THE UNIVERSITY OF TOKYO

Particle Acceleration during 3D Turbulent Magnetic Reconnection:

energy partitioning between thermal & nonthermal plasmas

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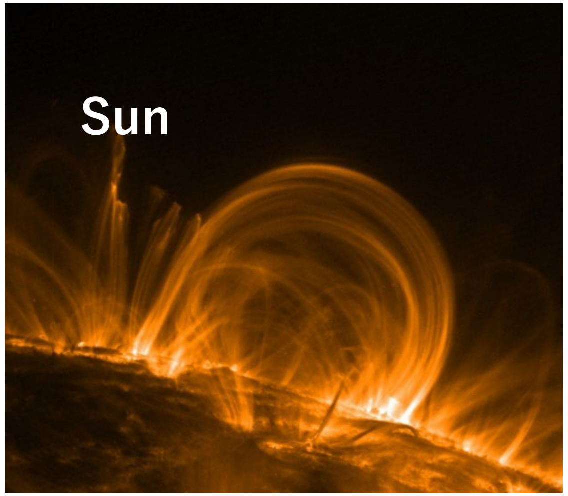
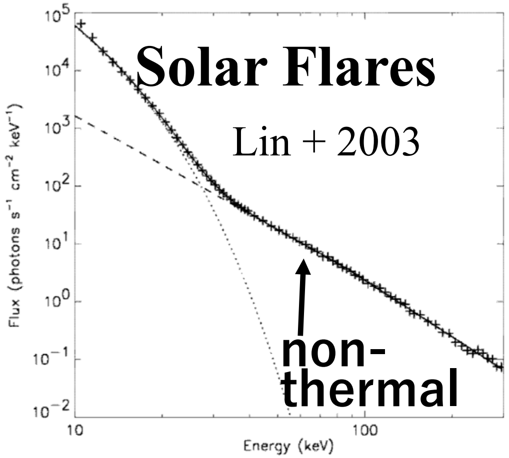
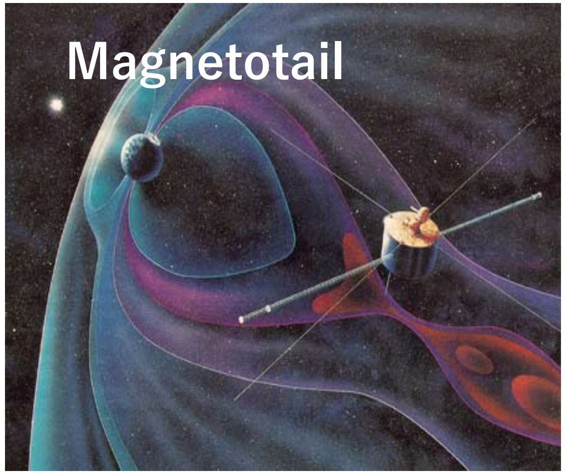
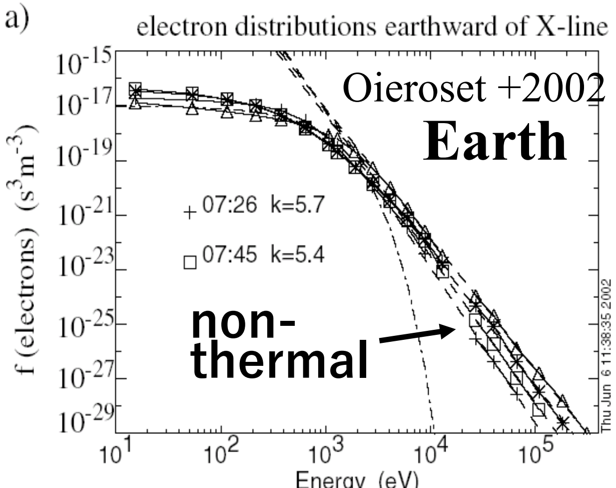
Magnetic Reconnection in Heliosphere

- Magnetic reconnection is the most plausible process of rapid magnetic energy dissipation
- Not only hot thermal plasma but also nonthermal particles are observed during reconnection in space such as Earth's magnetosphere, solar flares, etc.

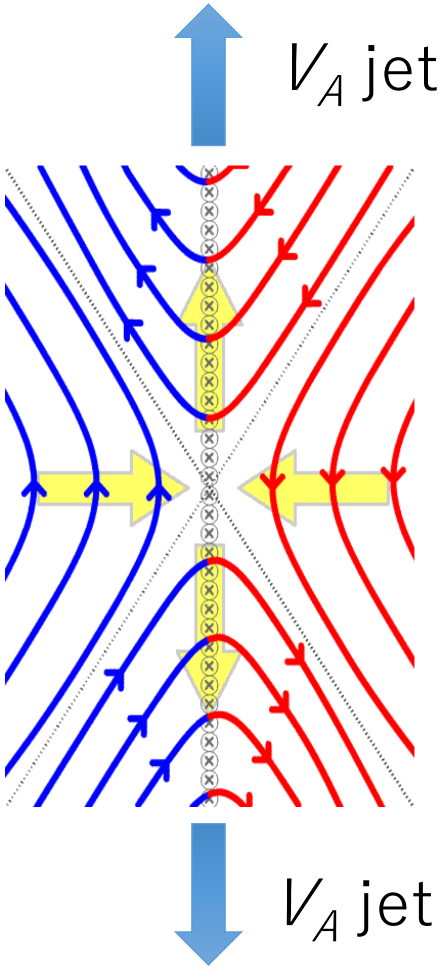








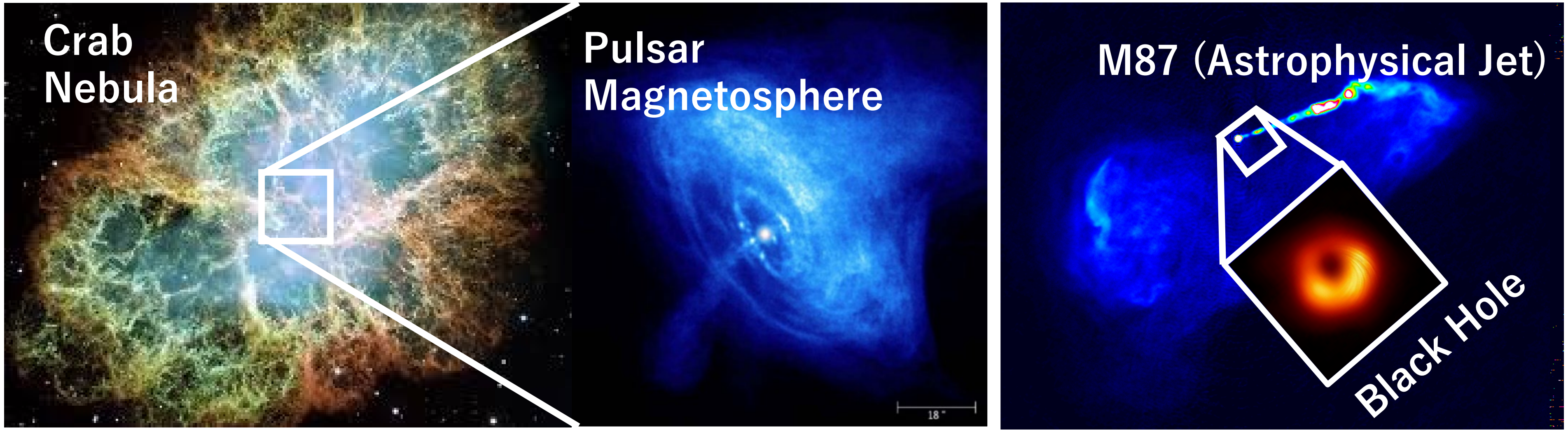
Hot & High-Speed jet



Giovaneli, Nature, 1949,
Sweet 1958, Parker 1957, Petschek 1964,
Furth, Killeen and Rosenbluth (FKR), 1964,…

Magnetic Reconnection in High Energy Plasma Universe

- Nonthermal particle acceleration is extremely efficient for high energy astrophysical objects such as pulsar magnetosphere, astrophysical jets etc.



magnetization parameter

$$\sigma \equiv B^2/(4\pi n(m_i + m_e)c^2)$$

Alfvén speed (V_A)

$$V_A/c = \sqrt{\sigma/(\sigma+1)} \approx 1 \quad for \;\; \sigma > 1$$

PIC simulation reveled the generation of hard energy spectrum in relativistic reconnection with σ>1

Zenitani &MH ApJL 2001; Sironi & Spitkovsky ApJL 2014; Guo+ ApJ 2014; Dahlin+ PoP 2017; ...

