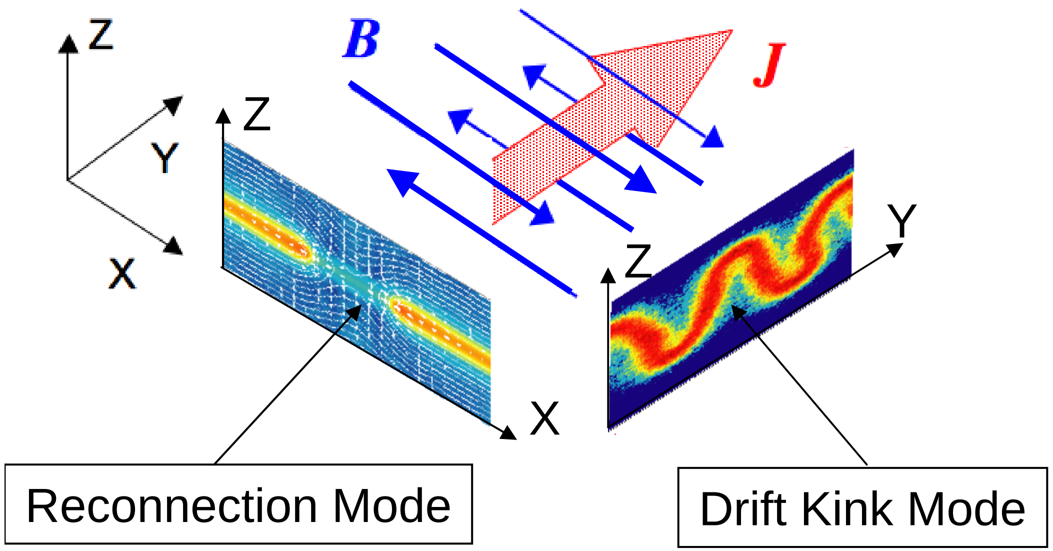
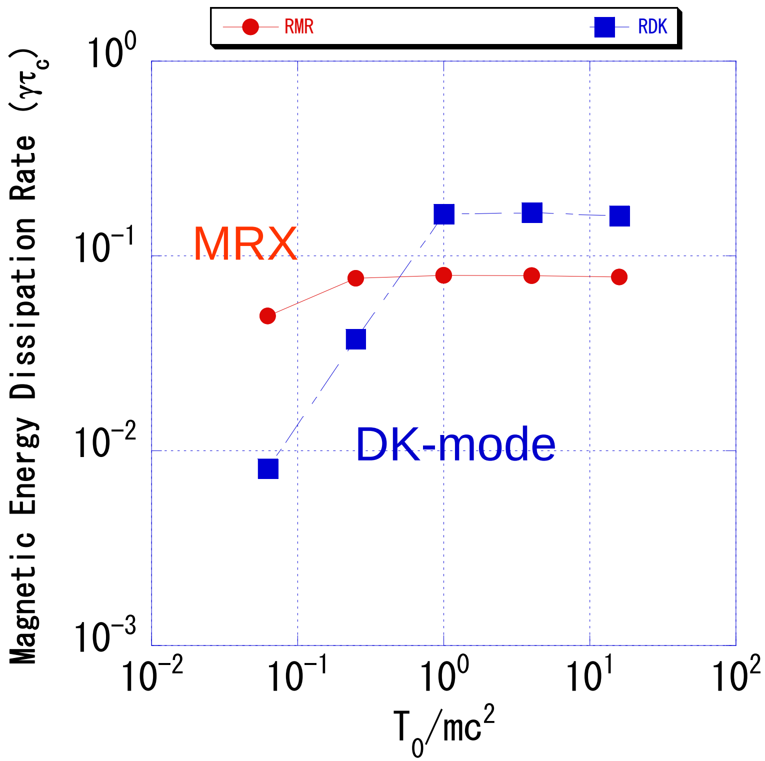
Radiation-Dominated Relativistic Current Sheets

