PARTICLE ACCELERATION DURING RELATIVISTIC MAGNETIC RECONNECTION

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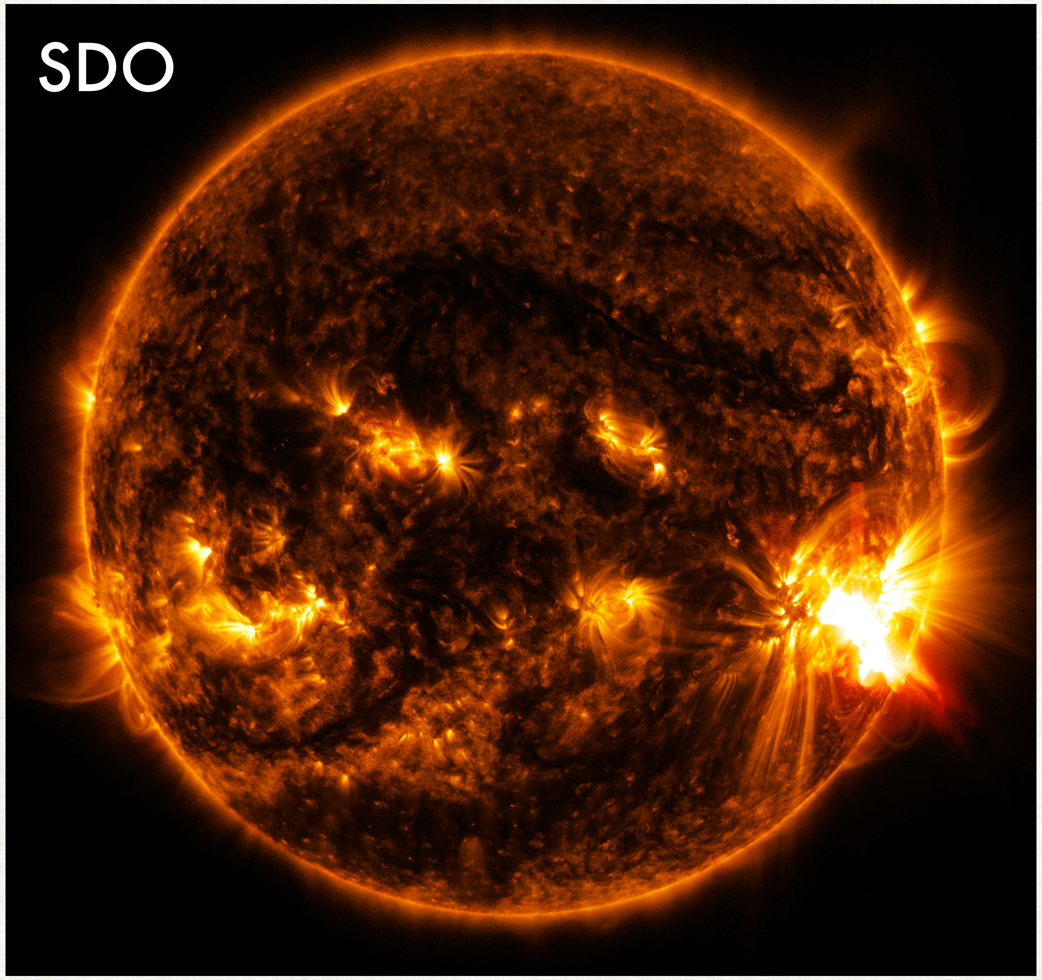
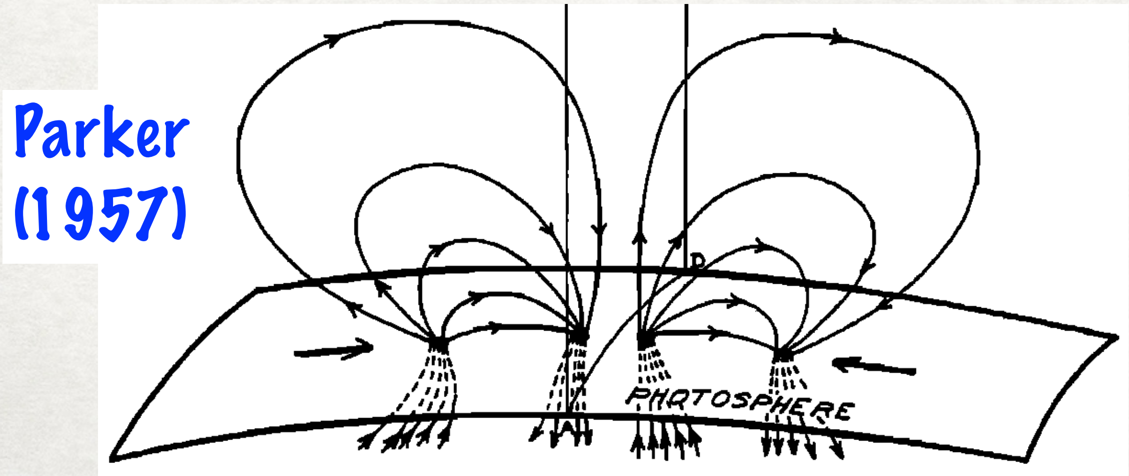
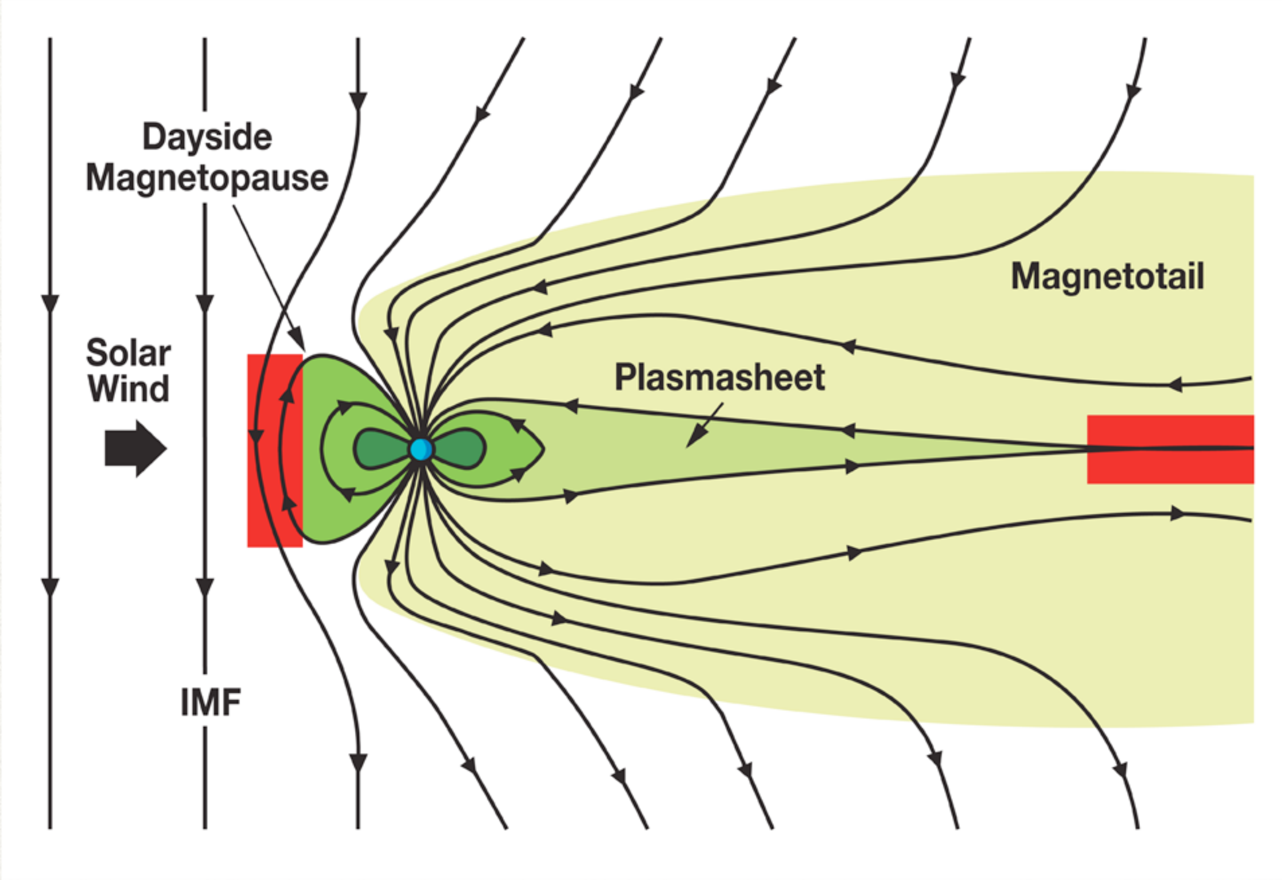
NON-RELATIVISTIC MAGNETIZATIONS

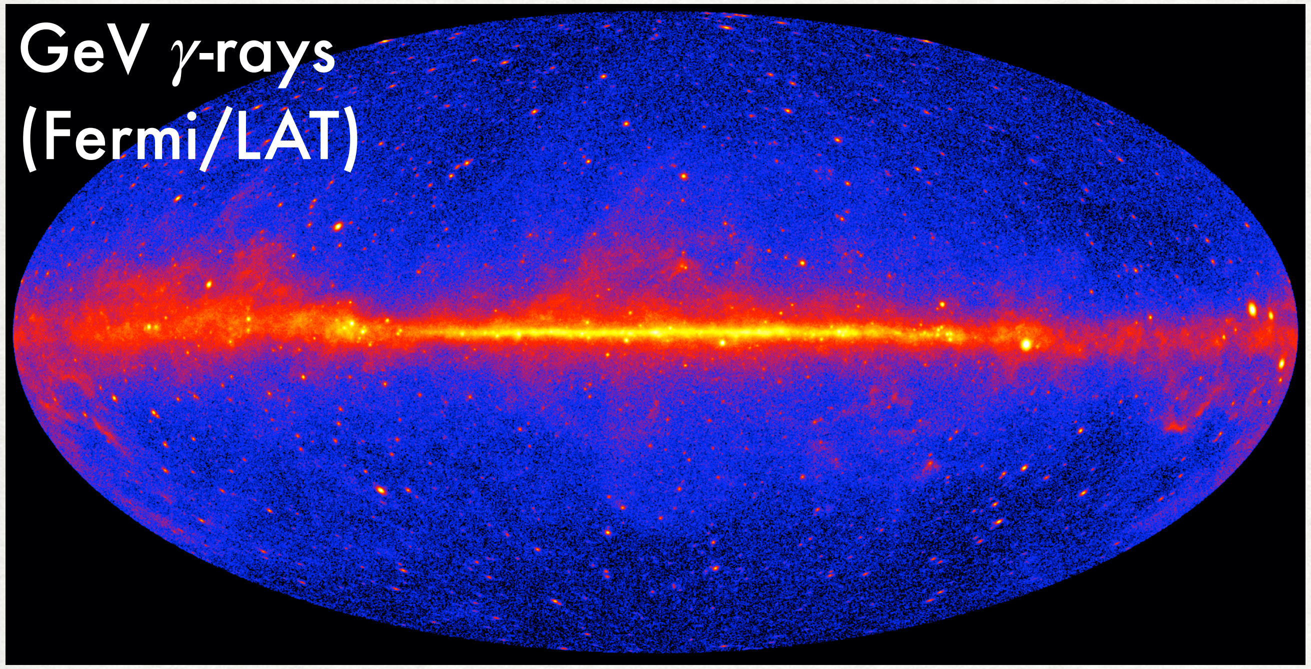
$$\sigma = \frac{B^2/4\pi}{\rho c^2 + u_{\rm int} + P} \ll 1$$