Open Questions:

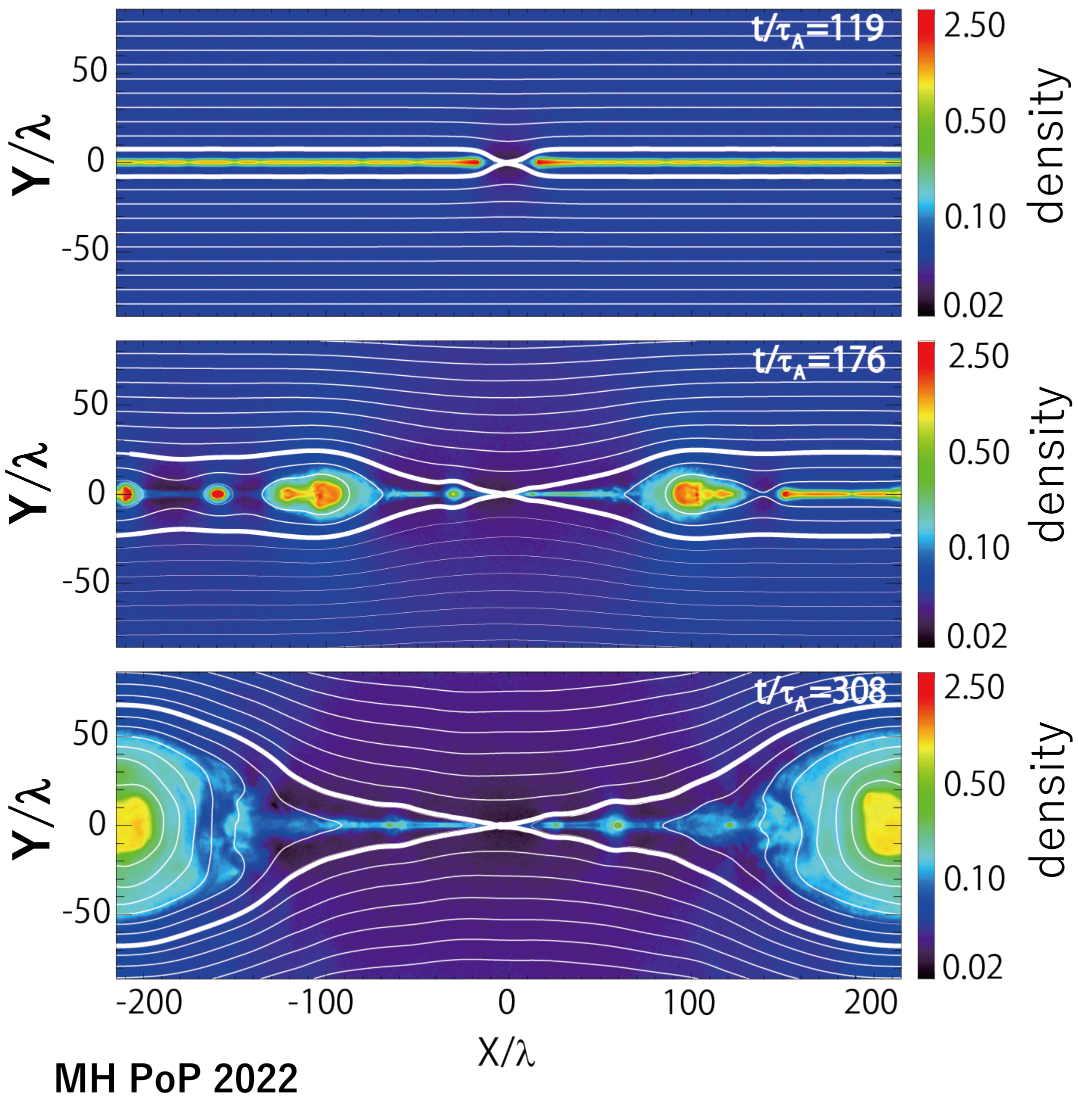
- **Relativistic reconnection efficiently generates non-thermal particles, whereas non-relativistic reconnection heats thermal plasma.**
- **However, the quantitative understanding of the energy partitioning between thermal and nonthermal plasma is poor.**
- **Efficiency of nonthermal particle acceleration as functions of plasma temperature T/mc^2 & guide magnetic field B_G**

(high Alfven speed ⇔ high temperature due to $B^2 = 8\pi NT$)

Reconnection in 2D-PIC Simulation

(pair plasma & Harris plasma sheet)

$T/mc^2 = 10^{-2}$ & B_G=0



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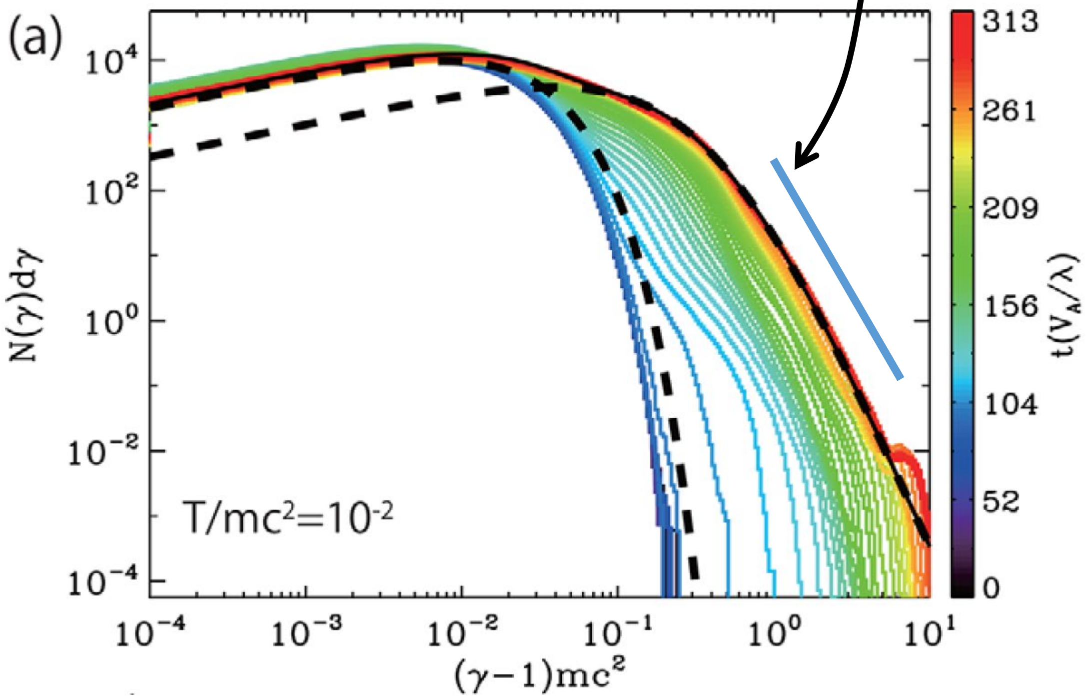
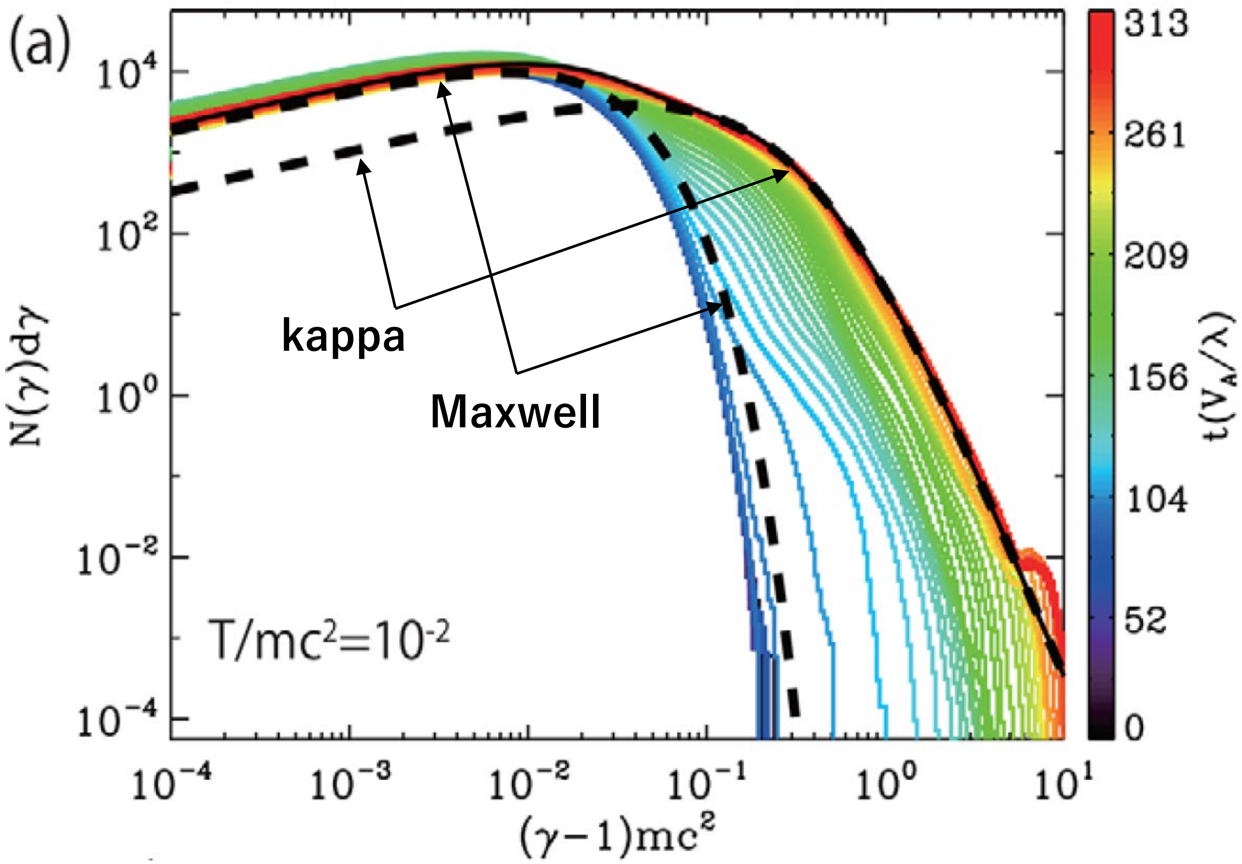
non-thermal particles, approximated by a power-law function