C. Jaroschek and M. Hoshino
University of Tokyo

Relativistic Current Sheet Instabilities

$V_A \sim c$, $T/mc^2 > 1$, Electron and Positron Plasmas



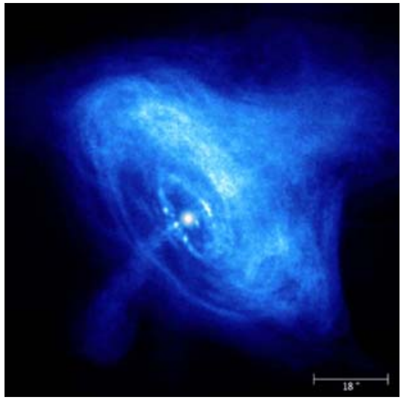


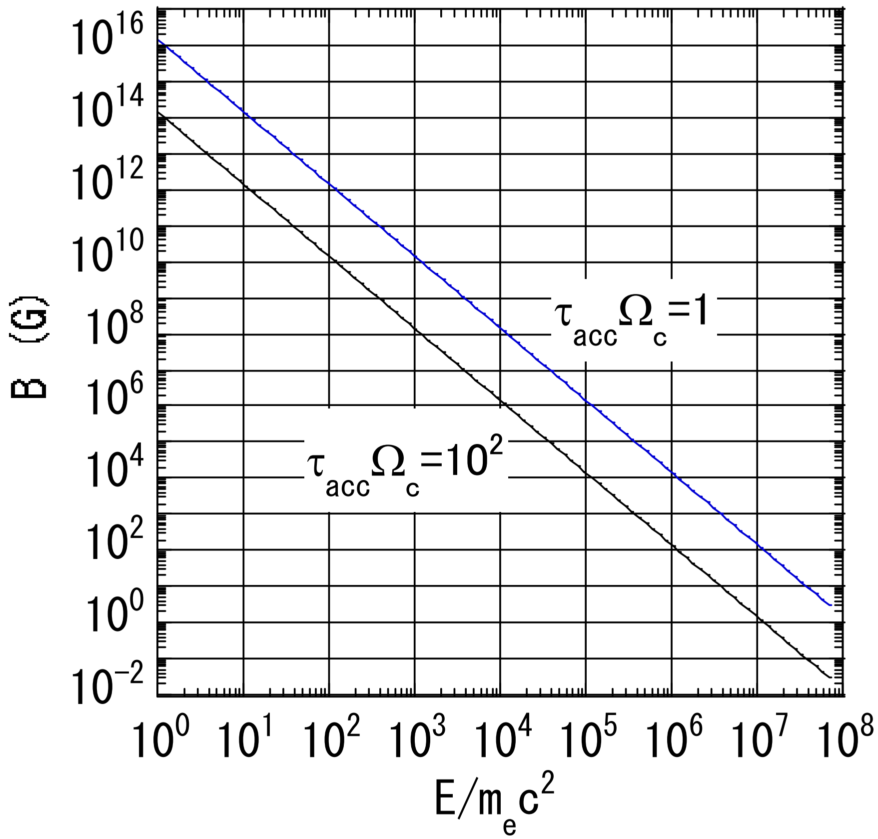
Open issue for relativistic Current Sheet

- radiation effect such as synchrotron cooling

$$\frac{\tau_{loss}}{\tau_{dyn}} \approx \left(\frac{10^2}{\tau_{dyn}\Omega_c}\right)\left(\frac{10^{14}G}{B}\right)\left(\frac{1}{E/mc^2}\right)^2$$

