

Diagnosing Non-Relativistic Particle Acceleration in Low-Beta Plasma



Turbulence with PIC Simulation TRISTAN Data

← Rui Huang¹ (rui-huang@uiowa.edu), Gregory G. Howes¹, Collin R. Brown², Luca Comisso³

¹Dept. of Physics & Astronomy, University of Iowa; ²Plasma Physics Division, Naval Research Laboratory;

³Dept. of Astronomy & Columbia Astrophysics Laboratory, Columbia University

1. Motivation: Solar Energetic Particles

- Non-thermal particles everywhere in space but acceleration mechanism unclear
- A fully 3D, high-resolution turbulence simulation now allows detailed study of particle energization
- So we apply our diagnostic tool to this data to investigate which mechanisms produce non-thermal particles in non-relativistic, low-beta turbulence

2. Data: Particle-in-Cell (PIC) Simulation

TRISTAN-MP: PIC simulation code, evolves:
Sample distribution function with N macroparticles

$$f_s(\vec{r}, \vec{v}, t) = \sum_{n=1}^N w_n \delta(\vec{x} - \vec{x}_n(t)) \delta(\vec{v} - \vec{v}_n(t))$$

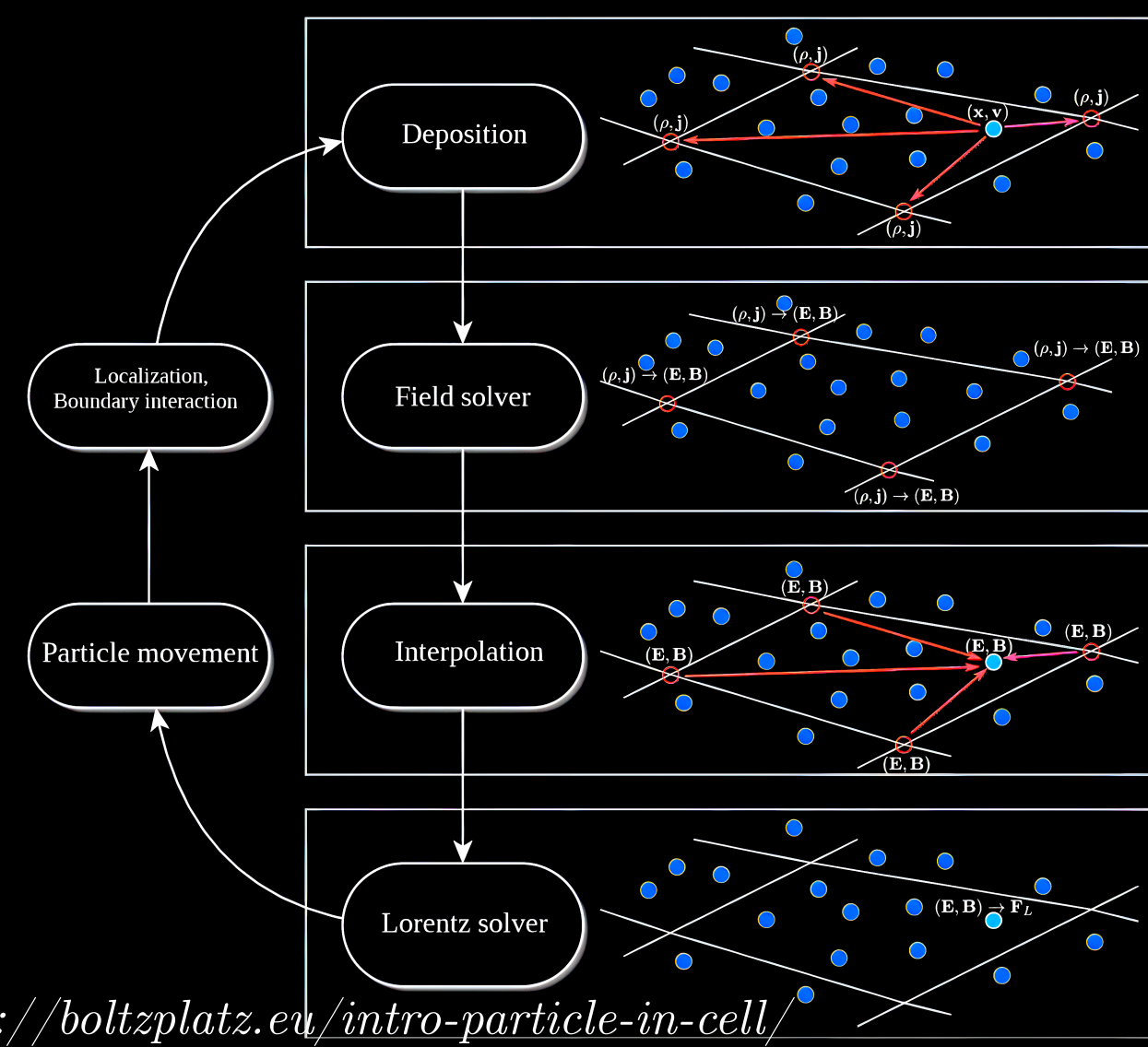
Evolution of EM fields

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \quad \frac{\partial \vec{D}}{\partial t} = \nabla \times \vec{H} - \vec{J}$$

Motion of each macroparticle