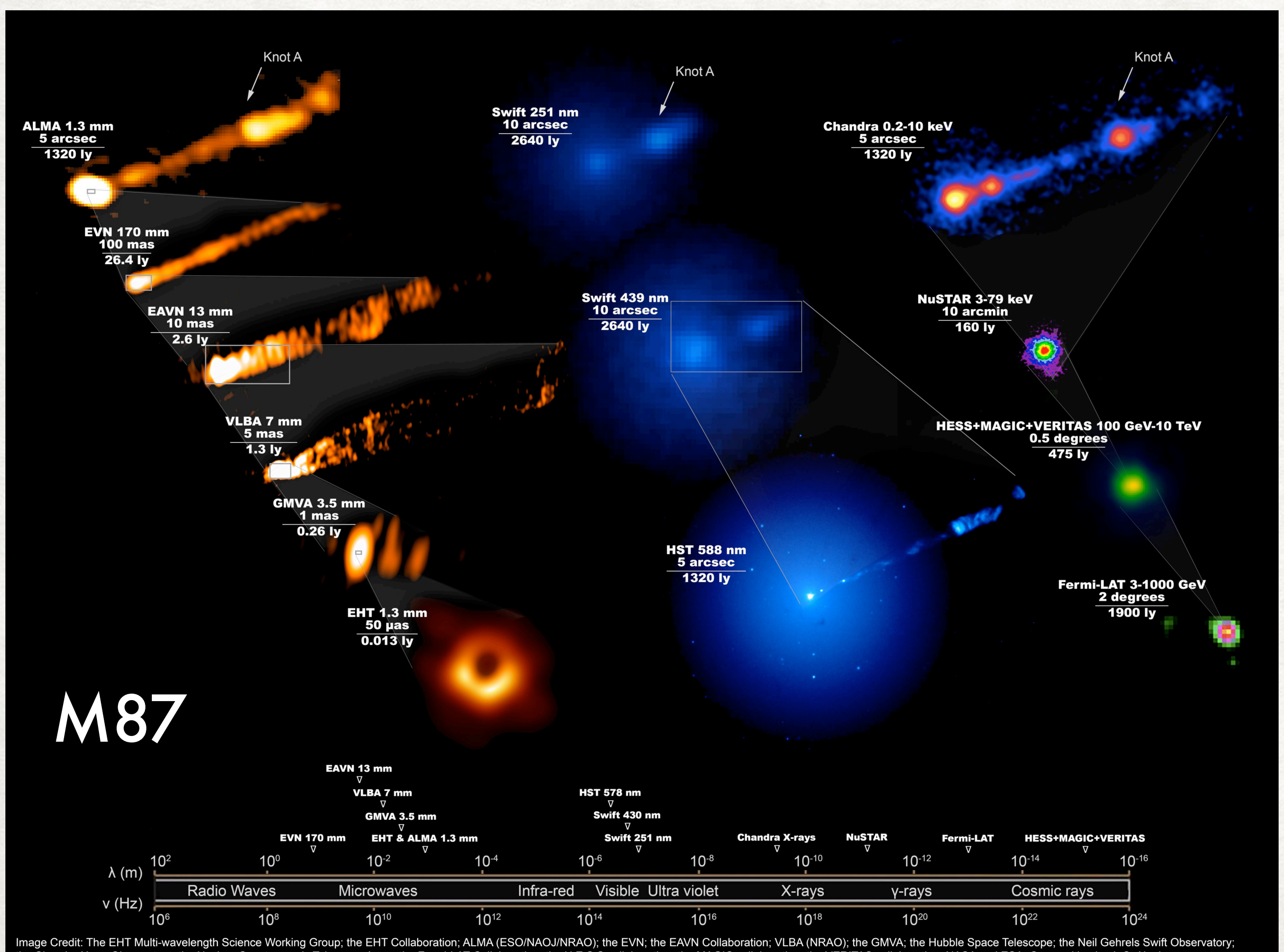


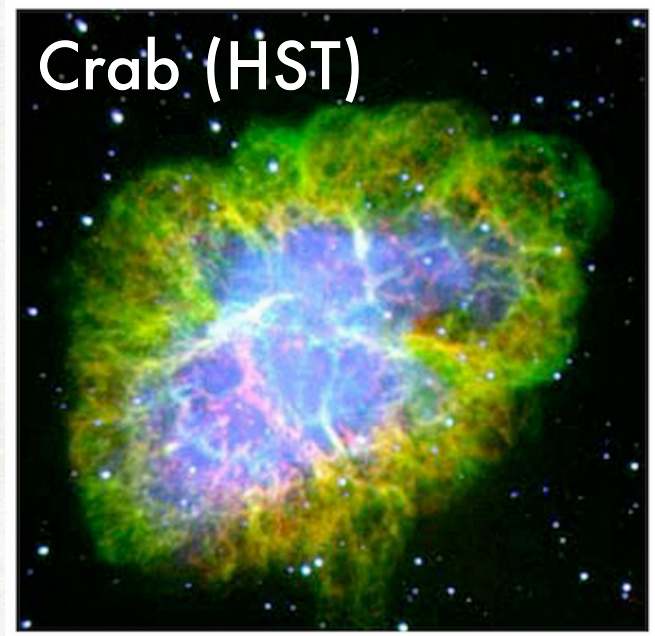


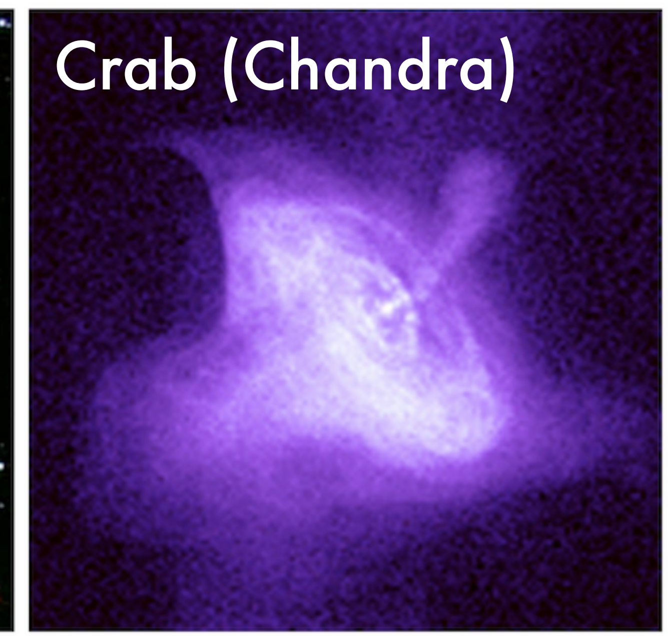
RELATIVISTIC MAGNETIZATIONS

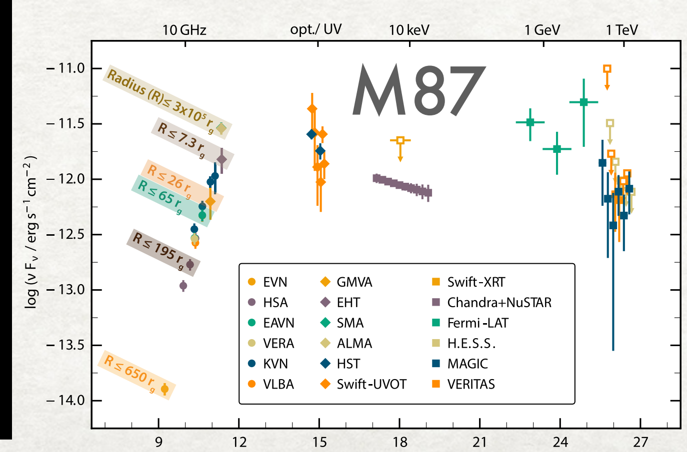


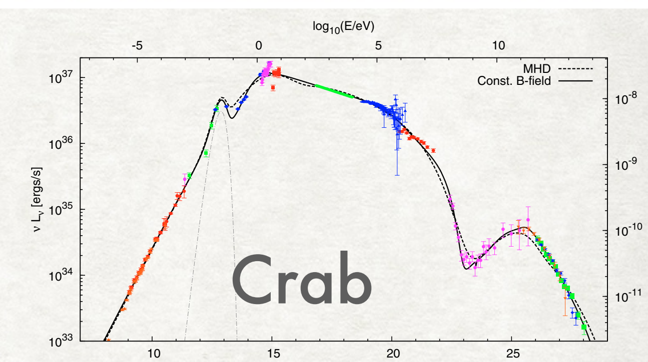
$$\sigma = \frac{B^2/4\pi}{\rho c^2 + u_{\rm int} + P} > 1$$





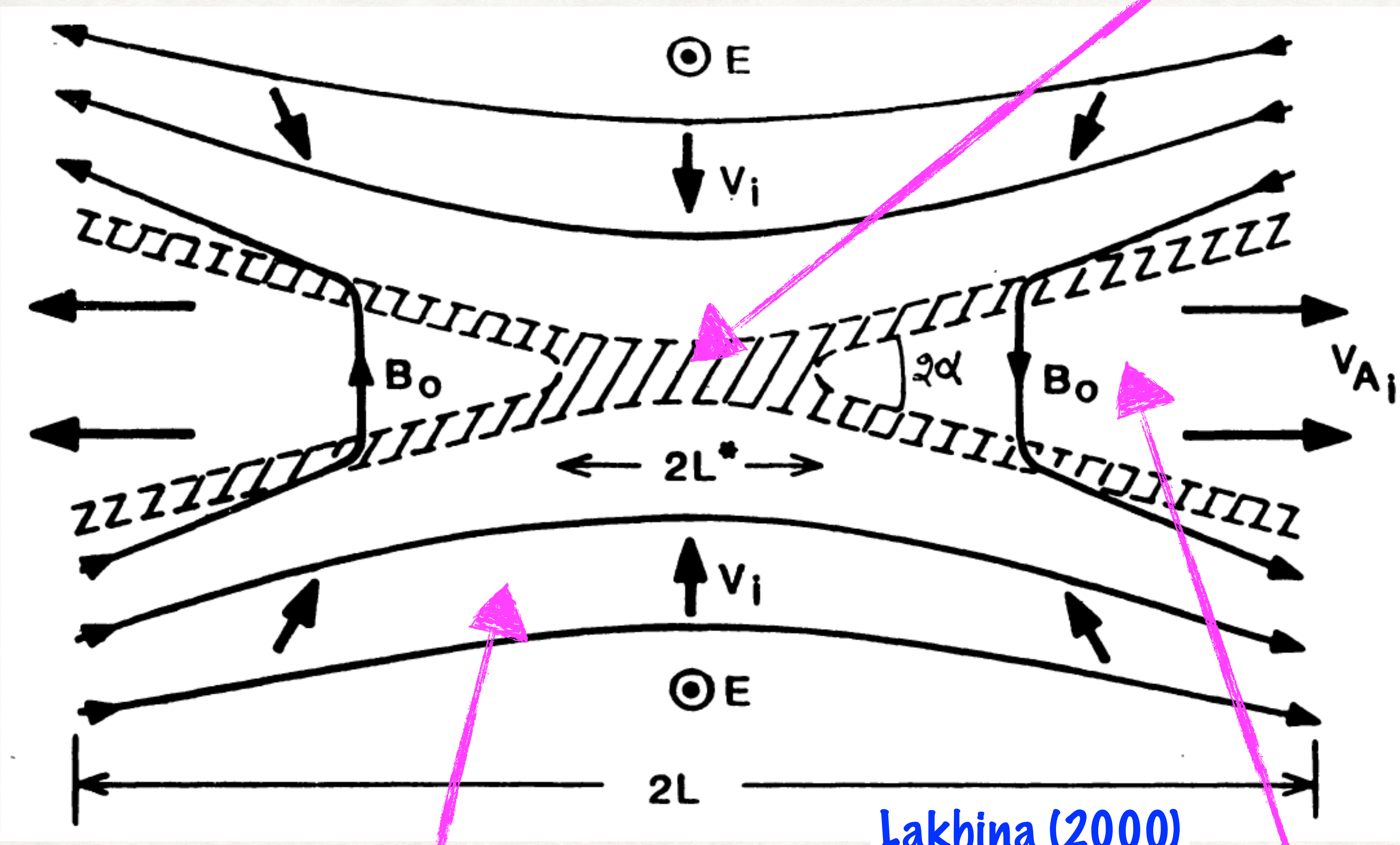






MAGNETIC RECONNECTION

magnetic diffusion region (X-point)



$E \sim (v_{in}/c)\, B_0$

$v_{in} \sim 0.1\, v_A$

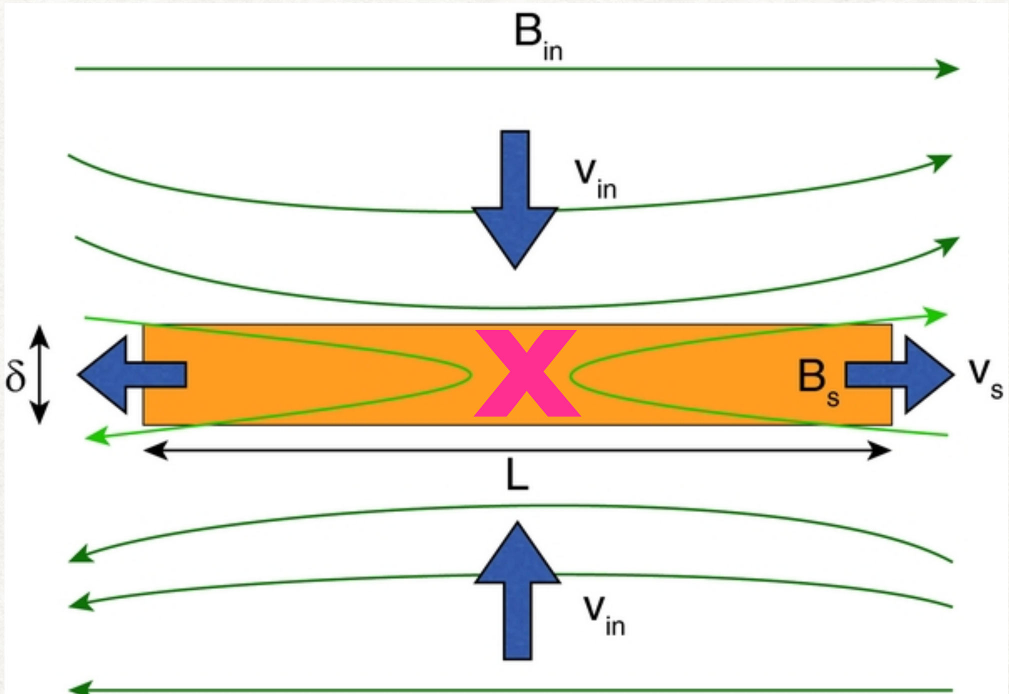
$v_{out} \sim v_A$

reconnecting magnetic field (background, upstream)

reconnection outflow (downstream)

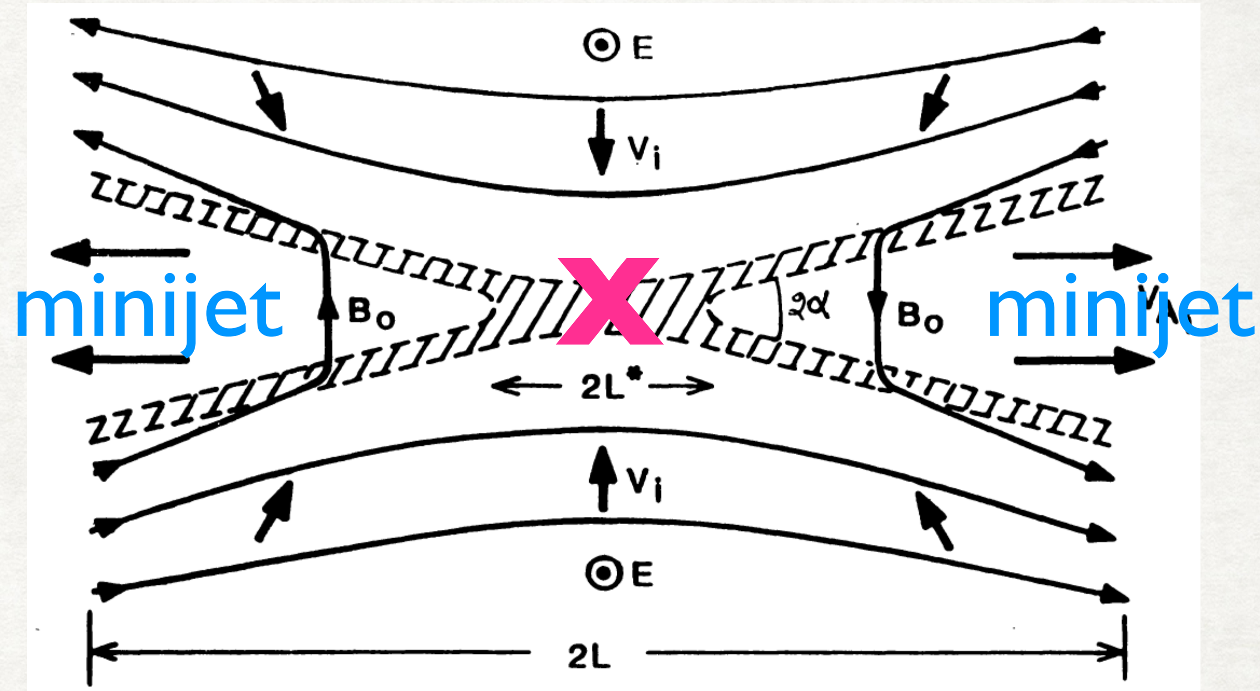
RECONNECTION MODELS

Sweet-Parker



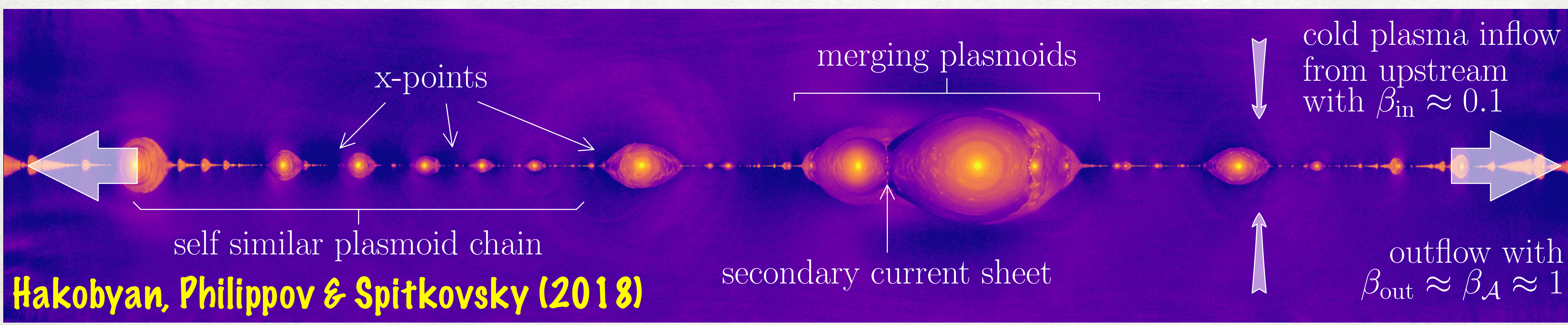
Takamoto (2013)

Petschek



Lakhina (2000)

plasmoid-dominated



Hakobyan, Philippov & Spitkovsky (2018)