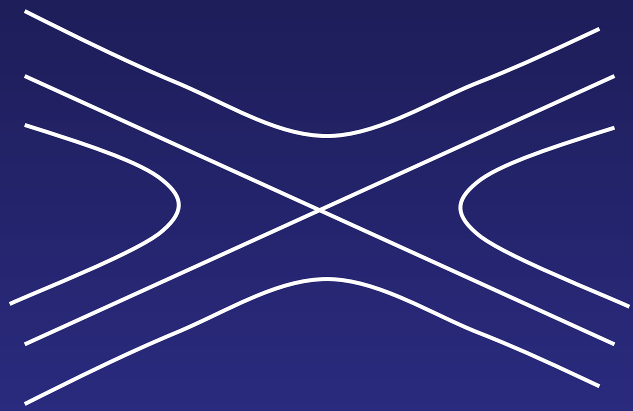
e.g. Magnetor,
Pulsar magnetosphere,…

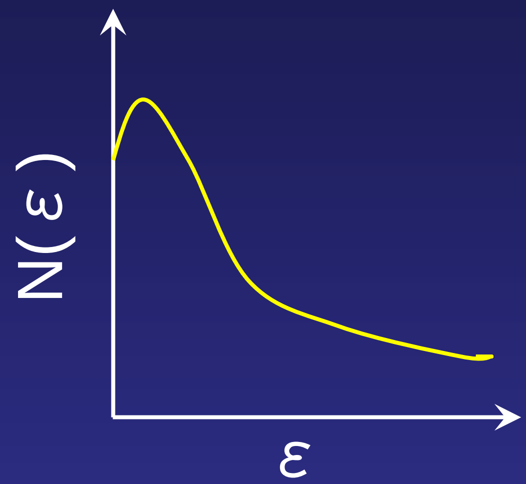




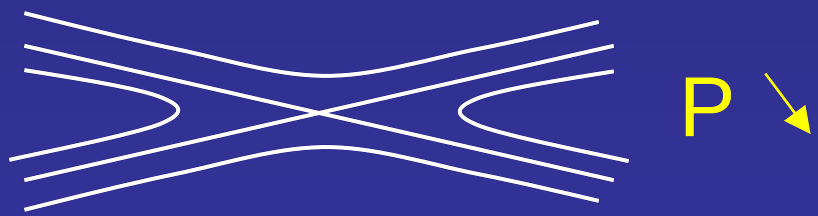
Synchrotron Radiation Effect

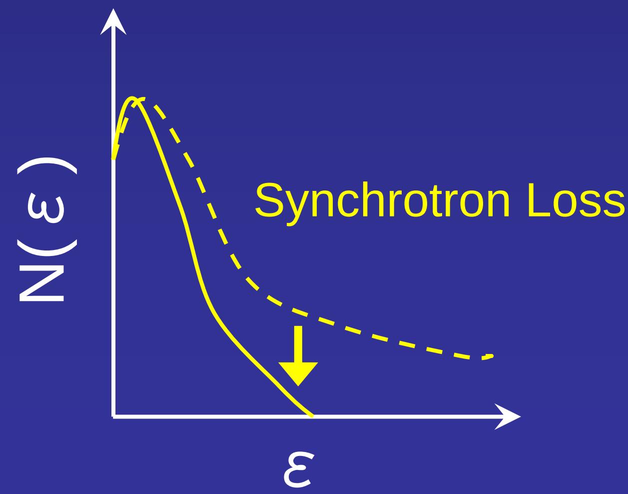
Without radiation loss





With radiation loss





Fast Reconnection

Radiation Loss Effect in PIC Simulation Code

Abraham-Lorentz Formula for Radiation Drag Force

$$mc\,\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + g^i \qquad \text{(Dirac Form)}$$

$$\begin{aligned} g^i &= \frac{2e^2}{3c}\left(\frac{d^2\,u^i}{ds^2} + u^i\frac{d\,u^k}{ds}\frac{d\,u_k}{ds}\right) \\ &= \frac{2e^3}{3mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l \quad - \quad \frac{2e^4}{3m^2c^5}F^{ik}F_{lk}u^l \quad + \quad u^i \cdot \frac{2e^4}{3m^2c^5}(F^{kl}u_l)(F_{km}u^m) \\ &= T_1 \quad + \quad T_2 \quad + \quad T_3 \end{aligned}$$

Radiation Loss Effect in PIC Simulation Code

Abraham-Lorentz Formula for Radiation Drag Force

$$\mathbf{T}_1 = \frac{2}{3}\gamma \cdot (\omega_{c0}\tau_0) \cdot (mc\omega_{c0}) \cdot (\, (\hat{\partial}_t + \hat{\mathbf{v}} \cdot \hat{\nabla})\hat{\mathbf{E}} + \hat{\beta} \times (\hat{\partial}_t + \hat{\mathbf{v}} \cdot \hat{\nabla})\hat{\mathbf{B}}\,)$$

$$\mathbf{T}_2 = \frac{2}{3} \cdot (\omega_{c0}\tau_0) \cdot (mc\omega_{c0}) \cdot (\, \hat{\mathbf{E}} \times \hat{\mathbf{B}} + \hat{\mathbf{B}} \times (\hat{\mathbf{B}} \times \beta) + \hat{\mathbf{E}}(\beta \cdot \hat{\mathbf{E}})\,)$$

$$\mathbf{T}_3 = -\frac{2}{3}\gamma^2 \cdot (\omega_{c0}\tau_0) \cdot (mc\omega_{c0}) \cdot \beta \cdot (\, (\hat{\mathbf{E}} + \beta \times \hat{\mathbf{B}})^2 - (\hat{\mathbf{E}} \cdot \hat{\beta})^2\,)$$