$N(\gamma) \propto \gamma^{-s}$



model fitting of nonthermal spectrum

Model fitting by “Maxwellian+kappa” function



1-D kappa distribution (T_κ, κ)

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

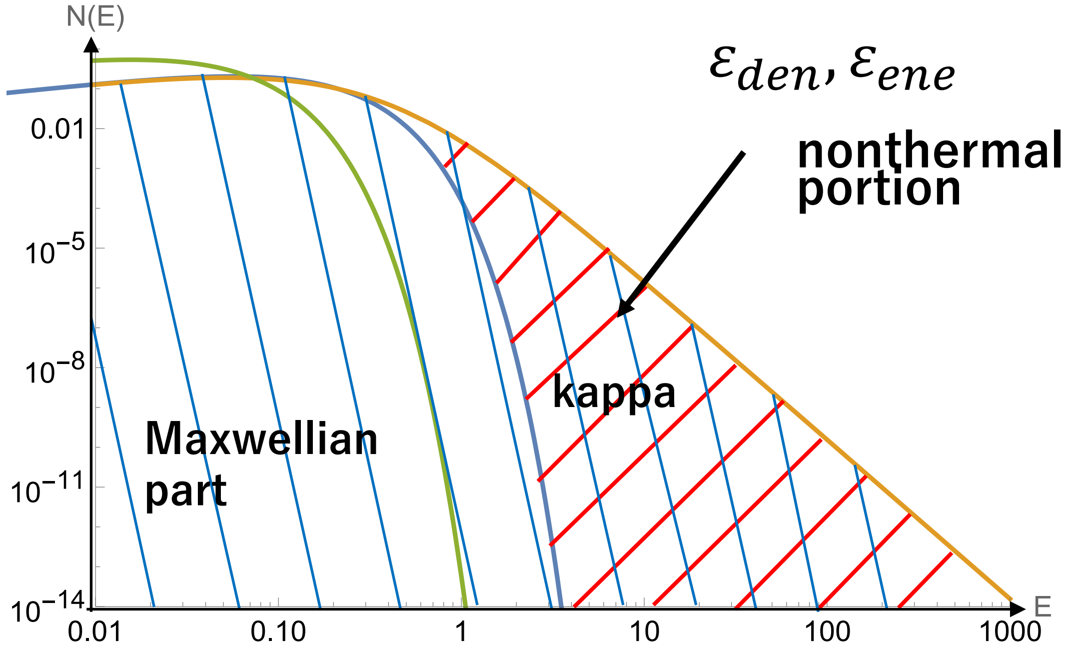
- kappa dist. consists of thermal Maxwellian & nonthermal power law part
- If $\kappa \rightarrow \infty$, kappa dist. becomes Maxwellian
- non-extensive statistical mechanics gives the theoretical basis for κ-dist. function by Tsallis (1998)

1-D Maxwell distribution (T_M)

$$N_M(\gamma) \propto \gamma\sqrt{\gamma^2 - 1}\ \exp\left(-\frac{\gamma - 1}{T_M/mc^2}\right)$$

this model fitting of (Maxwell + kappa) is very good !!

nonthermal number density and energy density



1-D kappa distribution (T_κ, κ)

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

1-D Maxwell distribution (T_M)

$$N_M(\gamma) \propto \gamma\sqrt{\gamma^2 - 1}\ \exp\!\left(-\frac{\gamma - 1}{T_M/mc^2}\right)$$

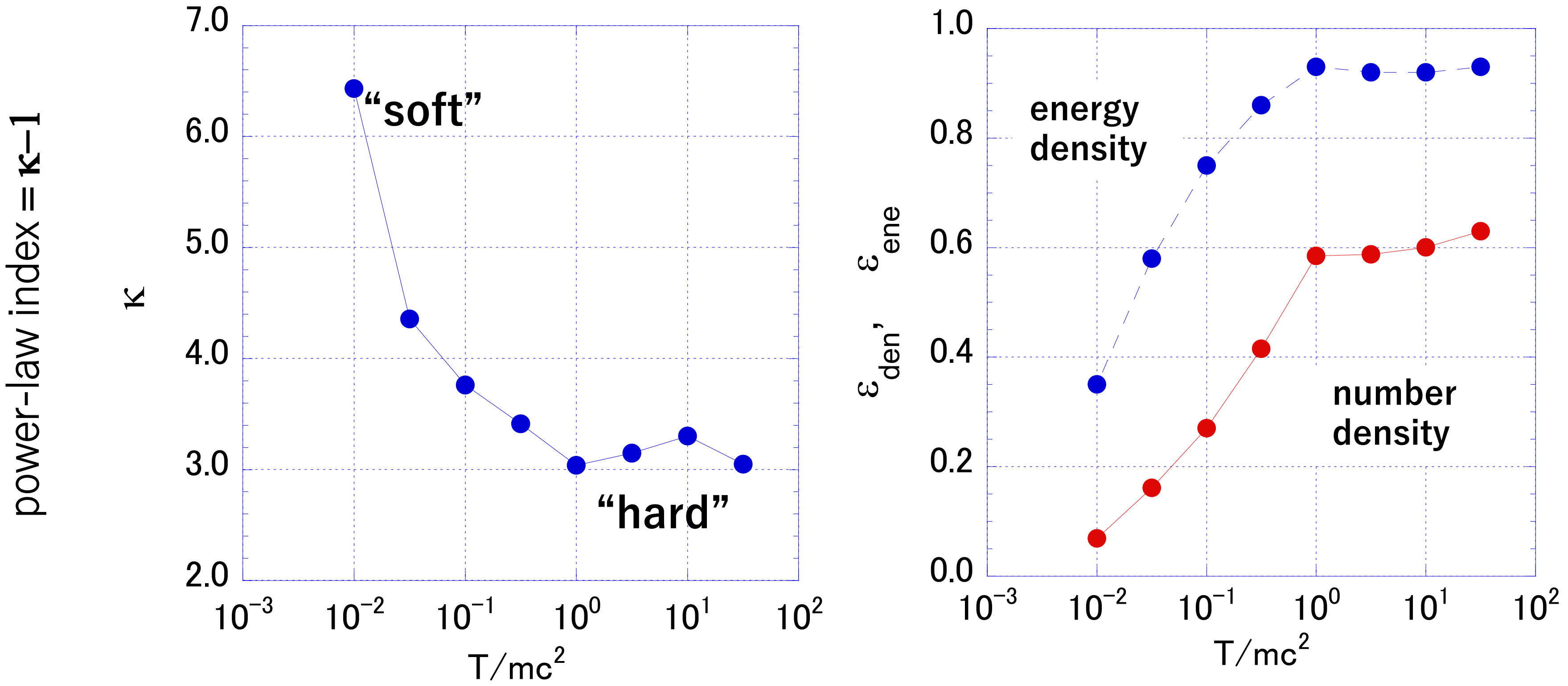
efficiency of nonthermal number/energy density