Petschek Model in Electron-Ion Plasma

- ion/electron skin depth

$$d = \sqrt{\frac{mc^2}{4\pi e^2 n}}$$

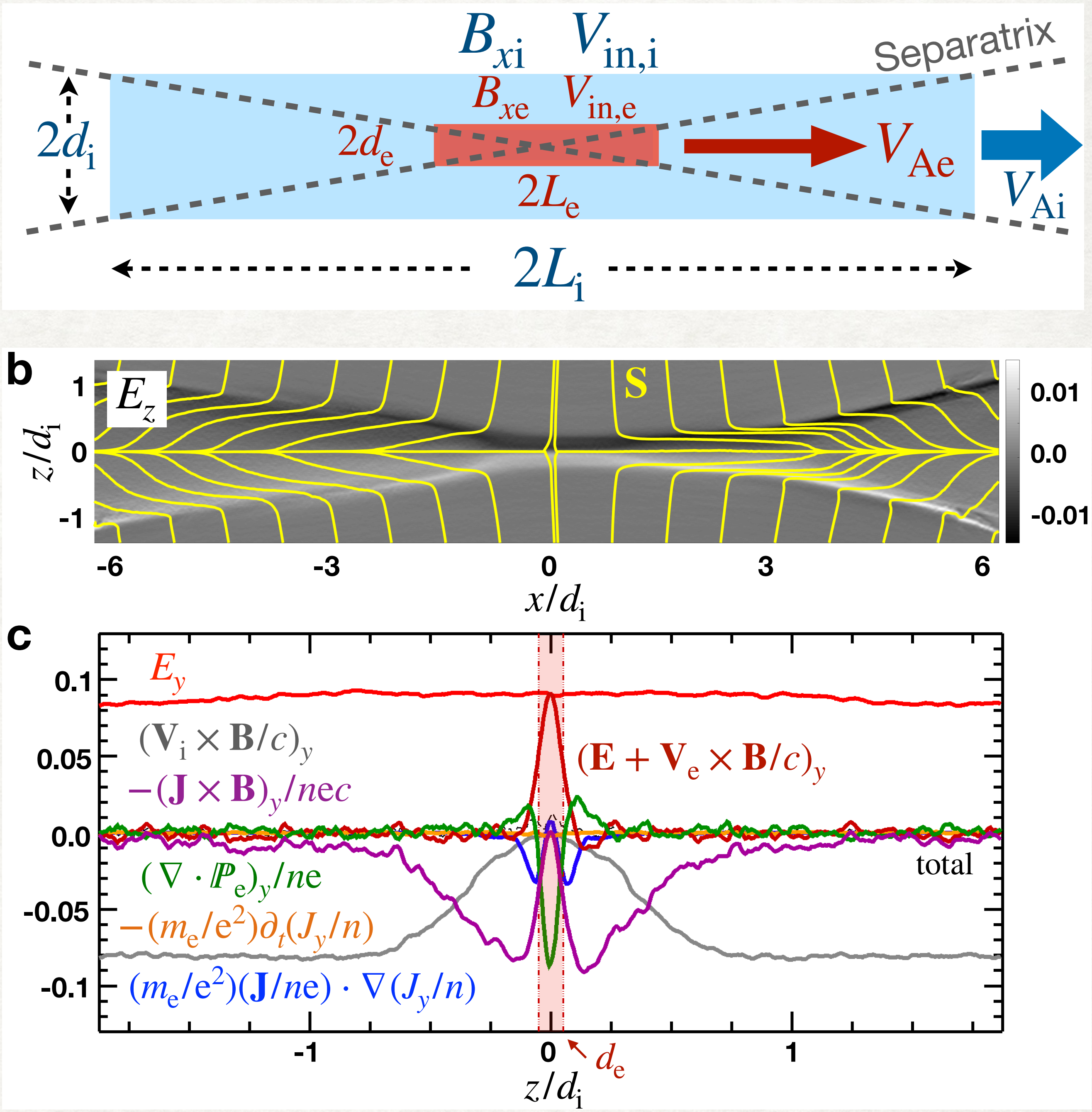
- nested diffusion regions

$$S = \frac{d_i}{L_i} = \frac{d_e}{L_e} \simeq \sqrt{\frac{\mu^{1/4} - 1}{3(\mu^{1/4} + 1)}} = 0.49$$

where $\mu = m_i/m_e = 1836$

- reconnection rate:

$$\beta \simeq S\sqrt{1 - S^2}\left(\frac{1 - S^2}{1 + S^2}\right)^2 = 0.16$$

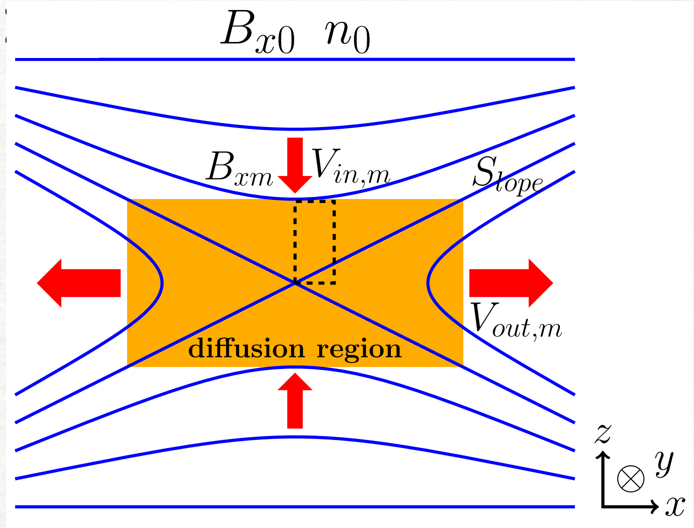


Liu et al. (2022)

Petschek Model in Relativistic Pair Plasma

modified Ohm's law

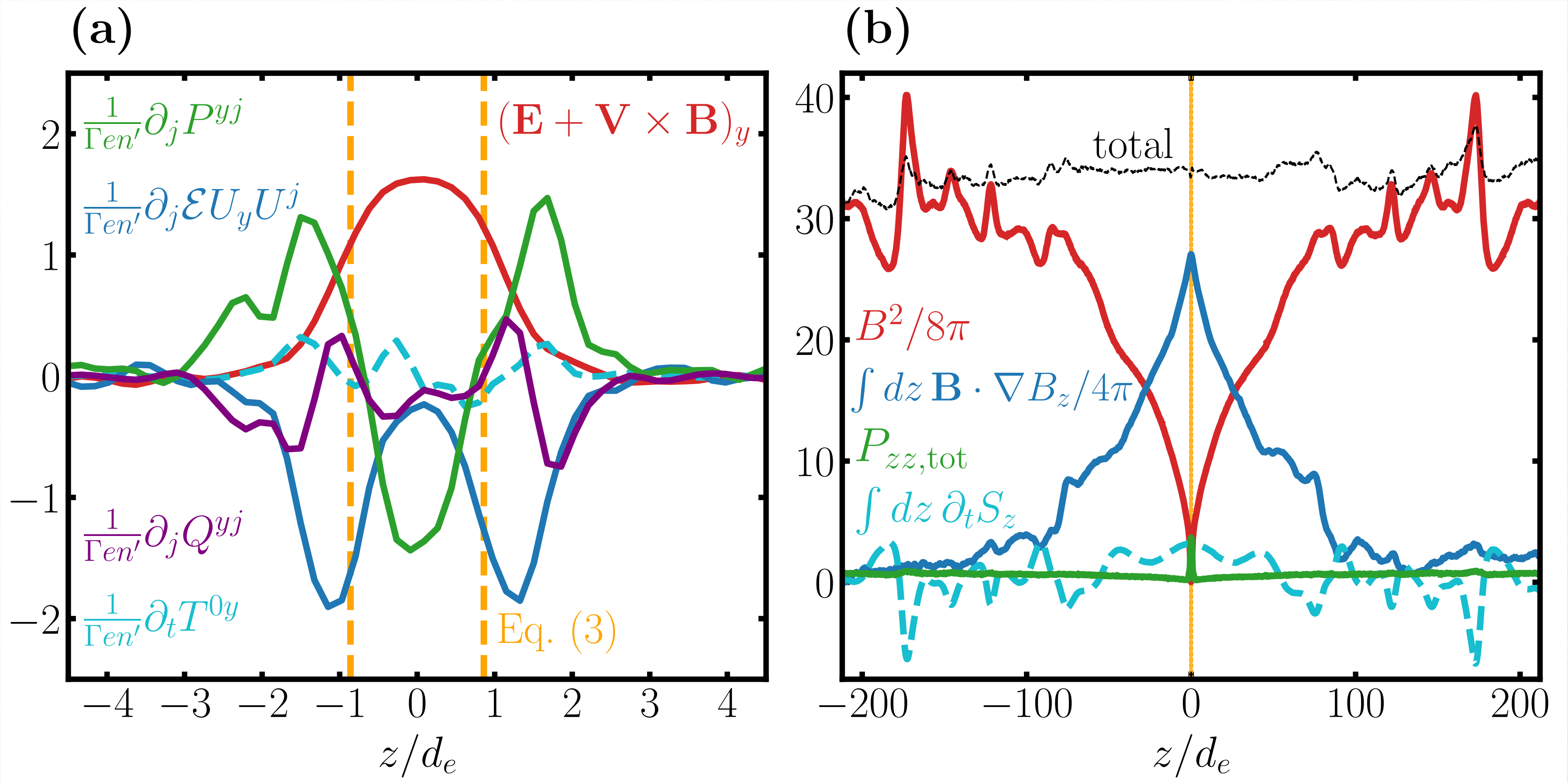
$$\mathbf{E}+\mathbf{V}\times\mathbf{B} = -\frac{1}{\Gamma e n'}\left[\partial_j\left(\mathcal{E}U^iU^j + Q^{ij} + P^{ij}\right) + \partial_t T^{i0}\right]$$



and the diffusion region width– The following derivation of the relativistic Ohm's law is due to Zenitani [24]. The stress-energy tensor can be decomposed as

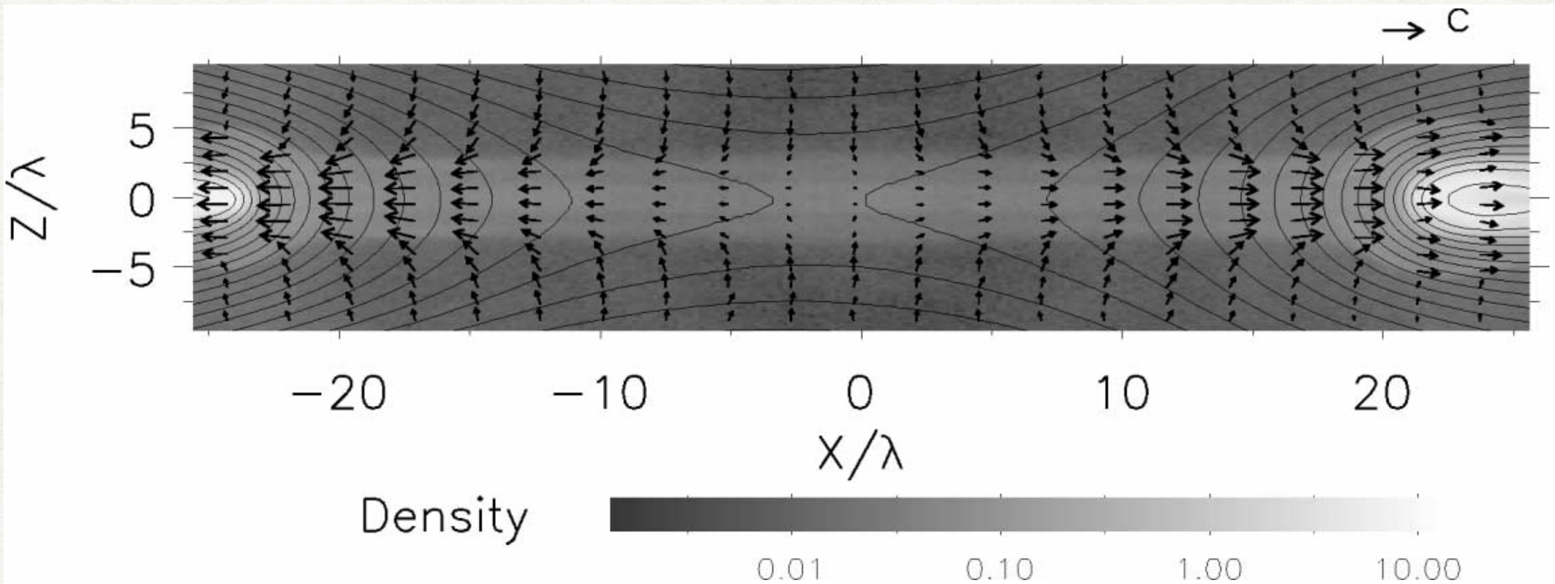
$$T^{\alpha\beta} = \mathcal{E}U^\alpha U^\beta + Q^{\alpha\beta} + P^{\alpha\beta} \tag{19}$$

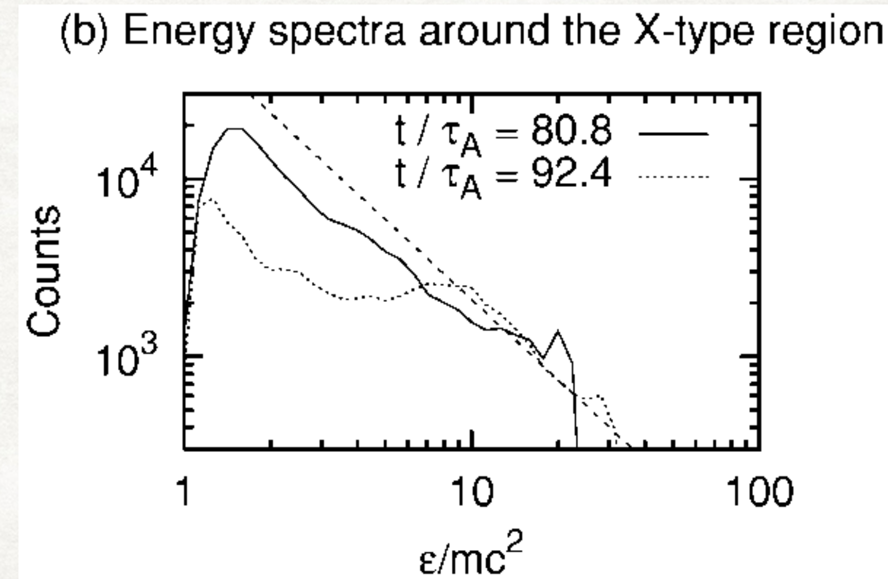
where U^α is an arbitrary flow 4-velocity. With $\Delta^{\alpha\beta} \equiv \eta^{\alpha\beta}+U^\alpha U^\beta$ as the projection tensor, $\mathcal{E} \equiv T^{\alpha\beta}U_\alpha U_\beta$ is the energy density in the U^α-moving frame. $Q^{\alpha\beta} = q^\alpha U^\beta + U^\alpha q^\beta$ is the heat flux tensor, where $q^\alpha \equiv -\Delta^\alpha_\beta T^{\beta\mu}U_\mu$ is the heat flux 4-vector. $P^{\alpha\beta} \equiv \Delta^\alpha_\mu \Delta^\beta_\nu T^{\mu\nu}$ is the pressure tensor projected in the U^α-moving frame.



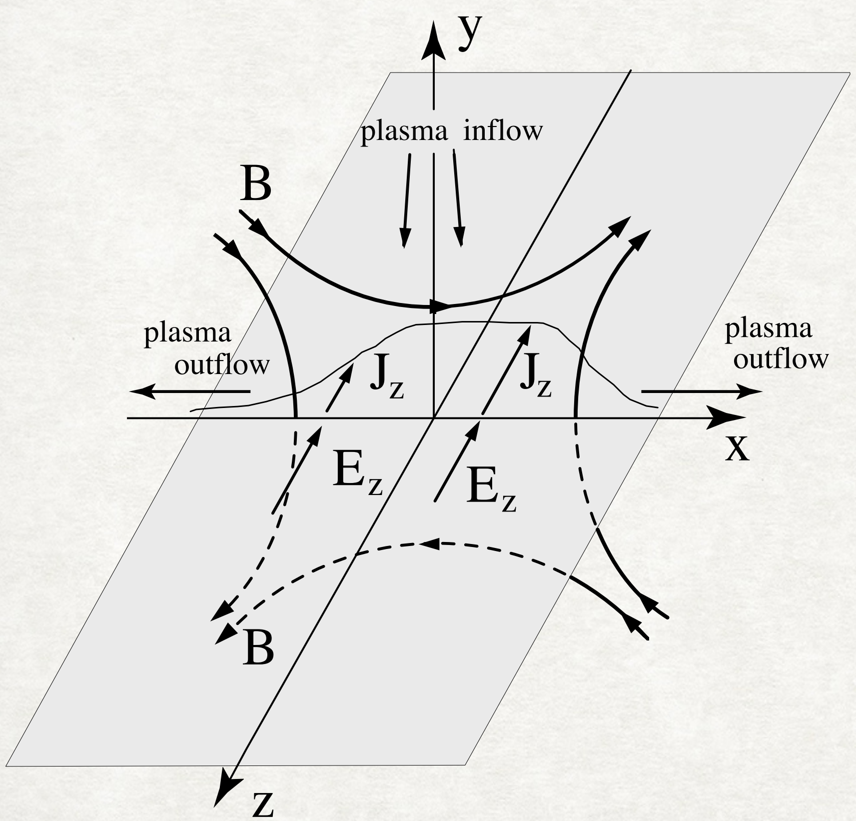
Goodbred & Liu (2023)

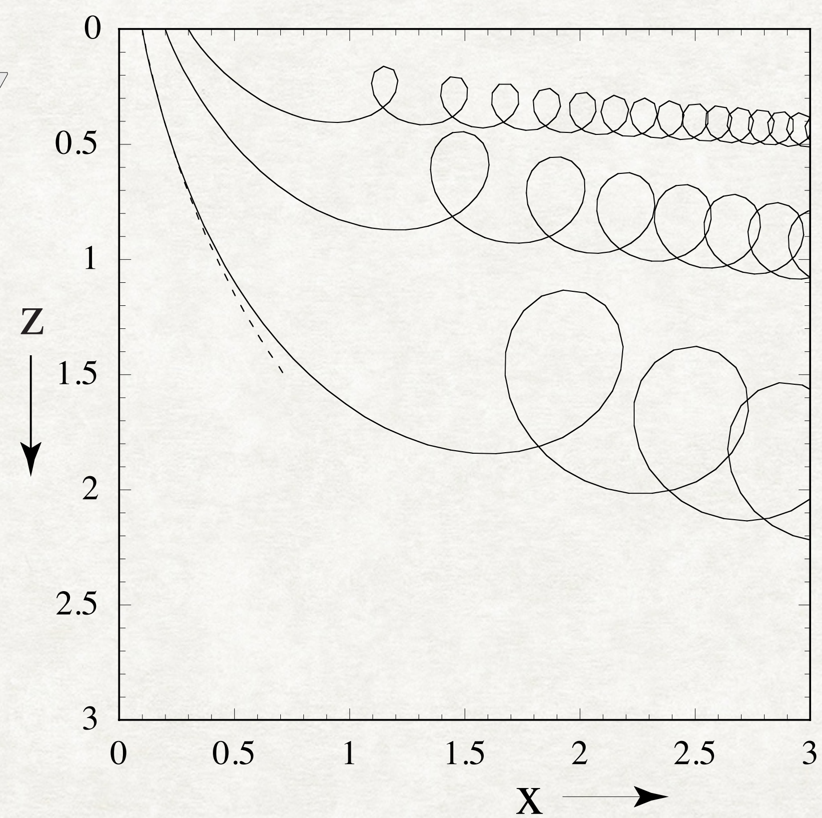
Particle Acceleration in Relativistic Reconnection