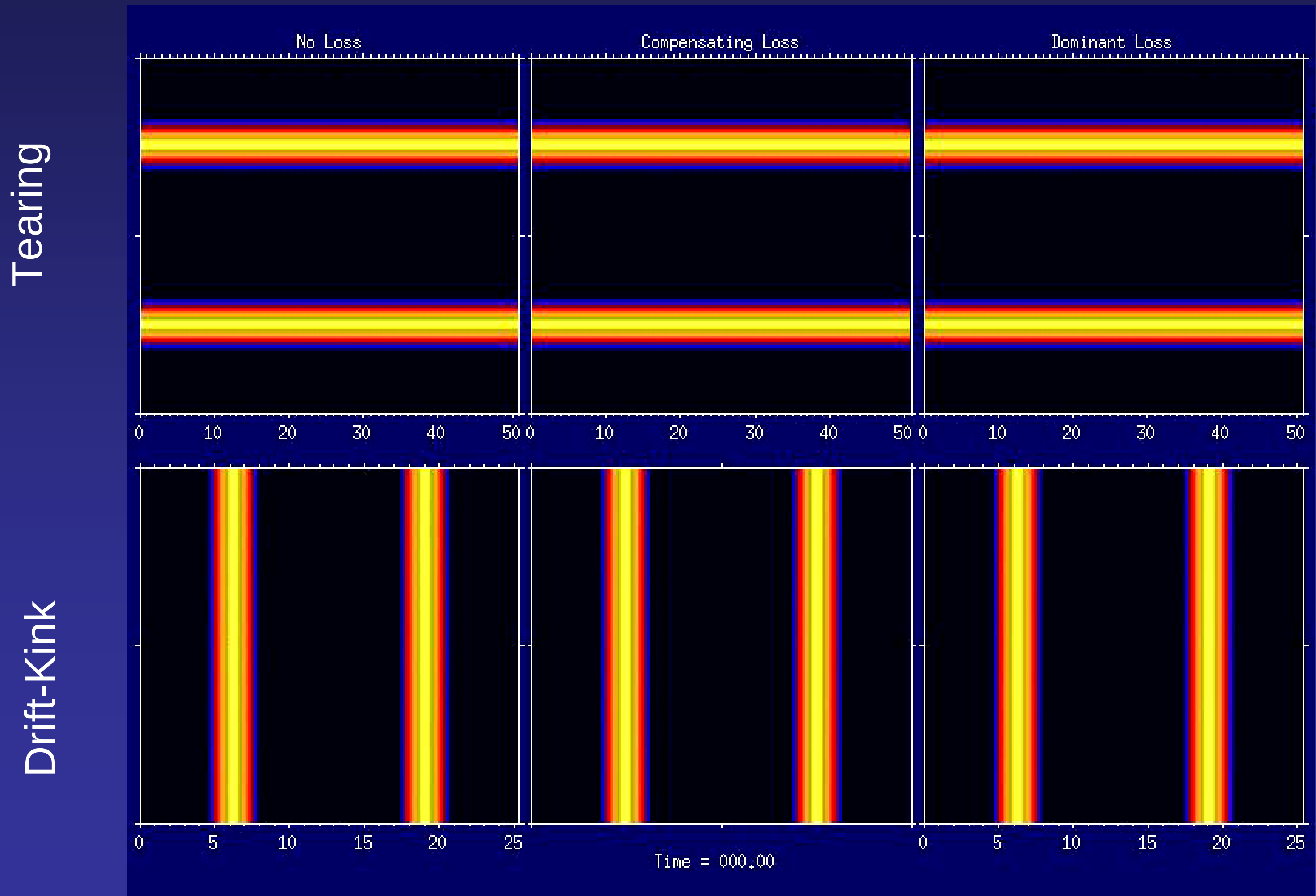
τ_0 : Light crossing time over classical electron radius (e^2/mc^2)/c ~ 10^-23 s