$$\varepsilon \equiv \frac{nonthermal\ portion\ (red)}{Maxwell\,(green) + kappa\ (blue)}$$

Acceleration efficiency as function of T/mc² $(B_G = 0)$

kappa part

$$N_\kappa(\gamma) \propto \gamma^2 \beta \left(1 + \frac{\gamma - 1}{\kappa T_\kappa / mc^2}\right)^{-\kappa-1}$$



- soft spectrum for non-relativistic reconnection
- high efficiency of nonthermal acceleration for relativistic reconnection

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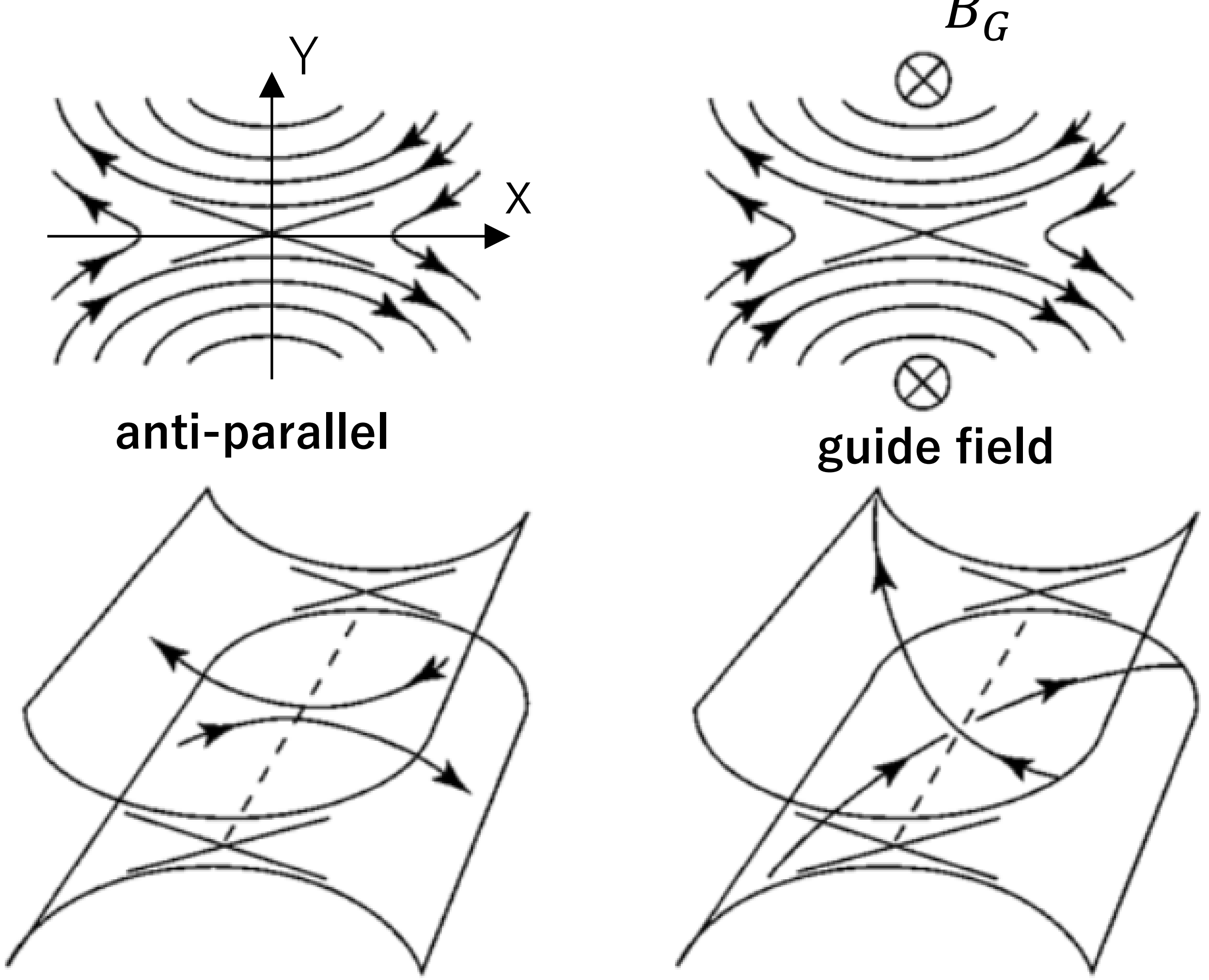
3D geometry of guide magnetic field reconnection $(\boldsymbol{B_G \neq 0})$



$$\vec{B}\,(x,y) = \nabla \times A_z(x,y)\vec{e}_z + B_G(x,y)\vec{e}_z$$

Anti-parallel reconnection $(B_G = 0)$

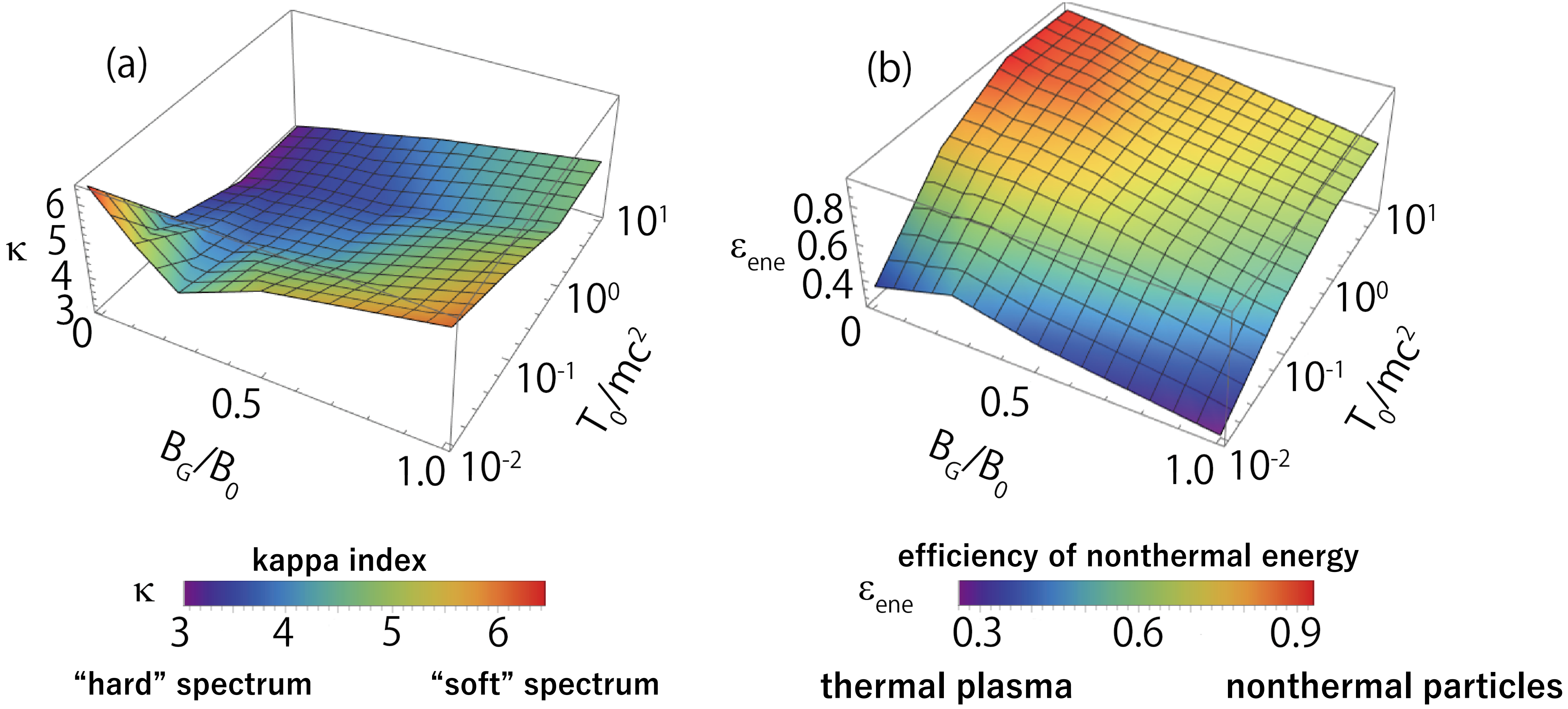
linear growth rate is fast
(order of Alfven transit time)