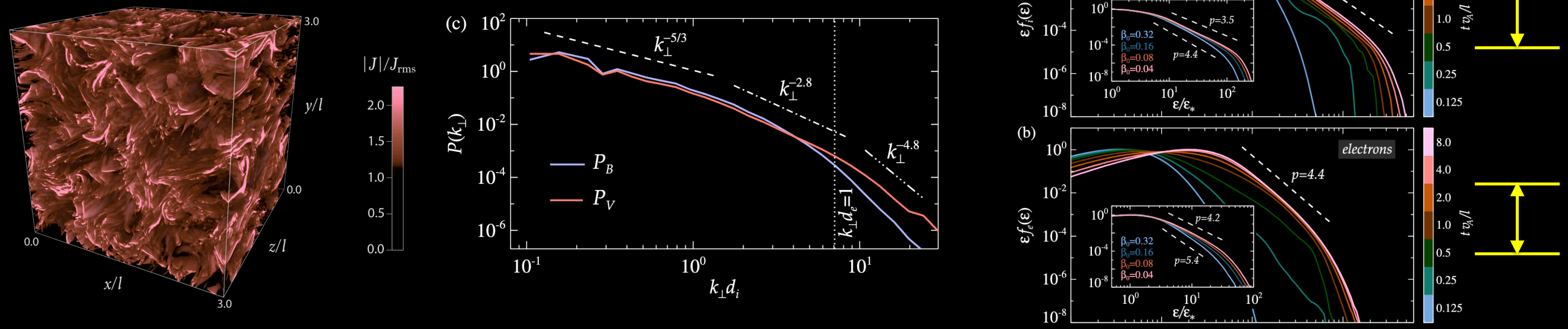
$$\frac{d\vec{x}}{dt} = \vec{v} \quad \frac{d(m\vec{v})}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$$

<https://boltzplatz.eu/intro-particle-in-cell/>



Simulation Details

[Comisso & Sironi, ApJL, 2022] Turbulent Energy Spectrum at $t = 1.25l/v_A$



- L^3 simulation box, $L = 60d_i$, periodic, $\rightarrow \Delta kd_i = \pi/30$
- Decaying turbulence, energy-carrying/injection scale $l = L/3$, $\rightarrow k_0 d_i = 0.314$
- $m_i/m_e = 50$, $T_{i0}/T_{e0} = 1$, $\beta_{i0} = 0.04$, $\vec{B}_0 = B_0 \hat{z}$,
RMS: $\langle \delta B^2(t=0) \rangle^{1/2} = B_0$
- Fiducial: $\beta_0 = \beta_{i0} + \beta_{e0} = 0.08$, $k_B T_0 = 0.02 m_e c^2 \rightarrow k_0 \rho_i = 0.0628$,
 $v_{i0} = 0.02c$, $v_{e0} = 0.14c$
- resolve $d_e = c/\omega_{pe}$ with 3.3 cells, $\rightarrow d_i = c/\omega_{pi}$ with 23.3 cells
- 1400^3 cells, 64 particles per cell, $\rightarrow 1.75 \times 10^{11}$ total particles,
 $\Delta x = 3/70 d_i$
- $\omega_{pe}/\omega_{ce} = \sqrt{4\pi n_0 e^2 / m_e} / (eB_0/m_e c) = 1$,
 $\rightarrow B_0 = c\sqrt{4\pi n_0 m_e}$,
 $v_A = B_0 / \sqrt{4\pi n_0 m_i} = 0.14c$
- $CC = c\Delta t/\Delta x = 0.45$, $\rightarrow \Delta t = 0.01928 d_i/c = 1.35 \times 10^{-4} l/v_A$