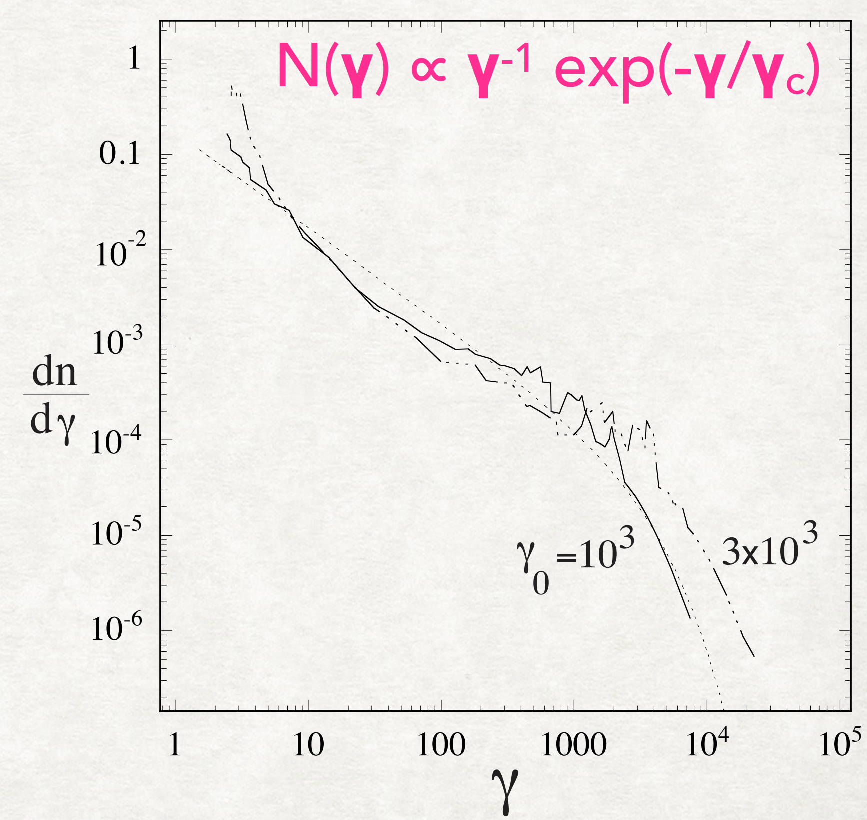




particle-in-cell simulations: Zenitani & Hoshino (2001)







iterative integration of test particles: Larrabee, Lovelace & Romanova (2003)

Hard particle spectra in relativistic reconnection

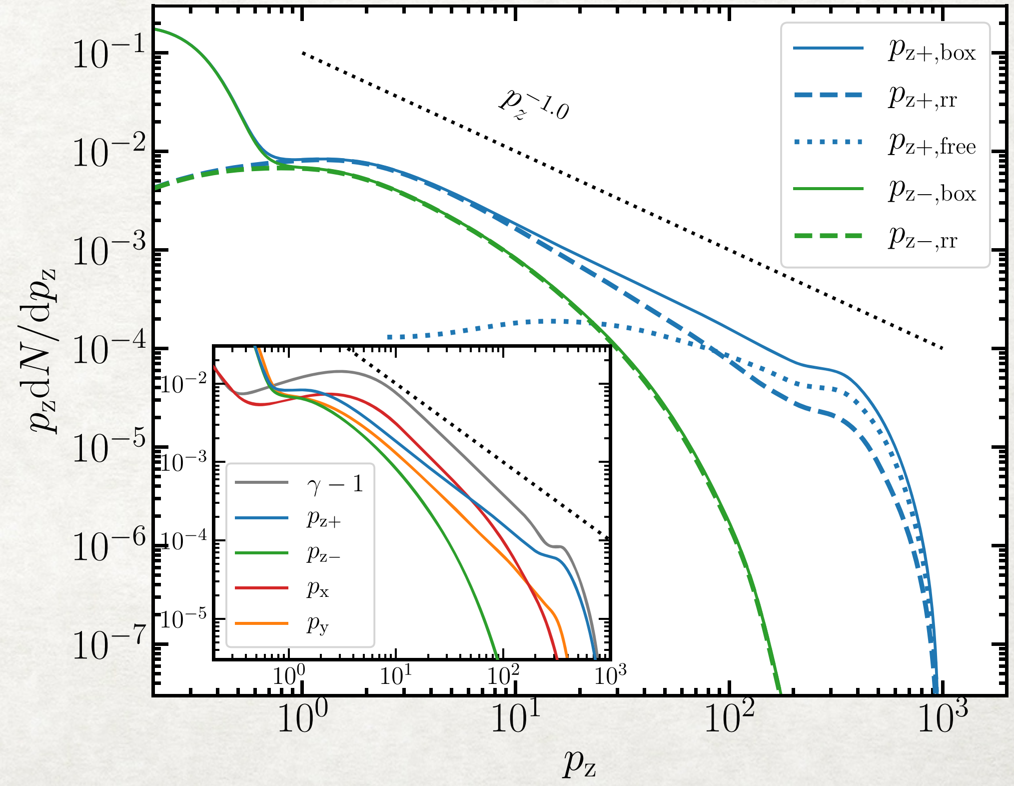
- reconnection produces power-law distributions that are hardening with increasing sigma
  $\mathrm{d}N/\mathrm{d}\gamma \propto \gamma^{-p}$ with $p \to 1$ for $\sigma \gg 1$
  (Sironi & Spitkovsky 2014, Guo et al. 2014, Werner et al. 2016)

- high-energy cut-off is exponential with $\gamma_{\max} \sim \mathcal{O}(\sigma)$

- $p \to 2$ in very large plasmoids in 2D
  (Petropoulou & Sironi 2018)

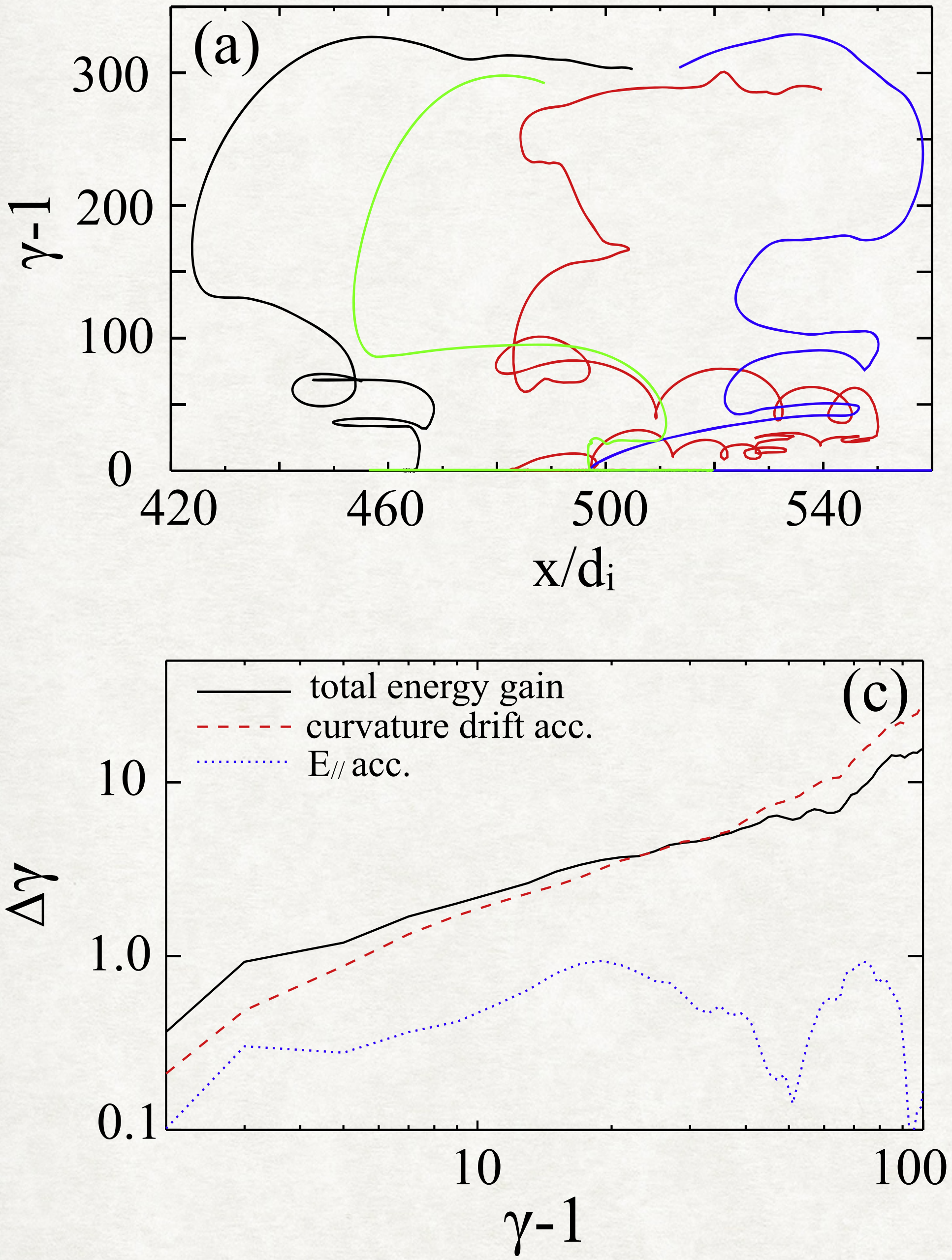
- 3D relativistic reconnection produces hard particle spectra
  $f(\gamma) \propto \gamma^{-p}$ with $p \sim 1.5$
  (Zhang, Sironi & Giannios 2021)

Zhang, Sironi & Giannios (2021)



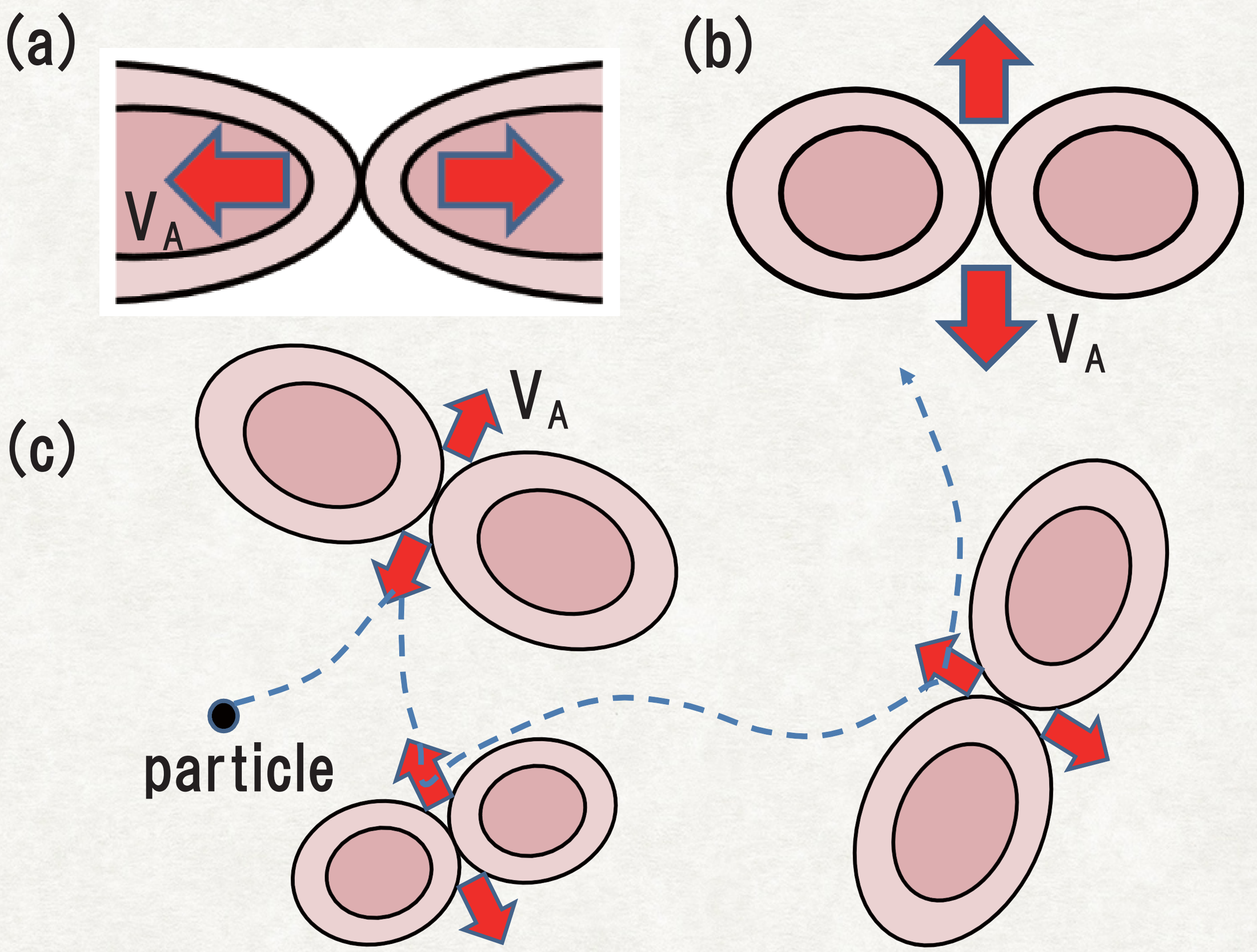
Fermi Process (?)

first-order



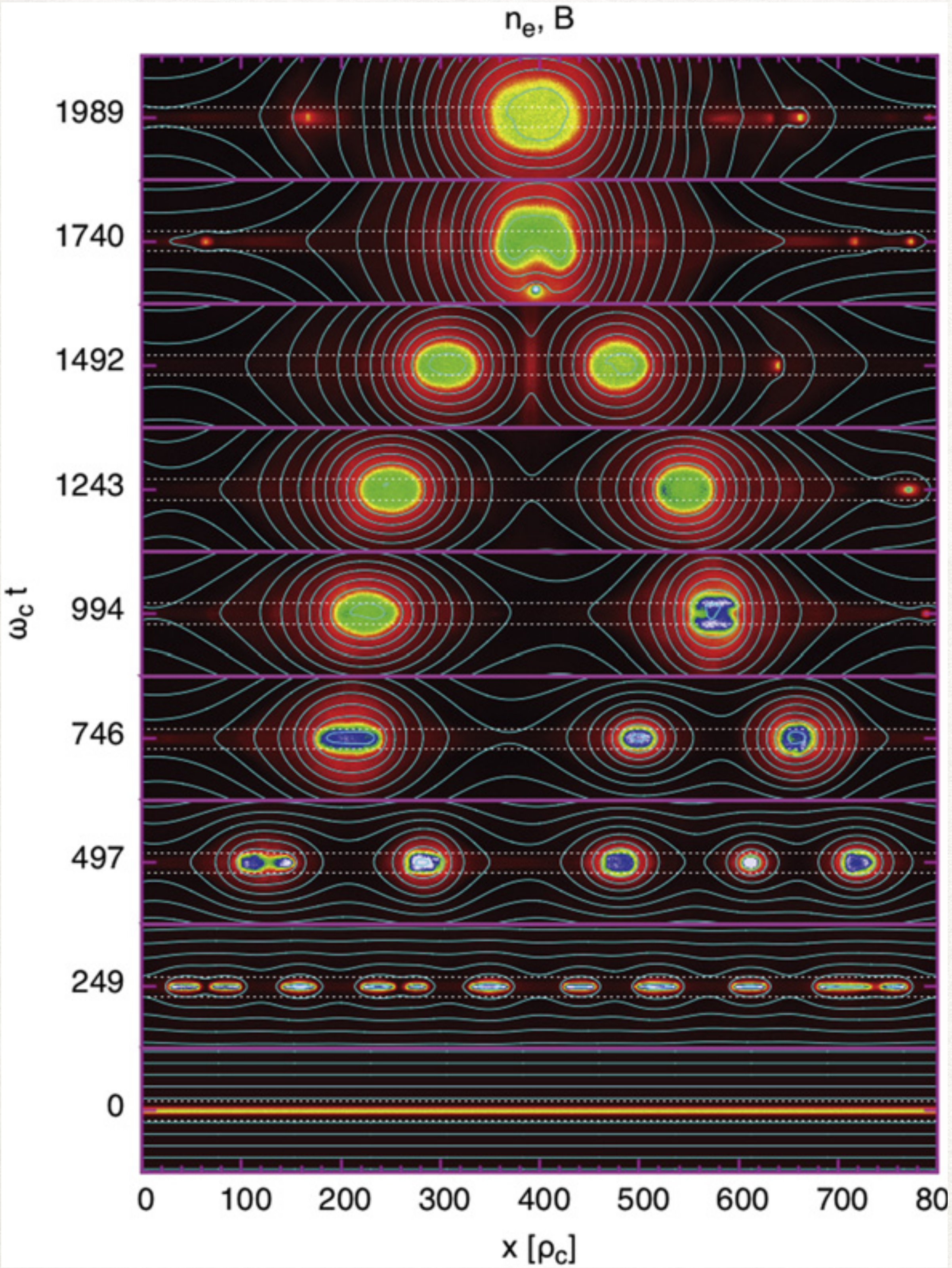
Guo et al. (2015)