Guide-field reconnection $(B_G \neq 0)$

linear growth rate is slow
$\Gamma_{B_G \neq 0}/\Gamma_{B_G = 0} \approx \sqrt{r_g/\lambda}\left(\frac{B_0}{B_G}\right)$,
because collisionless/inertia
conductivity is high at X-point

Galeev ＆Zeleny JETP 1977; Drake & Lee PRL 1977; Cpppi+ PRL 1979; Quest & Coroniti JGR 1982; MH JGR 1987;..

Effects of Guide Magnetic Field & Plasma Temperature



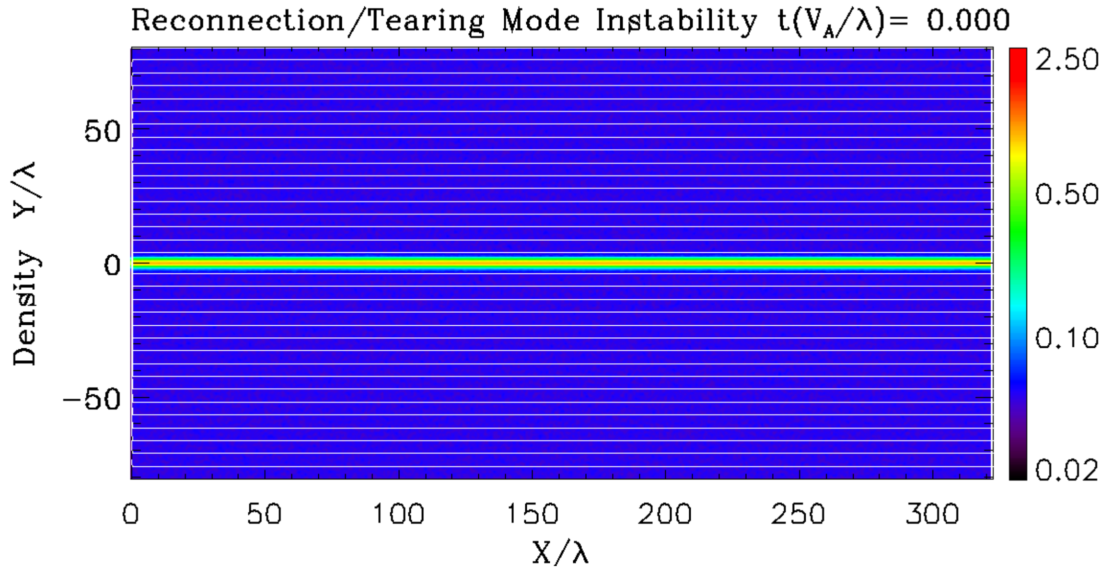
MH ApJ 2023

2D vs 3D Reconnection

cf. Daughton+ 2011

$B_G/B_0 = 1$ & $T/mc^2 = 1$

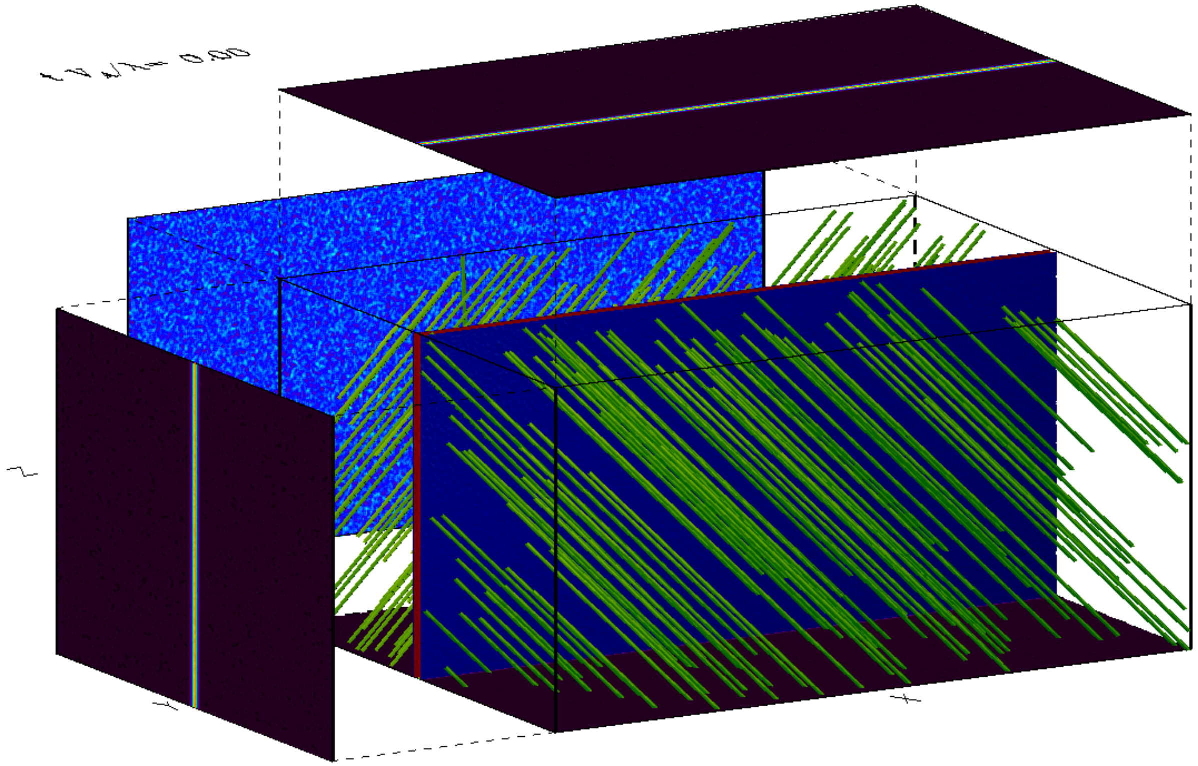
2D reconnection



density (color contour)
magnetic field lines (while)