Data We Have:
downsampled,
 1.1×10^7 particles,
 700^3 grids, $\Delta x = 3/35 d_i$

6. Summary: More Questions than Answers

- We applied the diagnostic tool FPC technique to PIC simulation TRISTAN data to identify dominant particle acceleration mechanisms in turbulence.
- Preliminary results confirmed the importance of local FAC due to large-amplitude turbulent field.
- FPCs from selected timeslices suggest possible iCD and eMRXN, though further evidence is needed.
- For more about my research, scan the QR code above.

3. Diagnostic Tool: Field-Particle Correlation (FPC)

FPCs are defined as:

$$C_{E_{\parallel},s}(\vec{r}_0, \vec{v}, t_0; \tau) = C_{E_{\perp},s}(\vec{r}_0, \vec{v}, t_0; \tau) \quad C_{E_{\perp},s}(\vec{r}_0, \vec{v}, t_0; \tau) = \left\langle -q_s \frac{v_{\perp}^2}{2} \frac{\partial f_s(\vec{r}_0, \vec{v}, t)}{\partial v_{\perp}} E_{\perp}(\vec{r}_0, t) \right\rangle_{\tau \text{ or } \vec{r}}$$

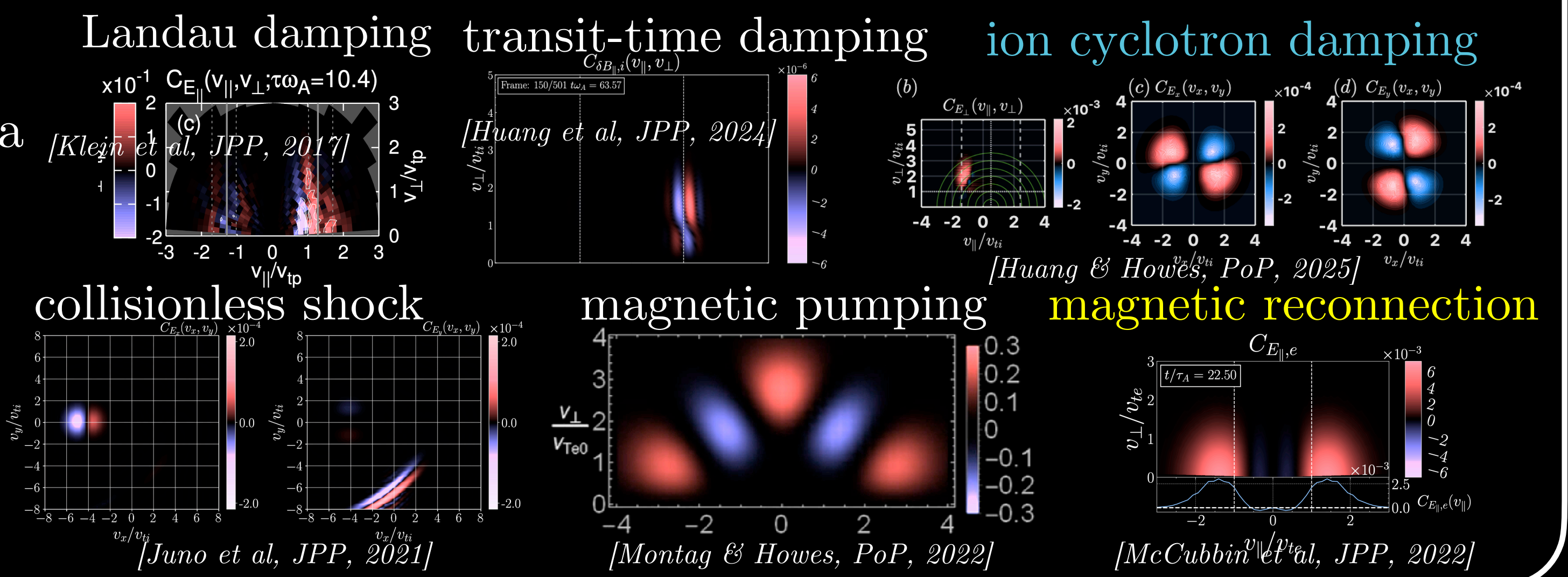
$$= \left\langle -q_s \frac{v_{\parallel}^2}{2} \frac{\partial f_s(\vec{r}_0, \vec{v}, t)}{\partial v_{\parallel}} E_{\parallel}(\vec{r}_0, t) \right\rangle_{\tau \text{ or } \vec{r}}, \quad C_{E_{\perp},s}(\vec{r}_0, \vec{v}, t_0; \tau) = C_{E_{\perp,1},s}(\vec{r}_0, \vec{v}, t_0; \tau) + C_{E_{\perp,2},s}(\vec{r}_0, \vec{v}, t_0; \tau)$$