second-order

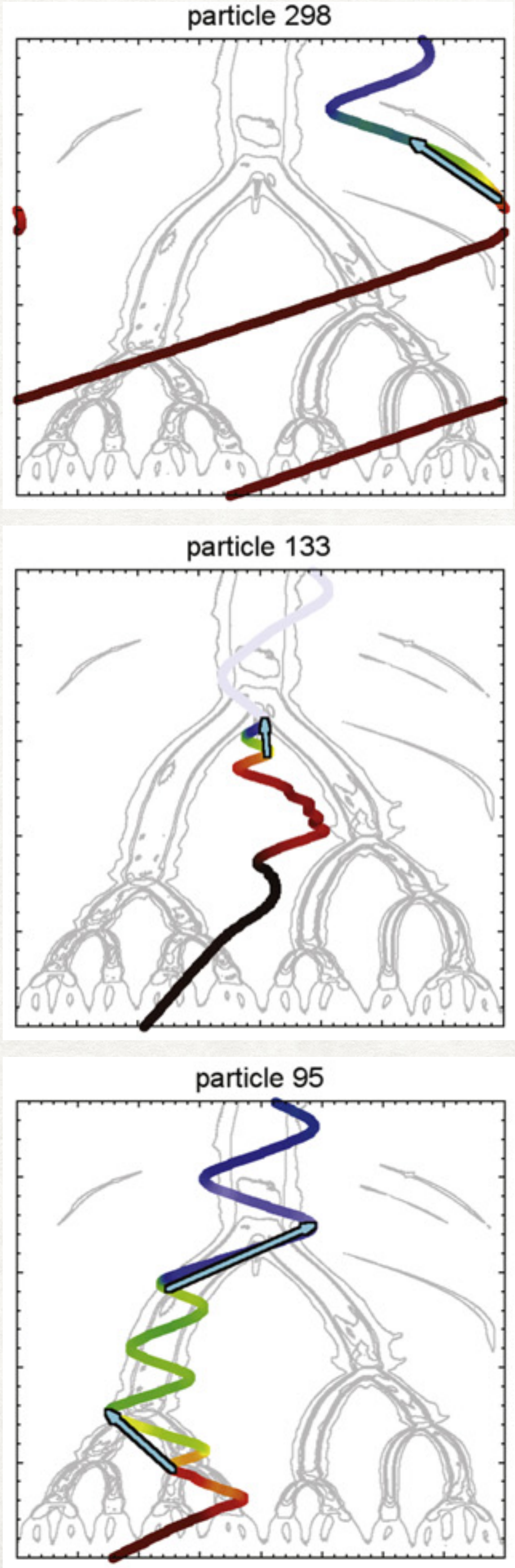


Hoshino (2012)

PARTICLE ACCELERATION SCENARIOS



KN, Uzdensky, Cerutti, Werner & Begelman (2015)



magnetic X-points

plasmoid mergers

within plasmoids

Particle acceleration sites

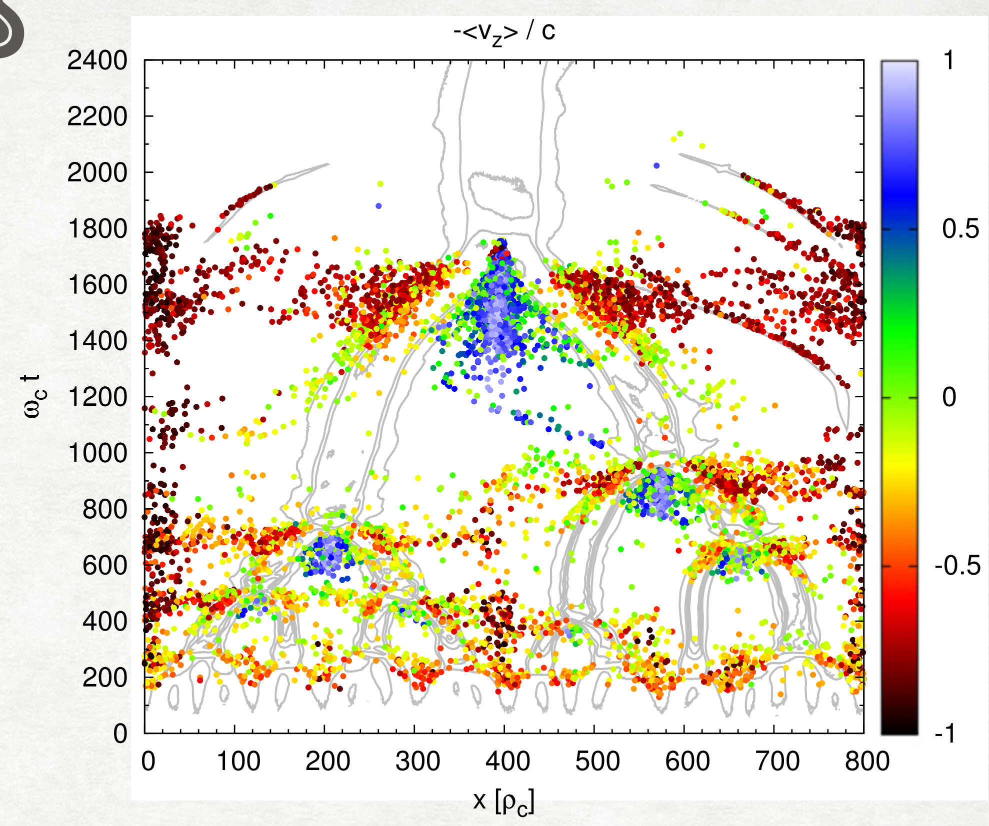
- **magnetic diffusion regions (X-points):**
  non-ideal E-fields (Zenitani & Hoshino 2001)
  most energetic particles pass through them
  (Sironi & Spitkovsky 2014)
  short interaction times (Guo et al. 2019)

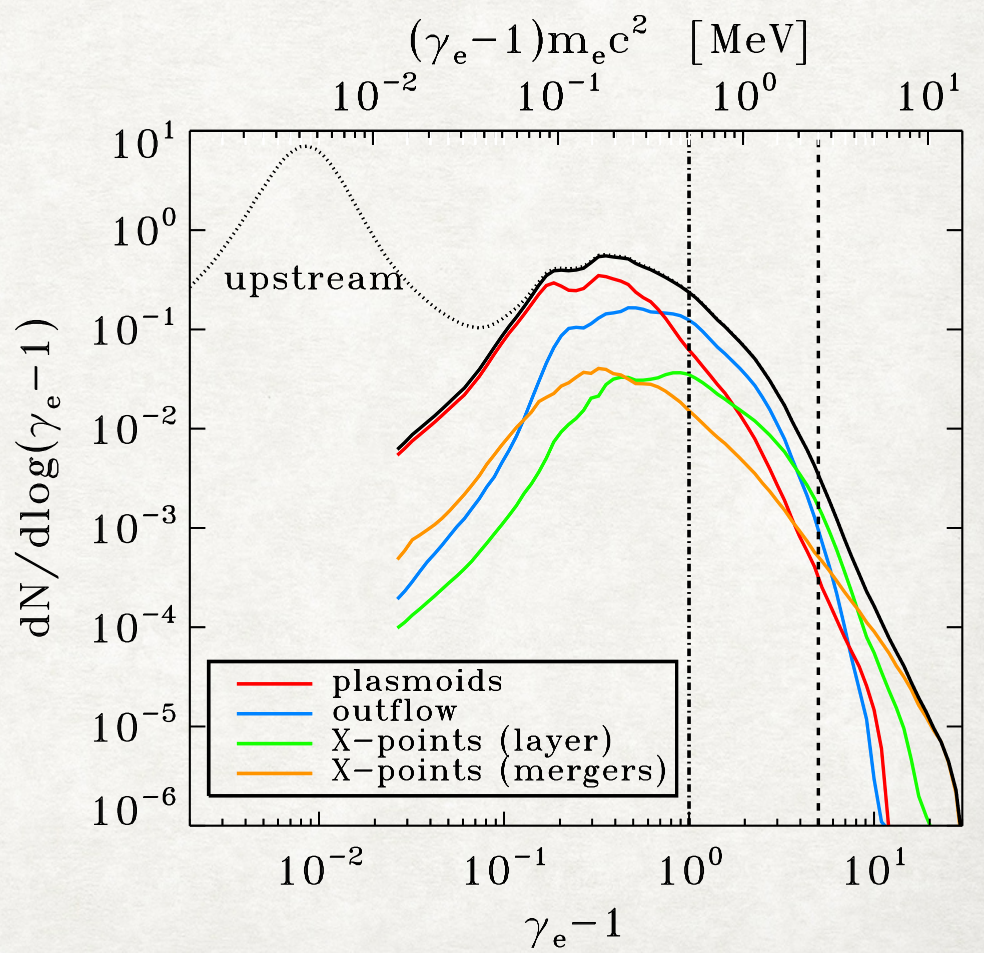
- **reconnection outflows (minijets):**
  Speiser orbits
  exceeding radiation reaction (Kirk 2004)
  low particle density

- **plasmoids:**
  converging magnetic mirror (Drake et al. 2006)
  compressed plasmoid cores (Petropoulou & Sironi 2018)
  particle traps (in 2D), high particle density
  relatively slow, imited by radiation reaction

- **plasmoid mergers:**
  secondary reconnection layers
  production of rapid and luminous flares
  (KN et al. 2015, Ortuño-Macías & KN 2020)

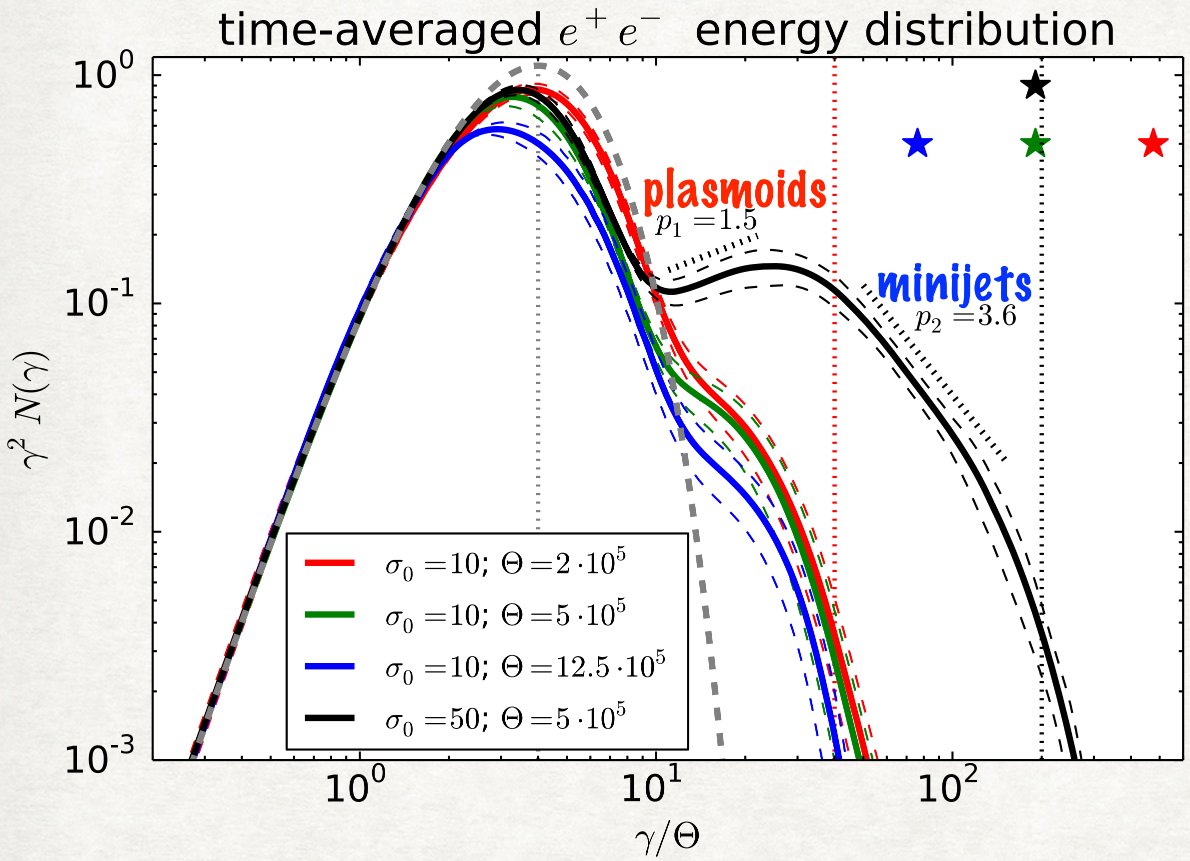
KN et al. (2015)