laminar island

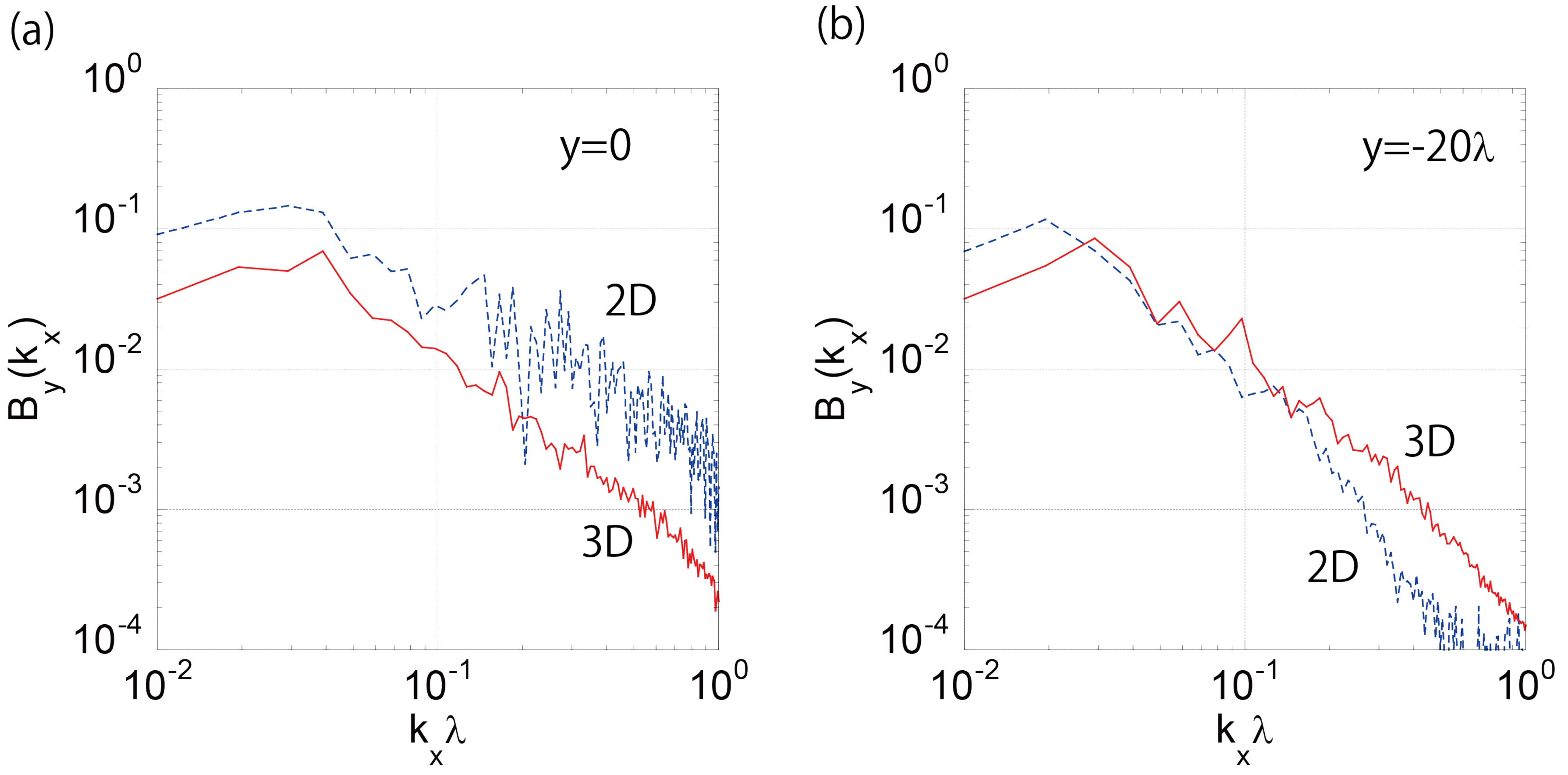
3D reconnection



magnetic field lines (green)