Average either over

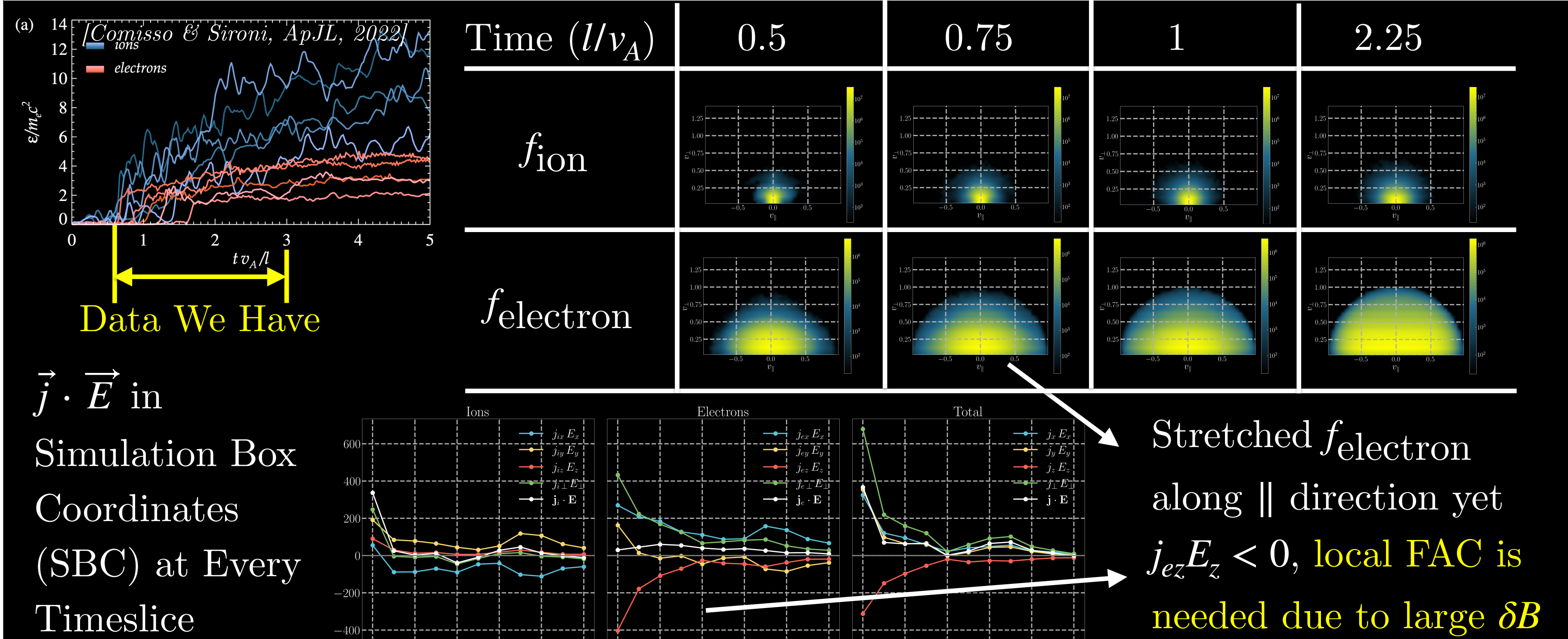
$$C_{E_{\perp},s}(\vec{r}_0, \vec{v}, t_0; \tau) = \left\langle -q_s \frac{v_{\perp}^2}{2} \frac{\partial f_s(\vec{r}_0, \vec{v}, t)}{\partial v_{\perp}} E_{\perp}(\vec{r}_0, t) \right\rangle_{\tau \text{ or } \vec{r}}, \quad \langle \dots \rangle_{\tau} = \frac{1}{\tau} \int_{t_0-\tau/2}^{t_0+\tau/2} (\dots) dt$$