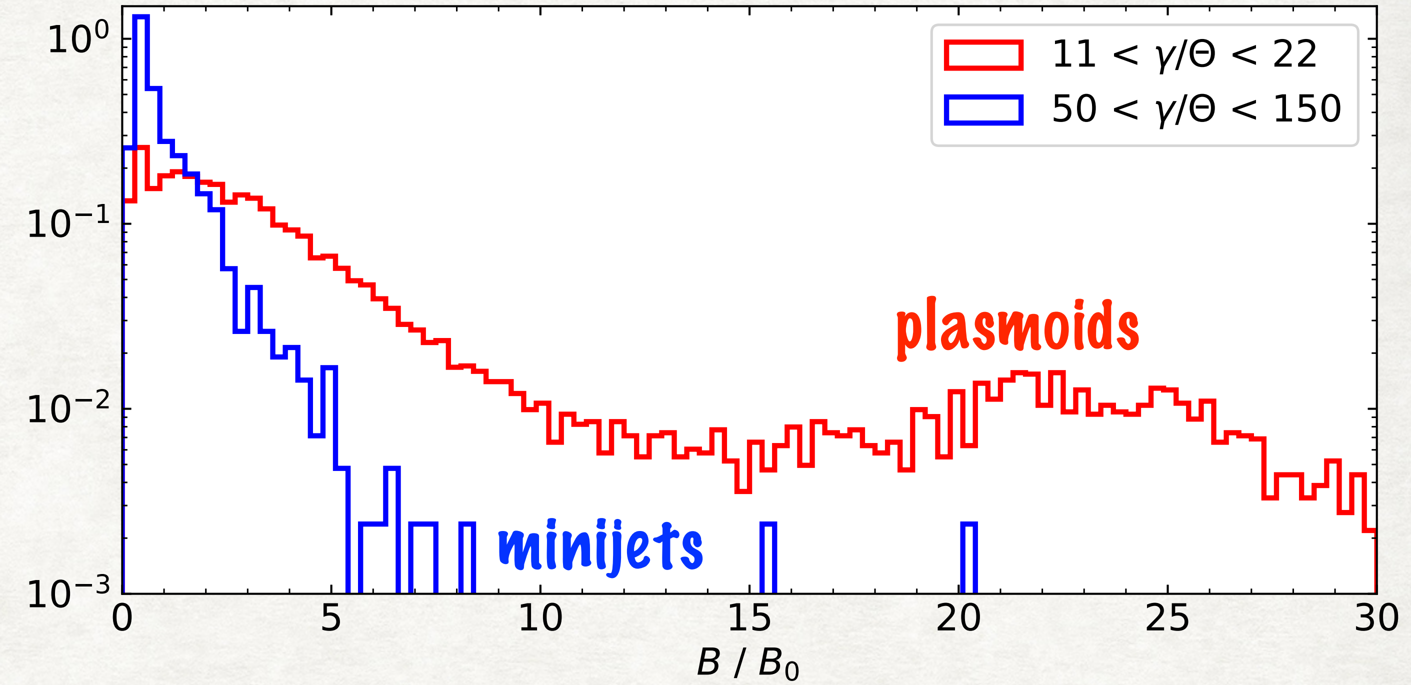


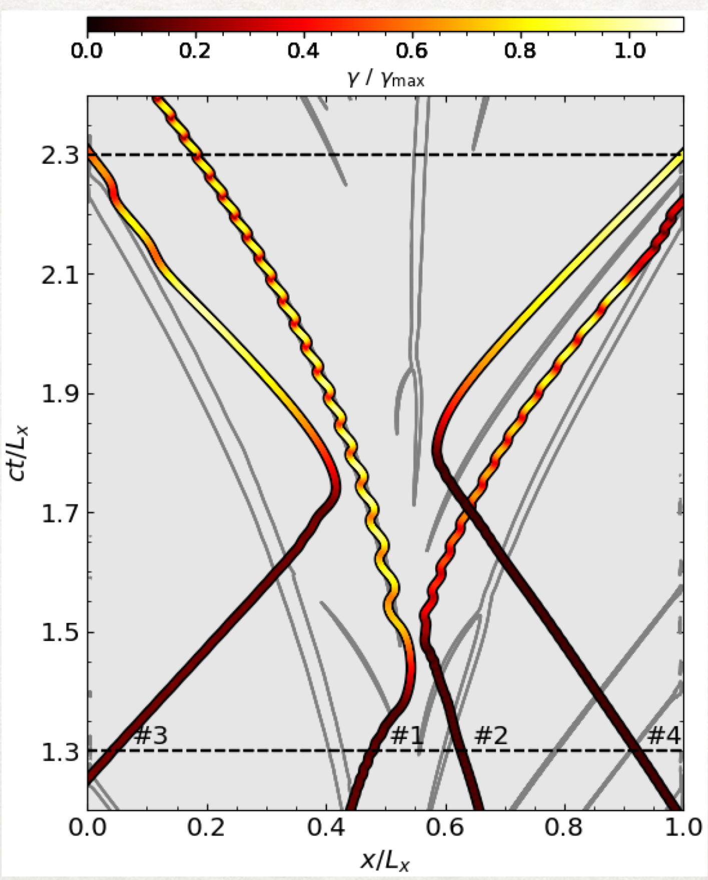


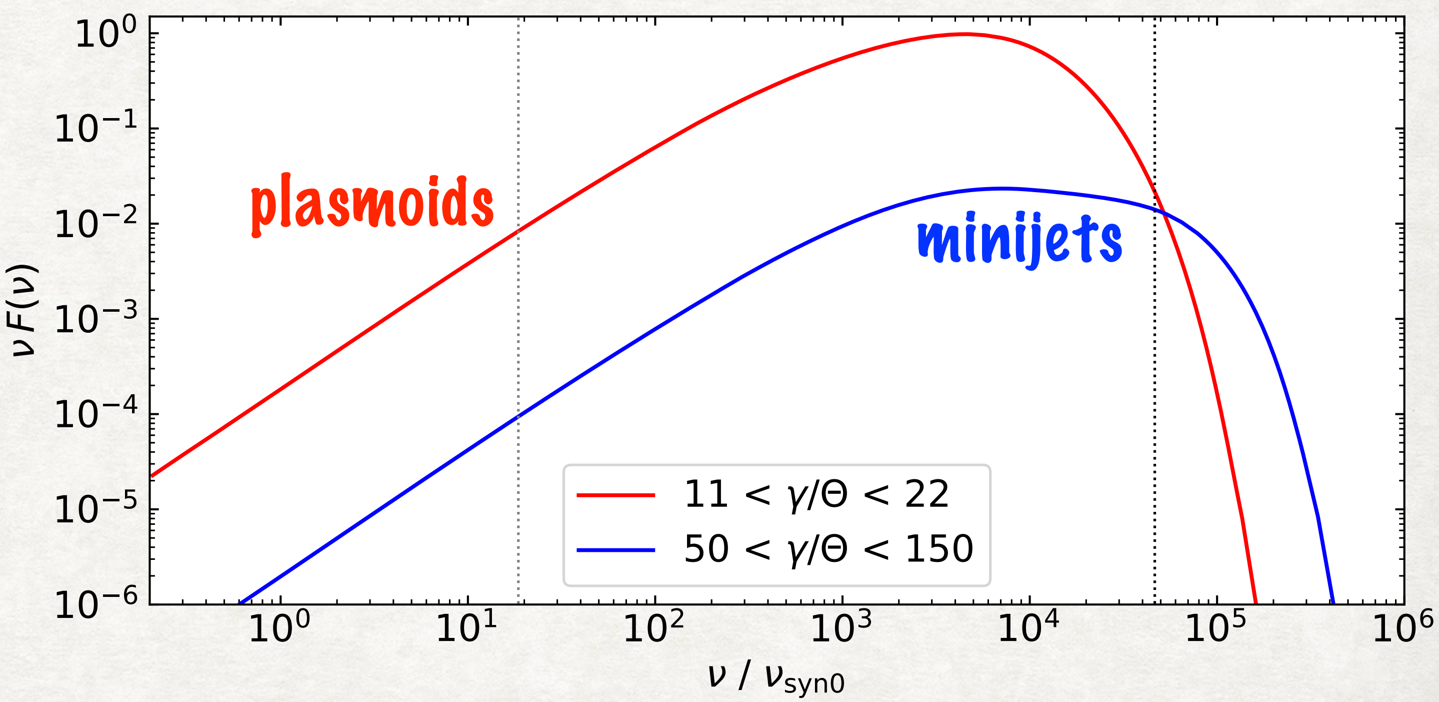
Sironi & Beloborodov (2020)

Particle acceleration: plasmoids vs minijets



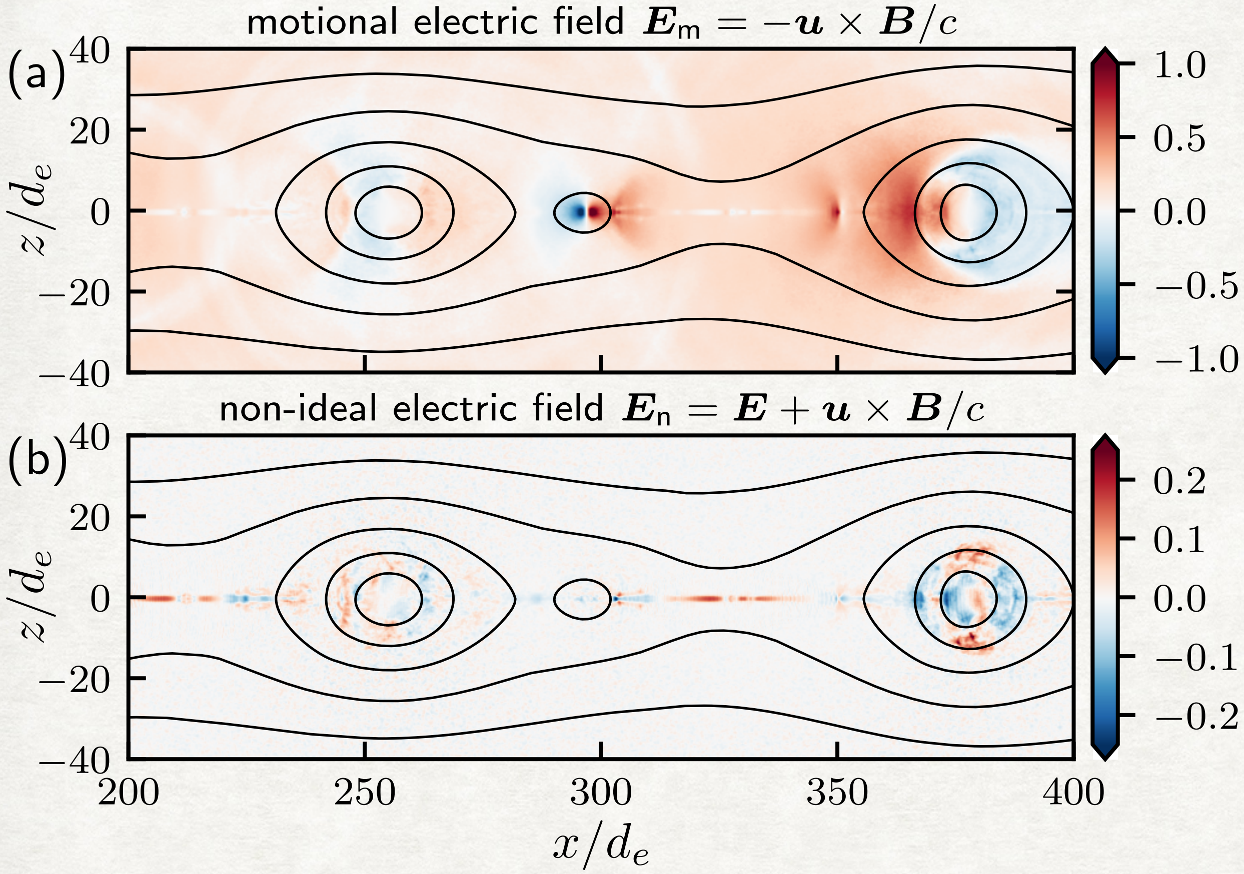


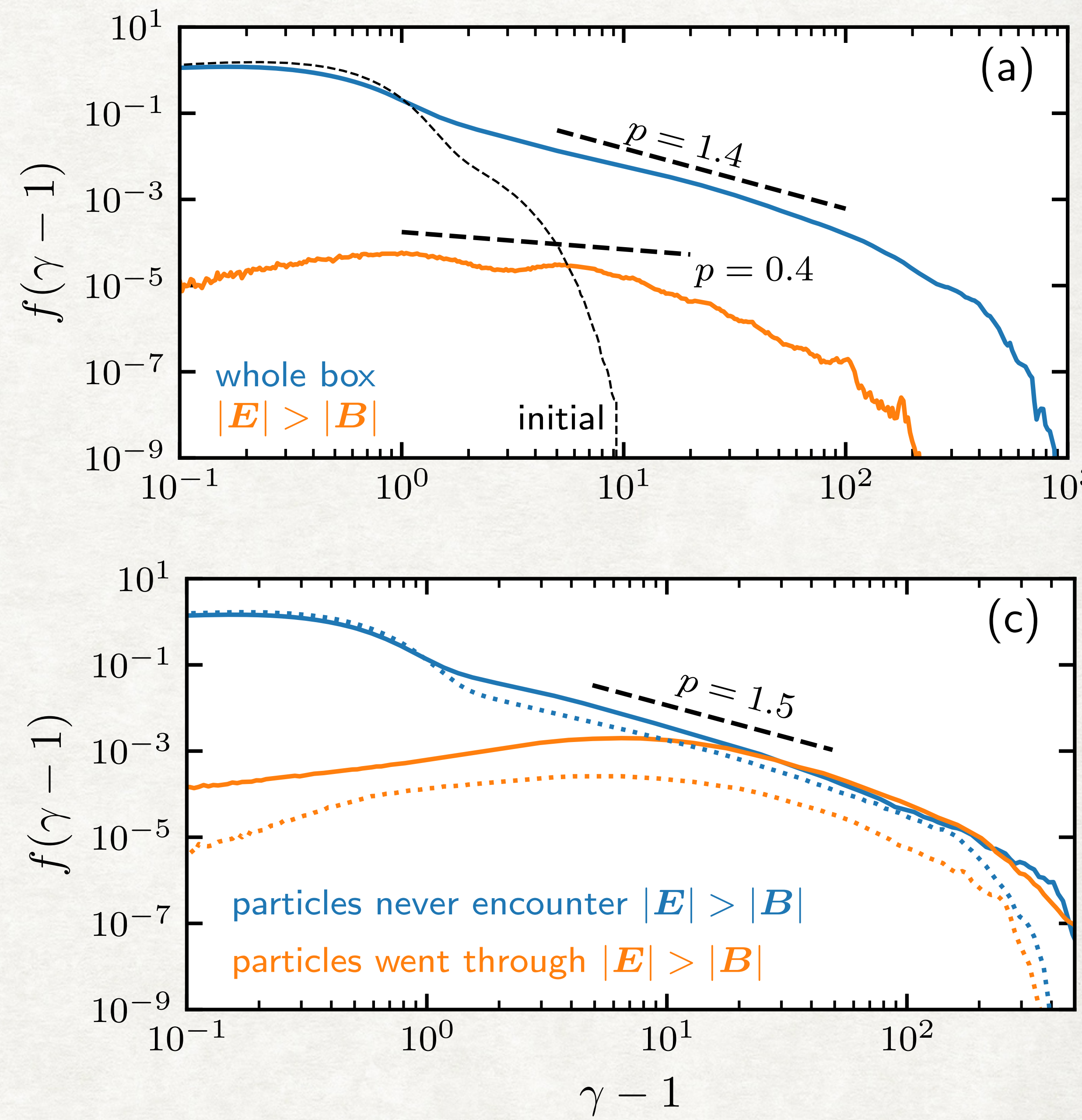


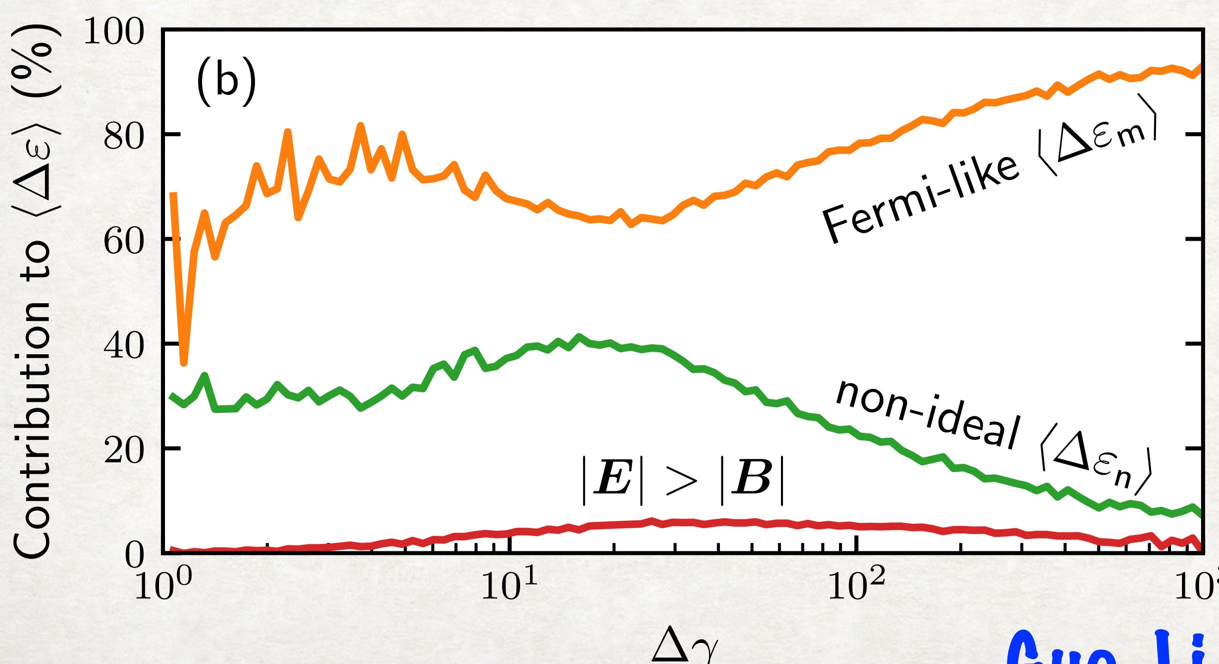


J. Ortuño-Macías & KN (2020)

Ideal vs. Non-Ideal Electric Field

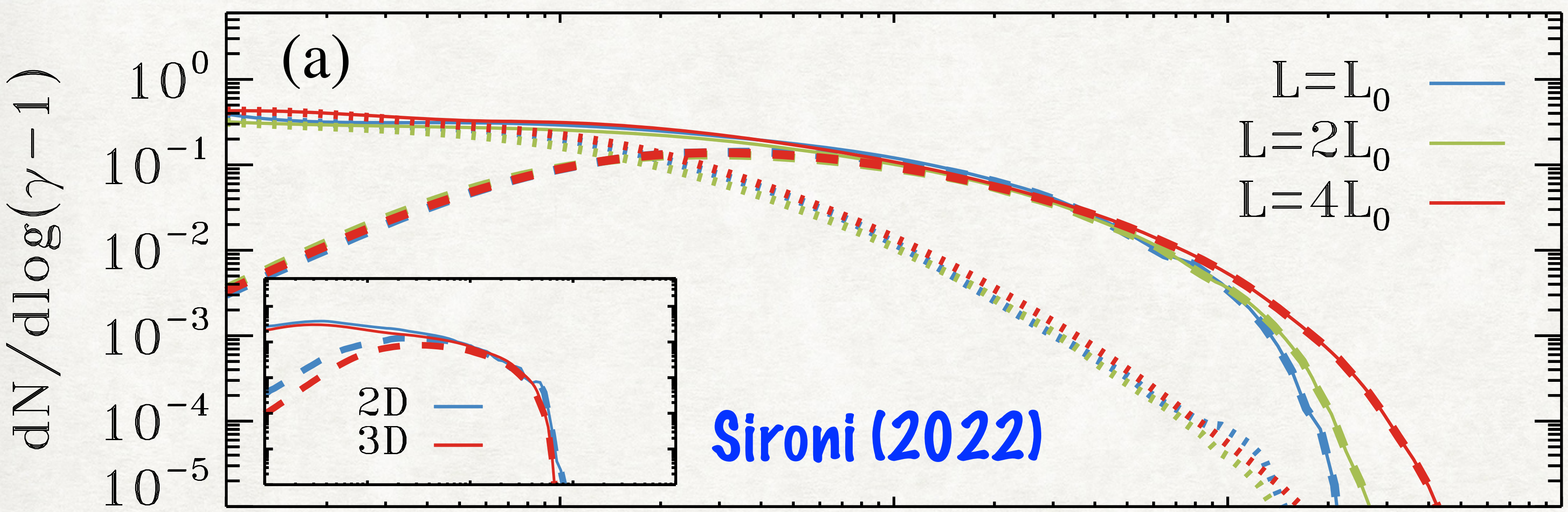






Guo, Li, Daughton, Kilian, Li, Liu, Yan & Ma (2019)

