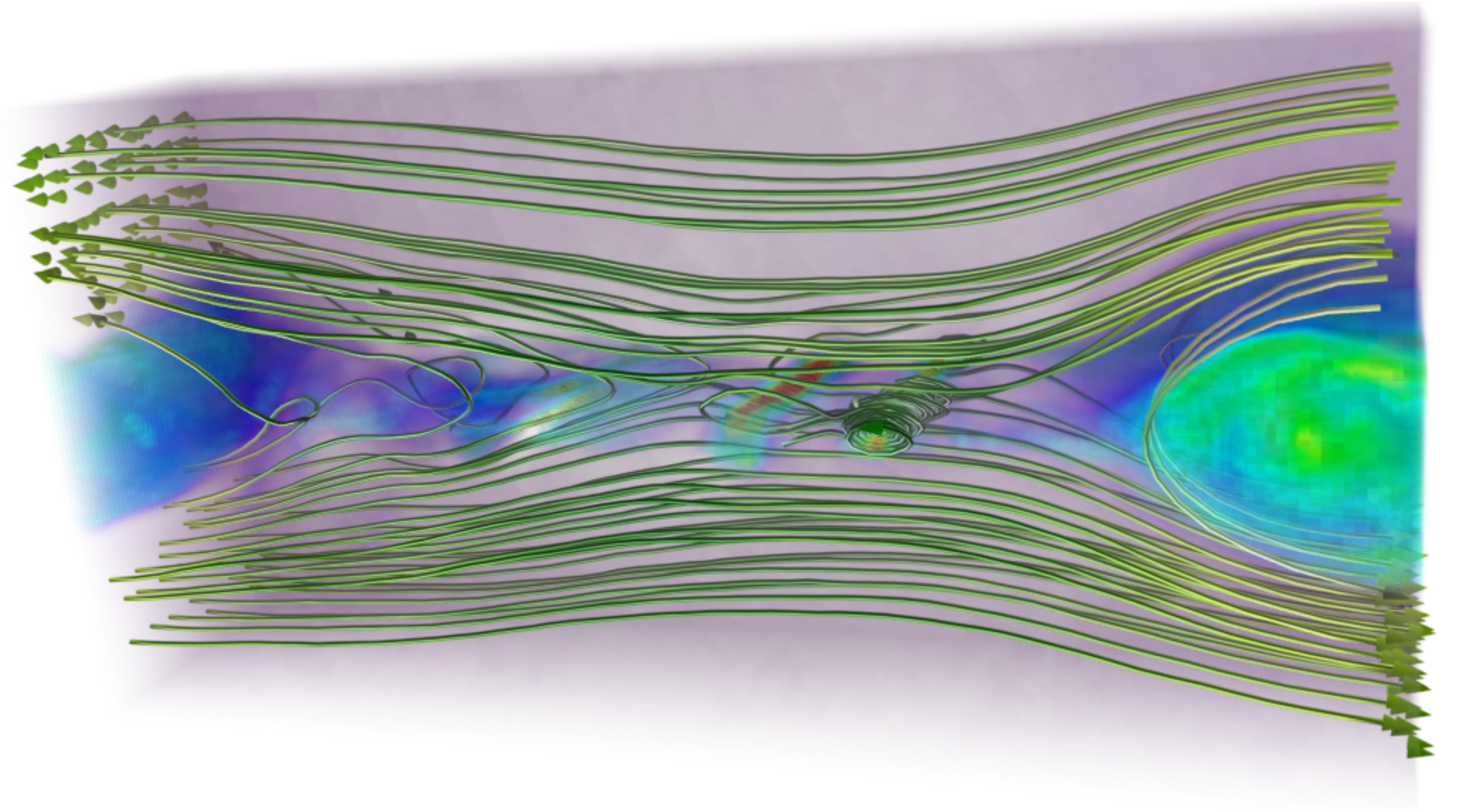
$$\frac{L_x}{d_e} = 1000 \qquad \sigma_{i,c} = 100$$





Conclusions

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Tearing studied using explicit PIC simulations

- Zelenyi theory along with Hoshino correction is confirmed with OSIRIS
- A new benchmark for tearing simulations available
- Large scale current sheets driven by tearing ruled out

Semi-implicit model has strong computational advantage for tearing

- Smaller spatial resolution is needed
- Lower time resolution and particles per cell for the same energy conservation
- Computational savings as high as 256 x

Large scale Relativistic reconnection

- Can be modelled with semi-implicit PIC (or even fluid) simulations
- We can now explore larger 2D and 3D system sizes with kinetic methods
- Energetic spectra may help explain cosmic rays and neutrinos found near AGNs

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