$$\langle \dots \rangle_{\vec{r}} = \frac{1}{xyz} \int_{z_0-z/2}^{z_0+z/2} \int_{y_0-y/2}^{y_0+y/2} \int_{x_0-x/2}^{x_0+x/2} (\dots) dx dy dz$$

- Calculate these terms from data
- Plot them on velocity space
- Different mechanisms have different patterns.



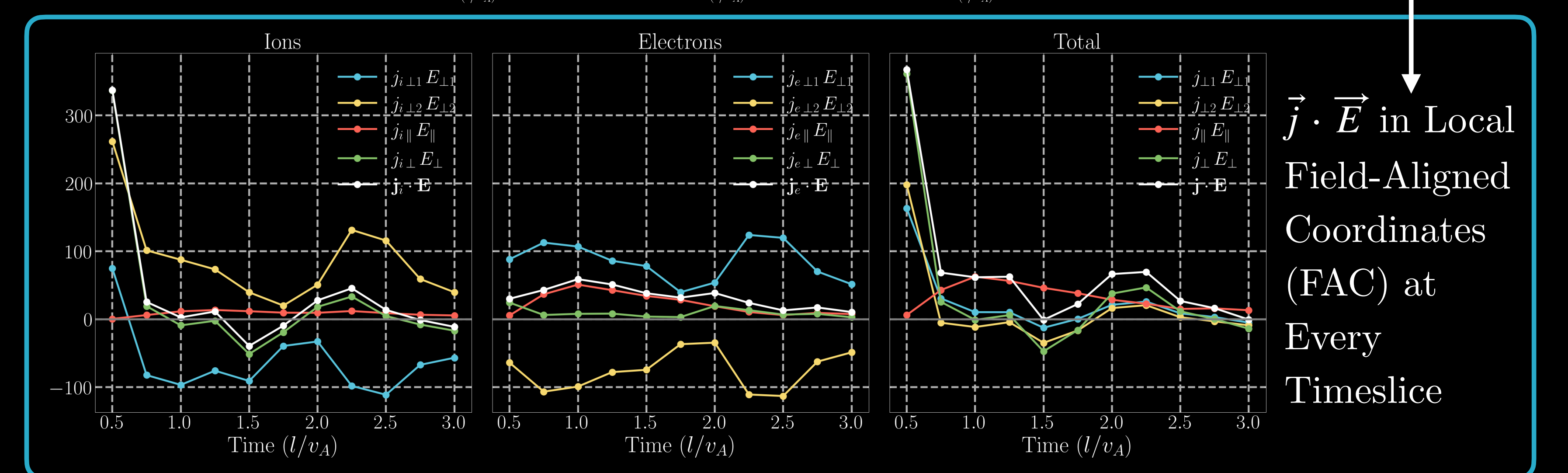
4. Results: The Importance of Local FAC



$\vec{j} \cdot \vec{E}$ in

Simulation Box Coordinates (SBC) at Every Timeslice

Stretched f_{electron} along \parallel direction yet $j_{ez} E_z < 0$, local FAC is needed due to large δB



- Ions: Rapid ion cyclotron damping (iCD) in the beginning?
- Electrons: Parallel energization due to magnetic reconnection (eMRXN)?
- Overview: $j_{s11} E_{11}$ and $j_{s12} E_{12}$ (for $s = i, e$) look symmetrical wrt 0, $E \times B$ drift?

5. Results: FPCs at Selected Timeslices