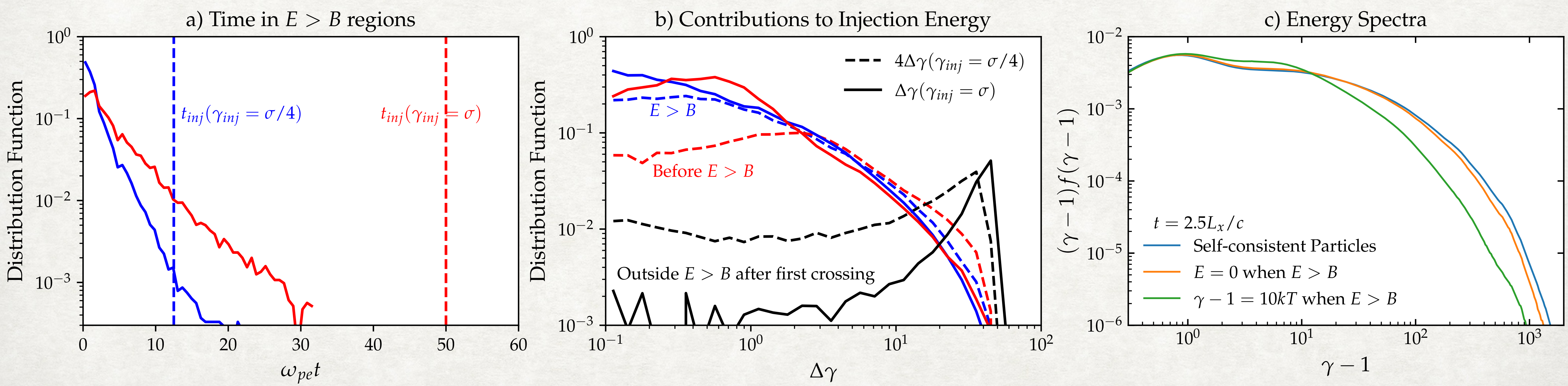
THE ROLE OF NON-IDEAL E-FIELD



dashed lines: particles that experienced E > B

dotted lines: particles that never experienced E > B

see also Gupta, Sridhar & Sironi (2025)



Guo et al. (2022)

Progress Since 2023

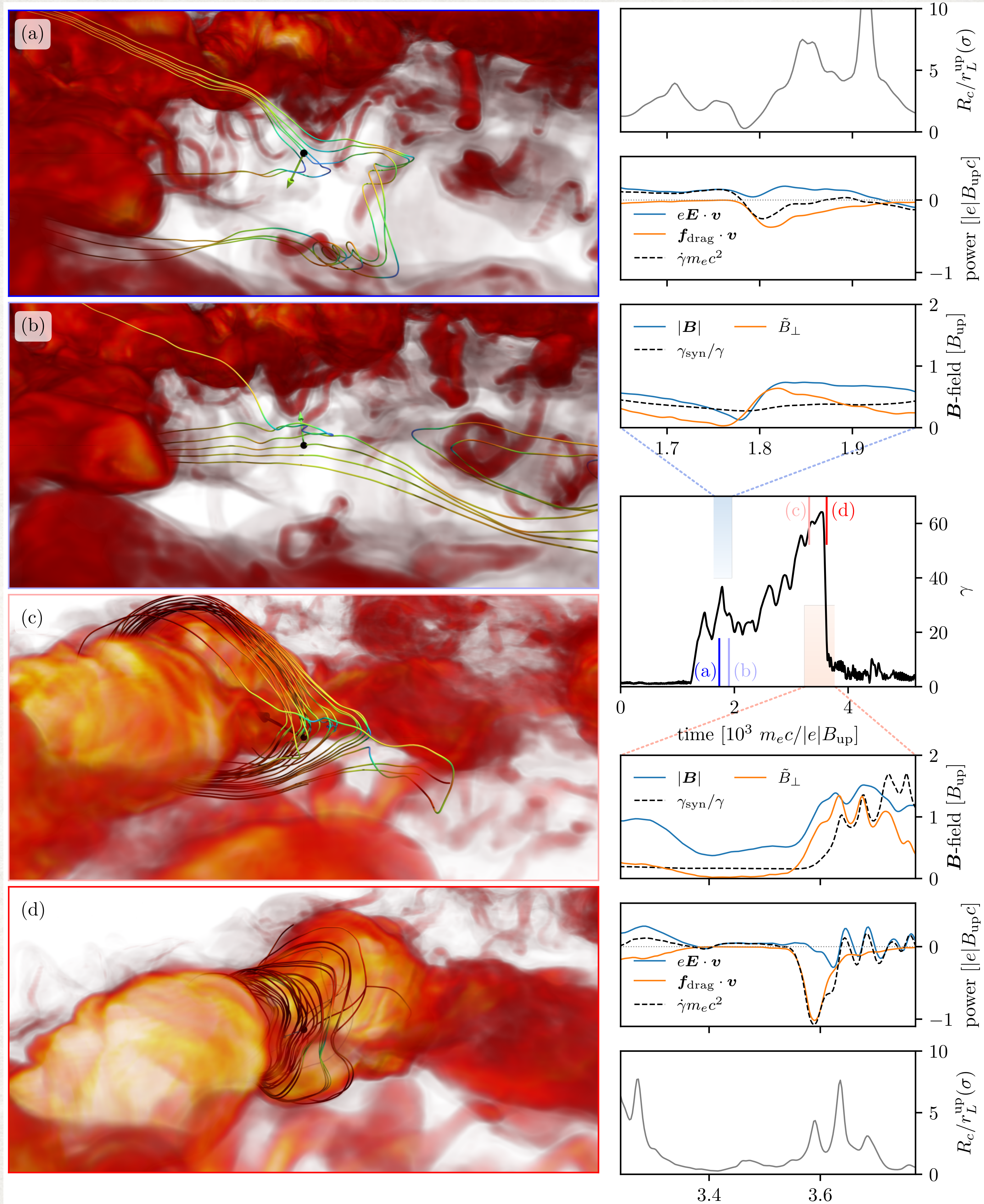
3D RECONNECTION WITH SYNCHROTRON COOLING

particle trapping in dense magnetic flux tubes:

- permanent in 2D
- temporary in 3D

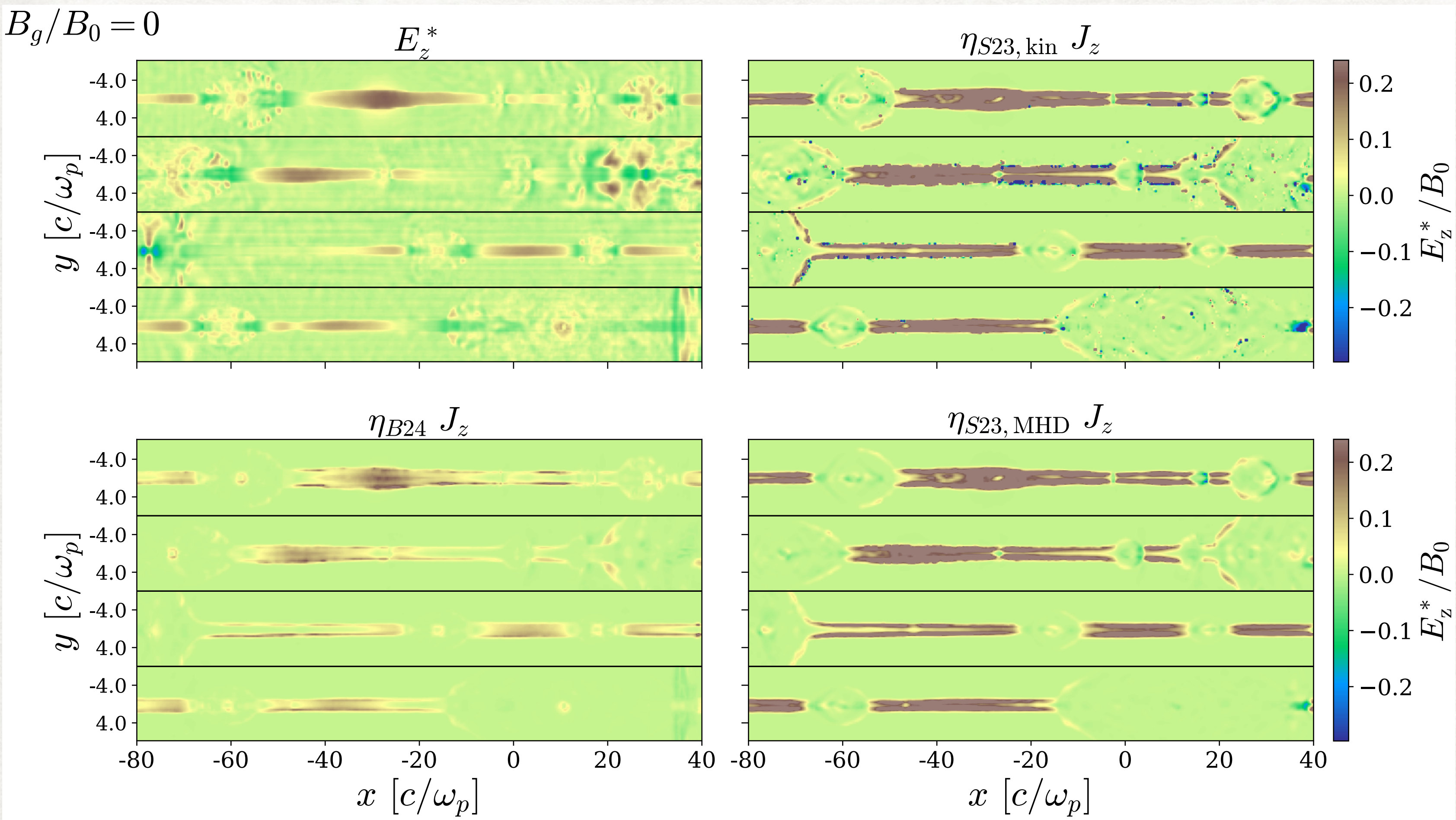
synchrotron cooling limits acceleration to low-$B_\perp$ regions

Chernoglazov, Hakobyan, & Philippov (2023)



see also:
Zhang, Sironi, Giannios & Petropoulou (2023)
Zhang, Guo, Daughton, Li & Li (2024)

Effective resistivity: PIC → MHD

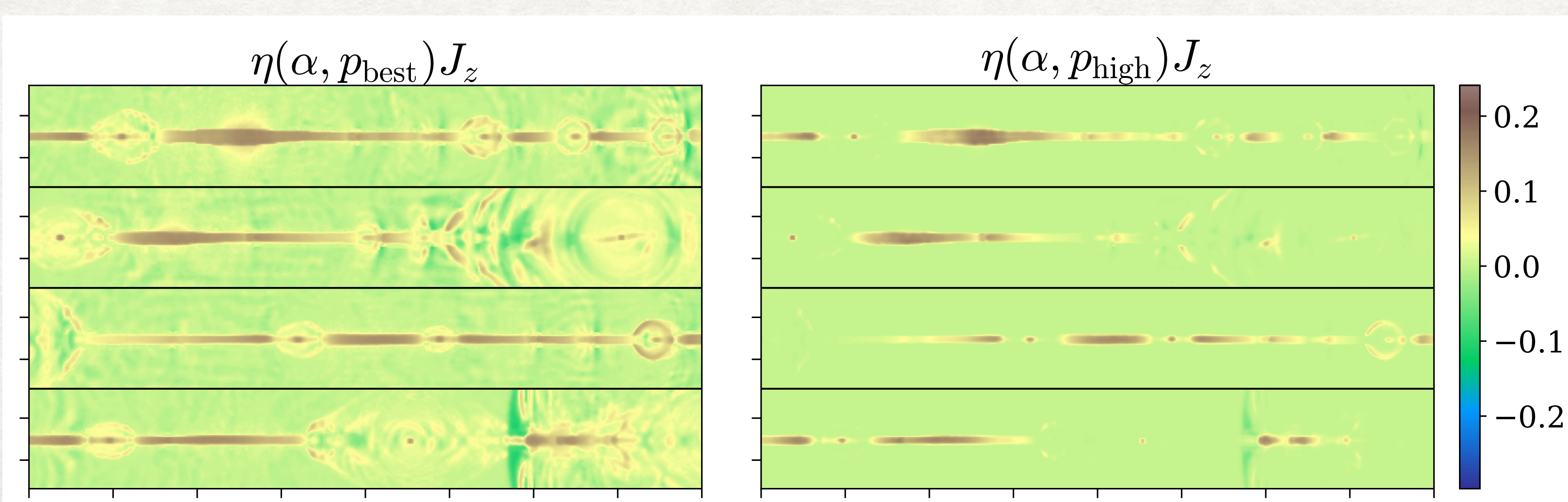


$$\eta_{S23,\mathrm{kin}} J_z = \left[\frac{m}{n_t e^2}\frac{\langle u_{ez}\rangle}{\langle v_{ez}\rangle}\partial_y \langle v_{ey}\rangle\right]$$

S23 = Selvi, Porth, Ripperda, Bacchini, Sironi & Keppens (2023)

$$\eta_{B24} = \frac{1}{e n_t c}\sqrt{\left(\frac{mc}{e}\partial_y v_y\right)^2 + (\Gamma E_z^*)^2}$$

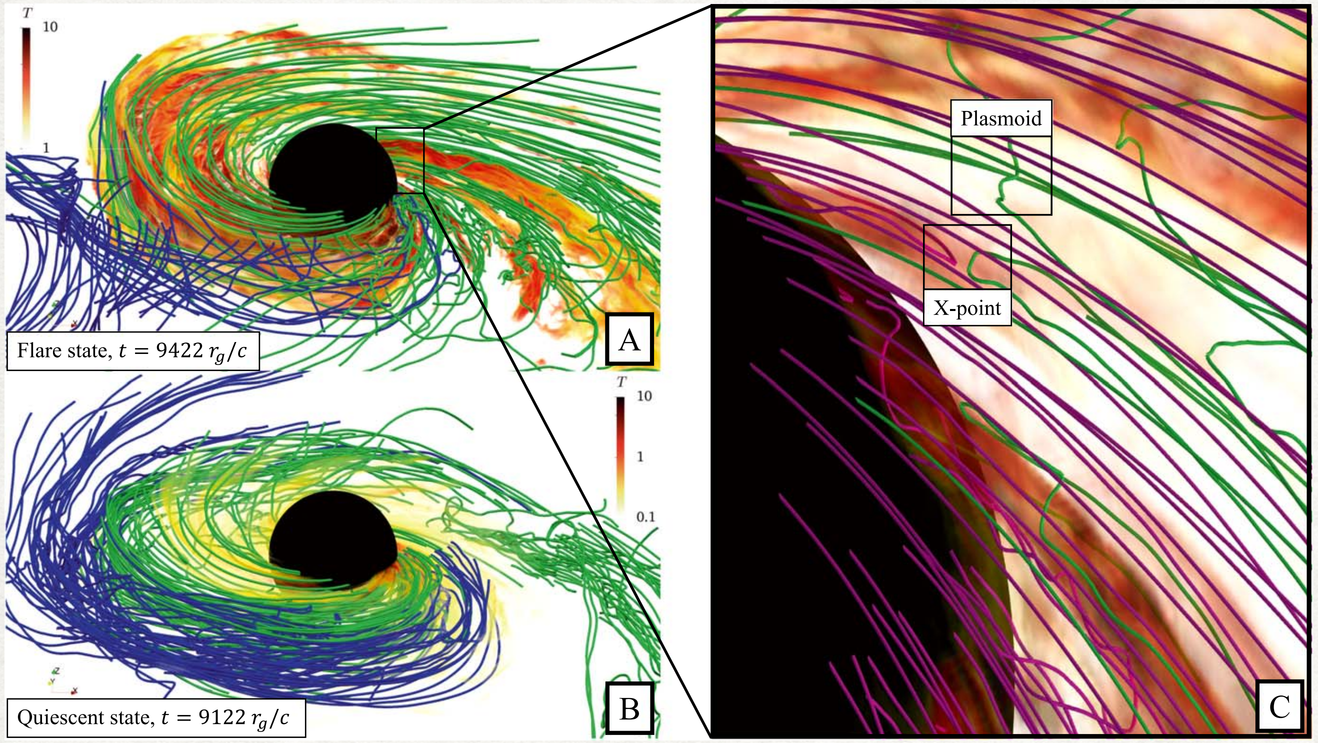
B24 = Bugli, Lopresti, Figueiredo, Mignone, Cerutti, Mattia, Del Zanna, Bodo & Berta (2024)



$$\eta_{\mathrm{eff}} = \frac{\alpha B_0}{|\mathbf{J}|\left[1 + (c/|\mathbf{v}_{dr}|)^{p+1}\right]}$$