patchy reconnection/turbulent

$$B_G/B_0 = 1$$

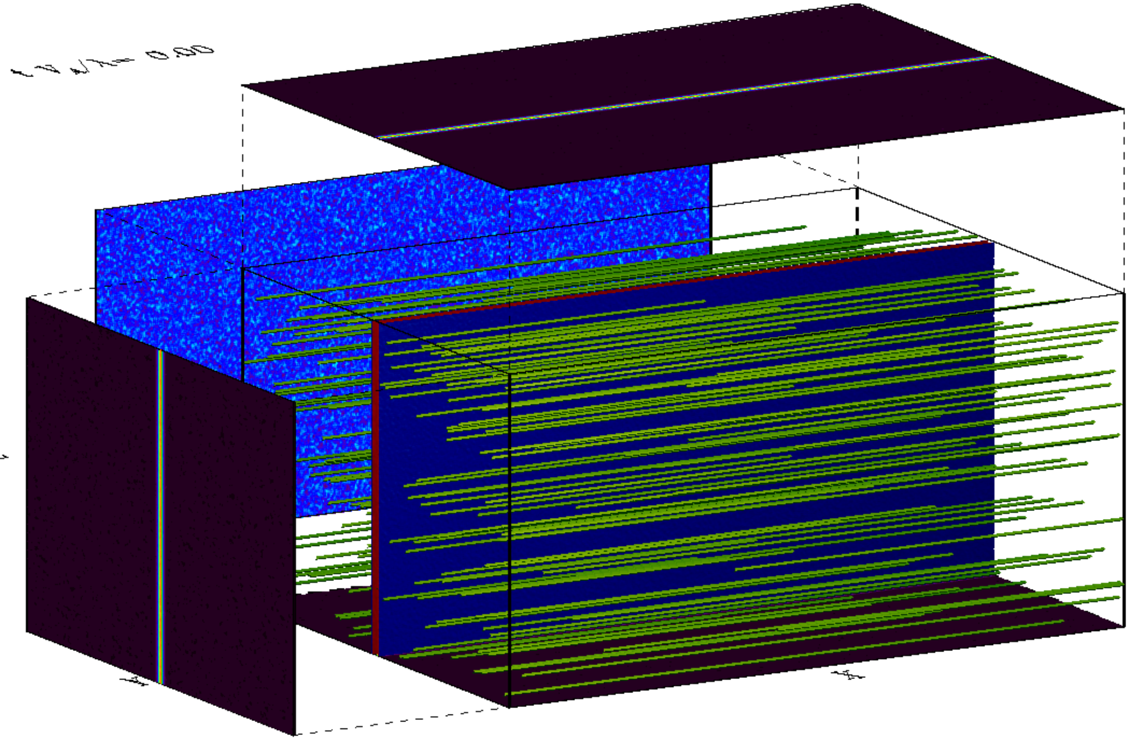


neutral sheet

edge of plasma sheet

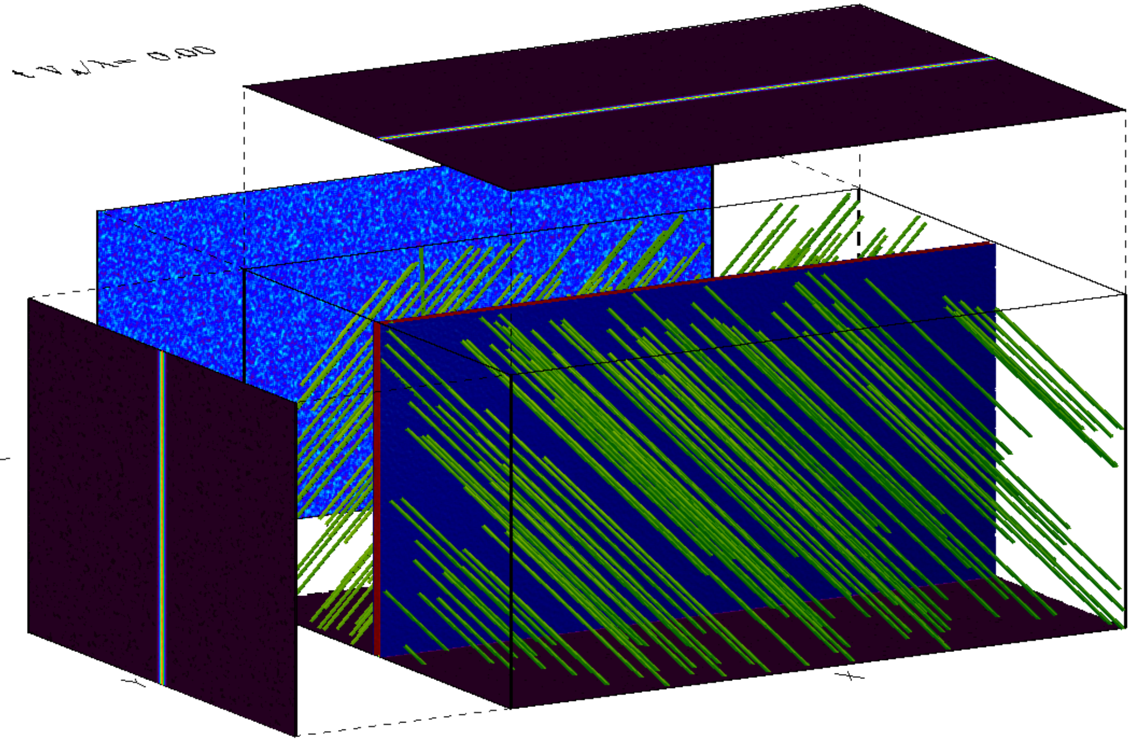
3D reconnections w/ & w/o guide field

$B_G/B_0 = 0$



laminar island

$B_G/B_0 = 1$



patchy reconnection/turbulent

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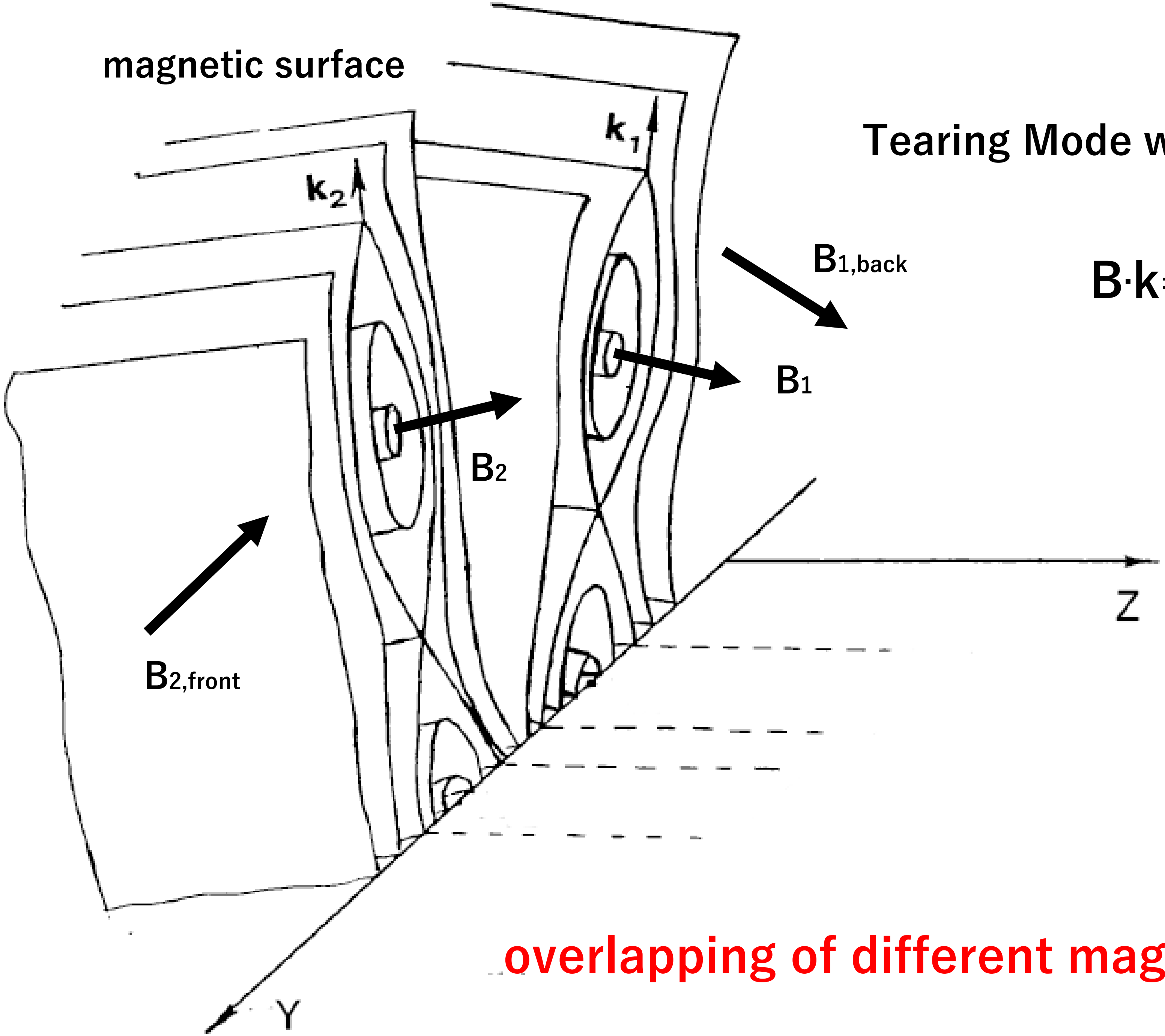
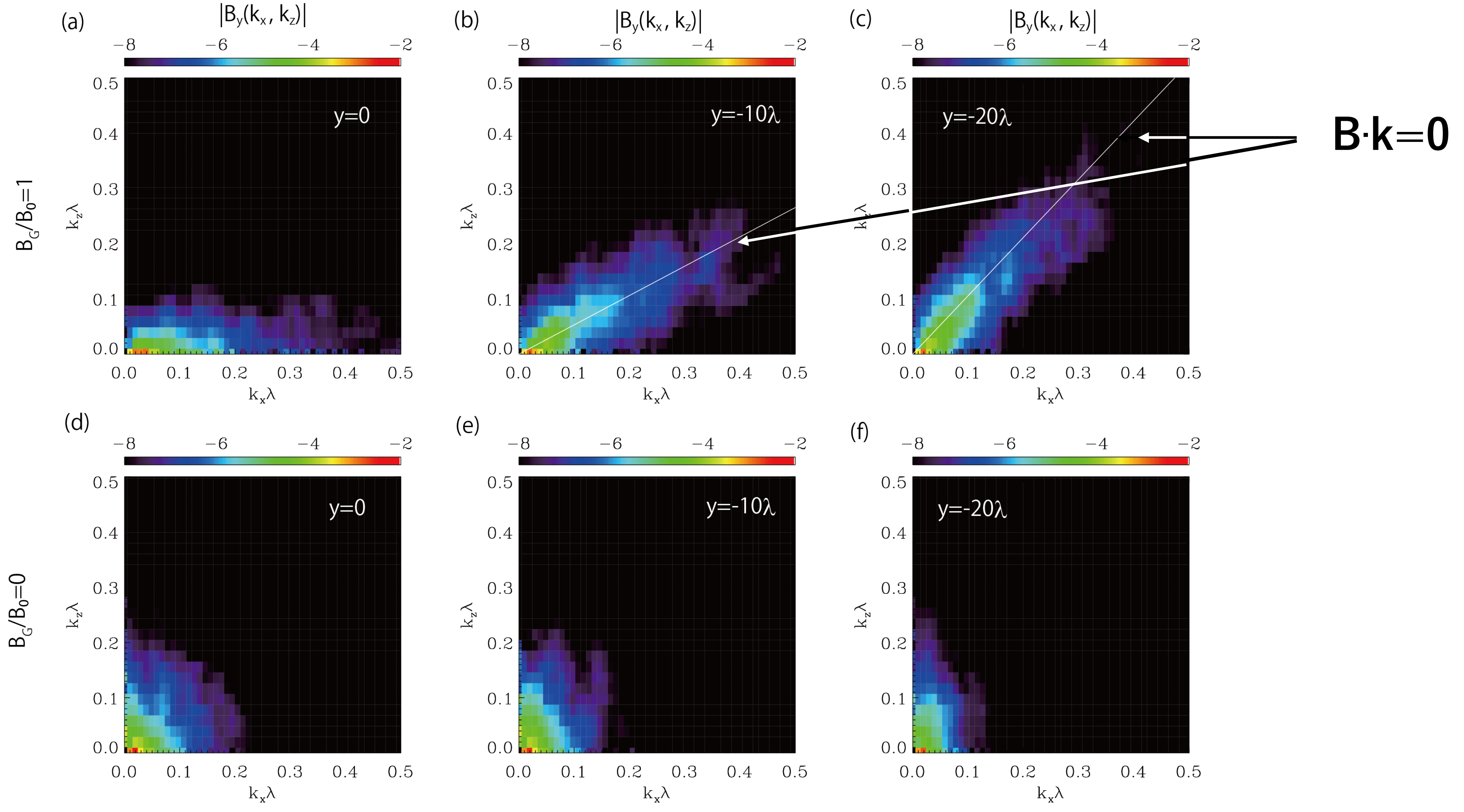
Tearing Mode with $B_G \neq 0$