Moran, Sironi, Levis, Ripperda, Most & Selvi (2025)

Reconnection by erupting (MAD) black holes

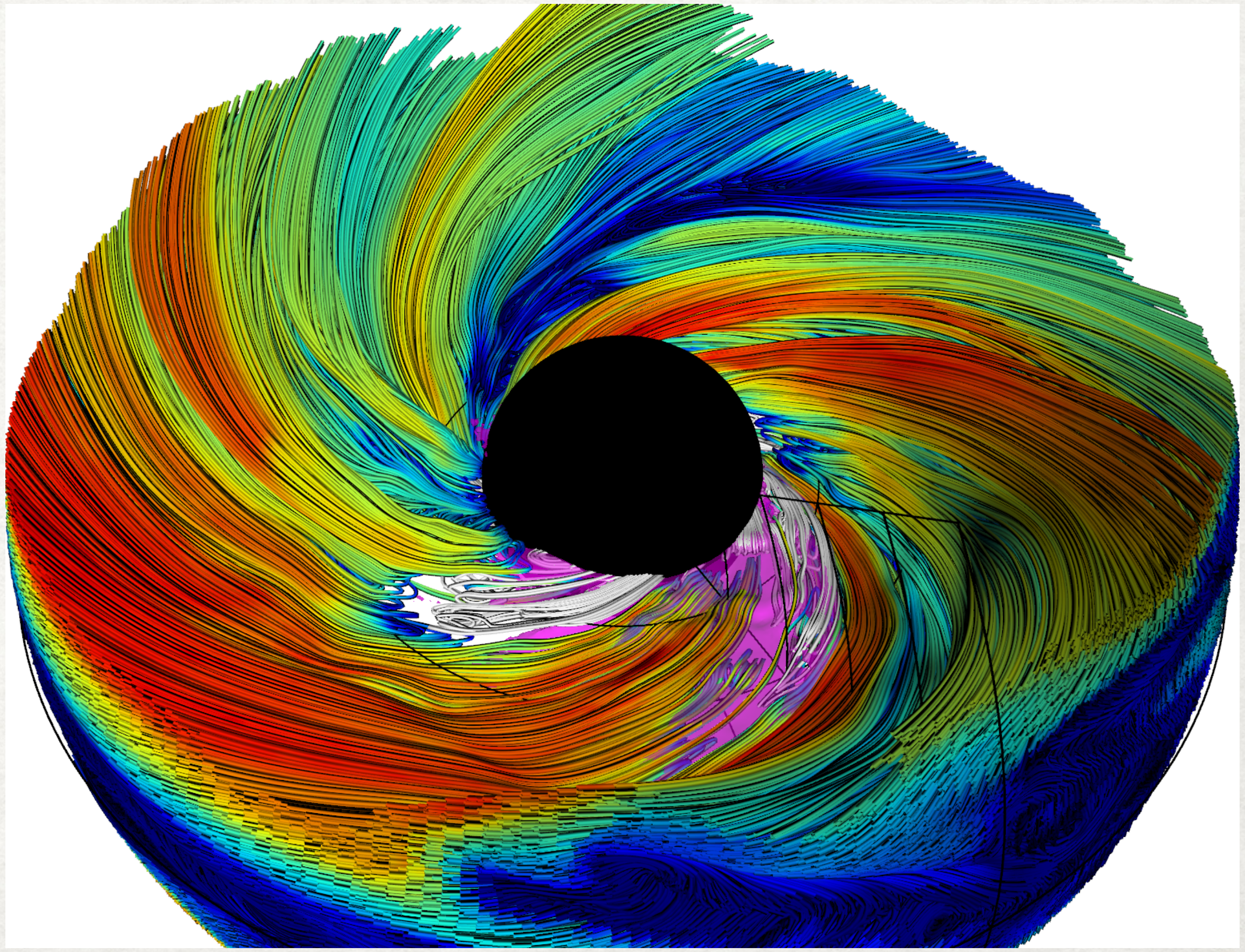


Ripperda, Liska, Chatterjee, Musoke, Philippov, Markoff, Tchekhovskoy, & Younsi (2022)

probably the best reconnection sites in the Universe (low guide field)

magenta: relativistically hot reconnection layer flattened along the equatorial plane

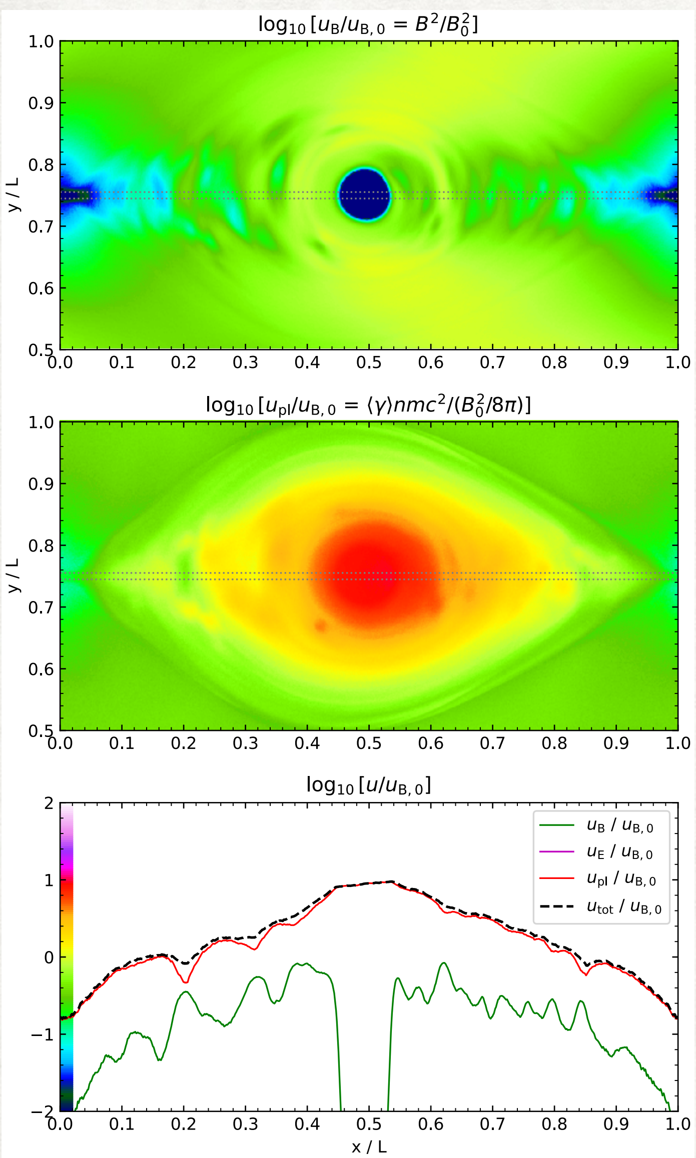
red: horizon-disconnected mass-depleted lines



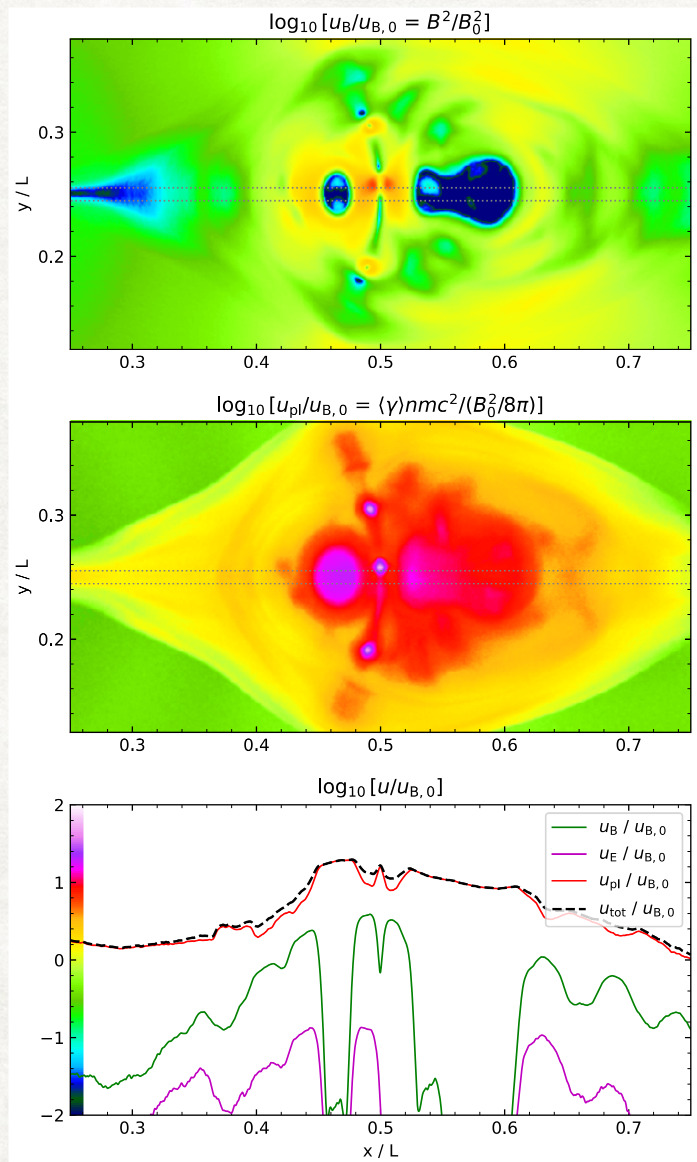
Nalewajko, Kapusta & Janiuk (2024)
POSTER

ENERGY DENSITY ENHANCEMENT BY MAGNETIC TENSION IN RECONNECTION PLASMOIDS

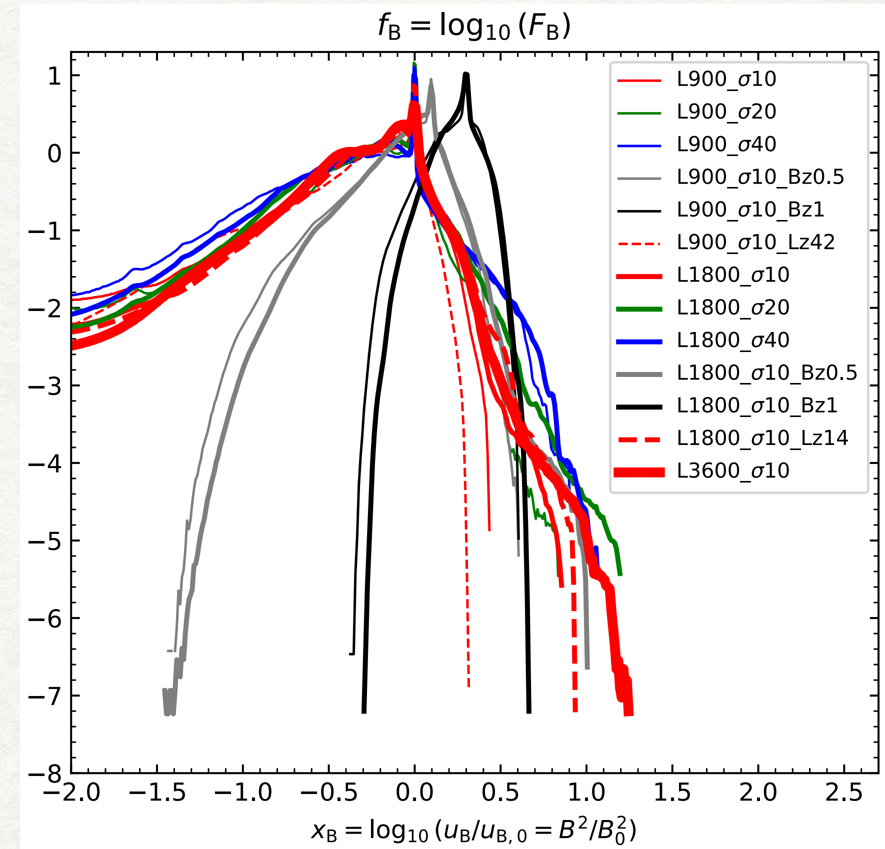
relaxed „monster” plasmoid



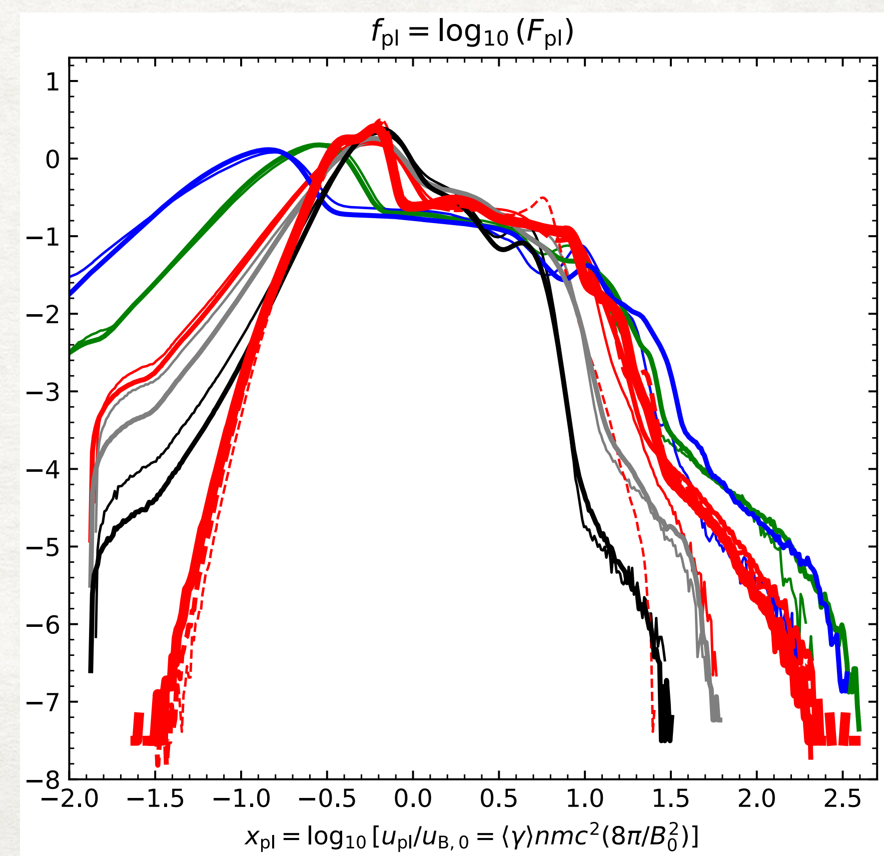
plasmoids merger



magnetic energy density



plasma energy density



Nalewajko (2025)

POSTER

SUMMARY

- Magnetic reconnection is a universal mechanism for dissipation of magnetic energy into motion, heat and non-thermal particles.

- In relativistically magnetized plasmas, for $\sigma = B^2/(4\pi w) \gg 1$, reconnection has been proven to be a very efficient mechanism of non-thermal particle acceleration, producing energy distributions $N(E) \propto E^{-p}$ with index $p \sim 1 - 2$.

- Particle acceleration in relativistic reconnection is a complex process, involving both ideal (motional) and non-ideal electric fields. The importance of non-ideal E-fields is debated. It has been described as a Fermi process.

- Reconnection layers develop substructures: X-points (diffusion regions), Alfvenic outflows (minijets), plasmoids (magnetic flux ropes). Particle acceleration can take place (1) between X-points and minijets (Speiser orbits), (2) between merging plasmoids, (3) within plasmoids (magnetic mirrors).

- 3D effects are important; low guide-field reconnection by erupting black holes; energy density enhancement.

Thank You!