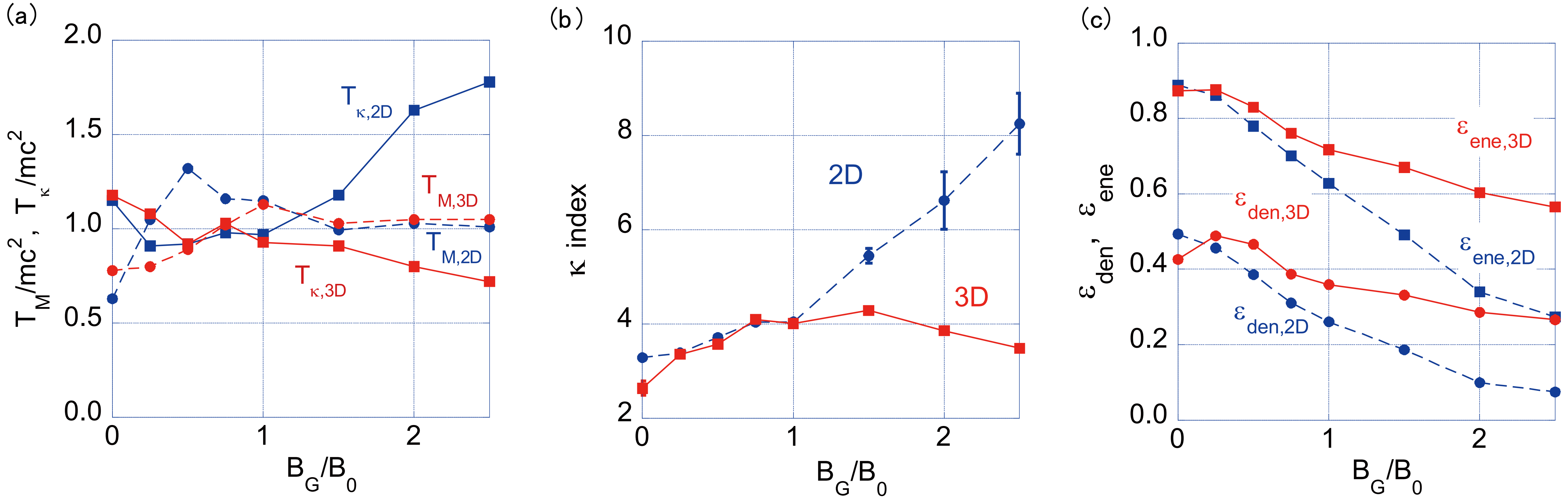
$B \cdot k = 0$



overlapping of different magnetic islands

Oblique tearing modes





- $T_{M,3D}$ and $T_{M,2D}$ are almost same as the initial temperature
- $T_{\kappa,2D}$ in 2D increases with increasing B_G/B_0, while $T_{\kappa,3D}$ in 3D keeps almost constant
- κ index in 2D increases with increasing B_G/B_0, whileκ index in 3D keeps almost constant
- Both ε_{ene} and ε_{den} decrease with increasing B_G/B_0 for 2D & 3D, but the decrease in 3D is smaller than that in 2D

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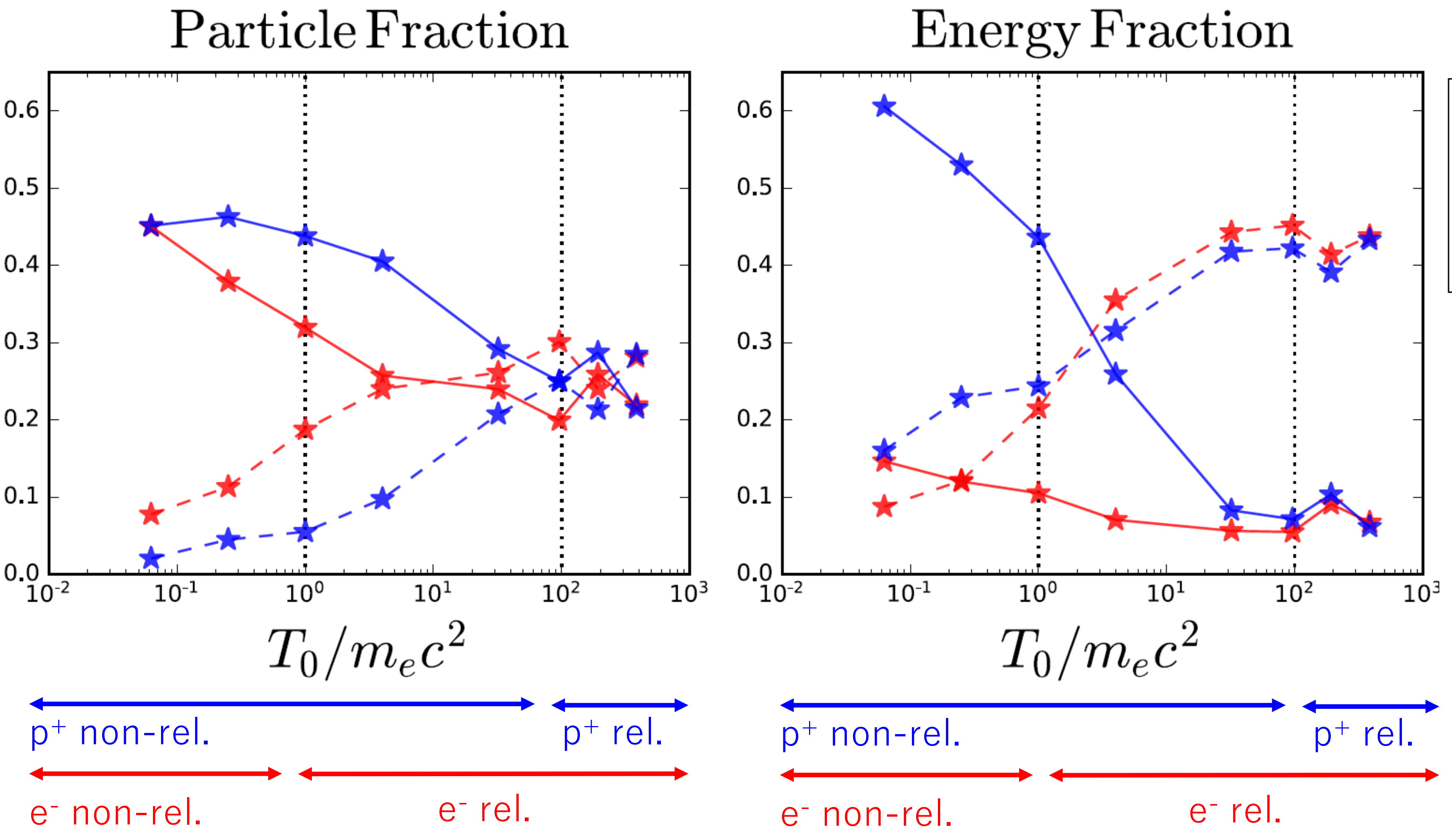
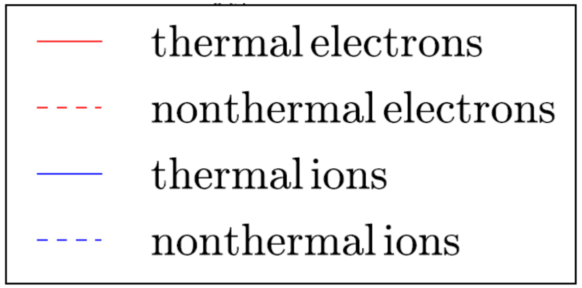
Ion & Electron Plasmas with m_i/m_e=100
2D & anti-parallel reconnection





Acceleration efficiency is enhanced as T_0 approaches the rest mass energy for each species

Conclusions

- Energy spectra can be well modeled by Maxwell + kappa distribution function for both 2D & 3D
- Efficiency of nonthermal particle acceleration increases with increasing temperature T for both 2D & 3D
- Efficiency of nonthermal particle acceleration decreases with increasing the guide magnetic field B_G for both 2D & 3D
- 3D guide-field reconnection shows a patchy and turbulent signature, and nonthermal particles acceleration in 3D is more efficient than that in 2D
- 3D guide-field reconnection maintains a hard energy spectrum with $\kappa \sim 4$
- Ion-electron reconnection (ongoing)