Main Radiation Effect is Synchrotron Radiation

(cf. Noguchi et al. 2005)

Time Evolution of MR & DKI

No Radiation Loss	Intermediate	Dominant Radiation Loss
$\alpha = 0$	$\alpha = 10^{-12}$	$\alpha = 10^{-11}$

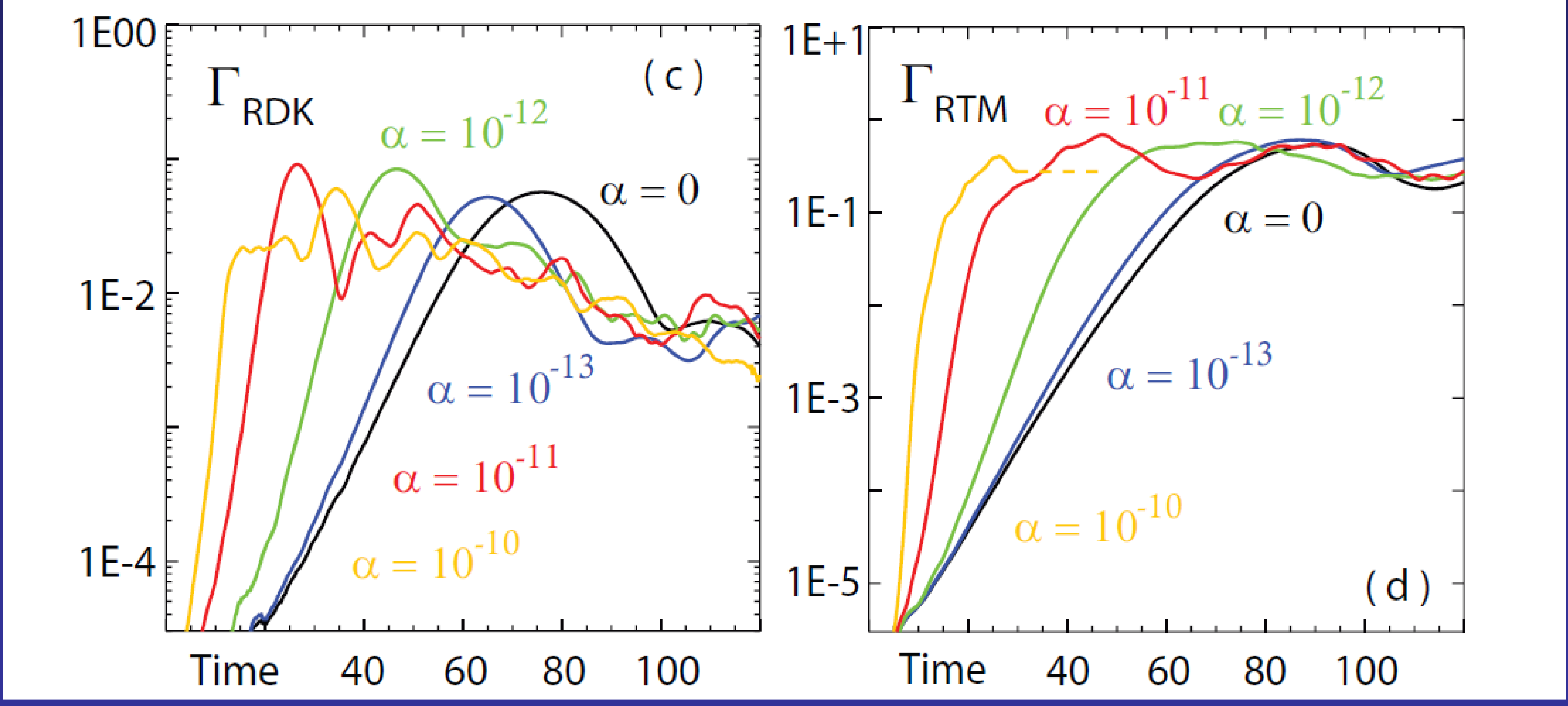


Growth Curves

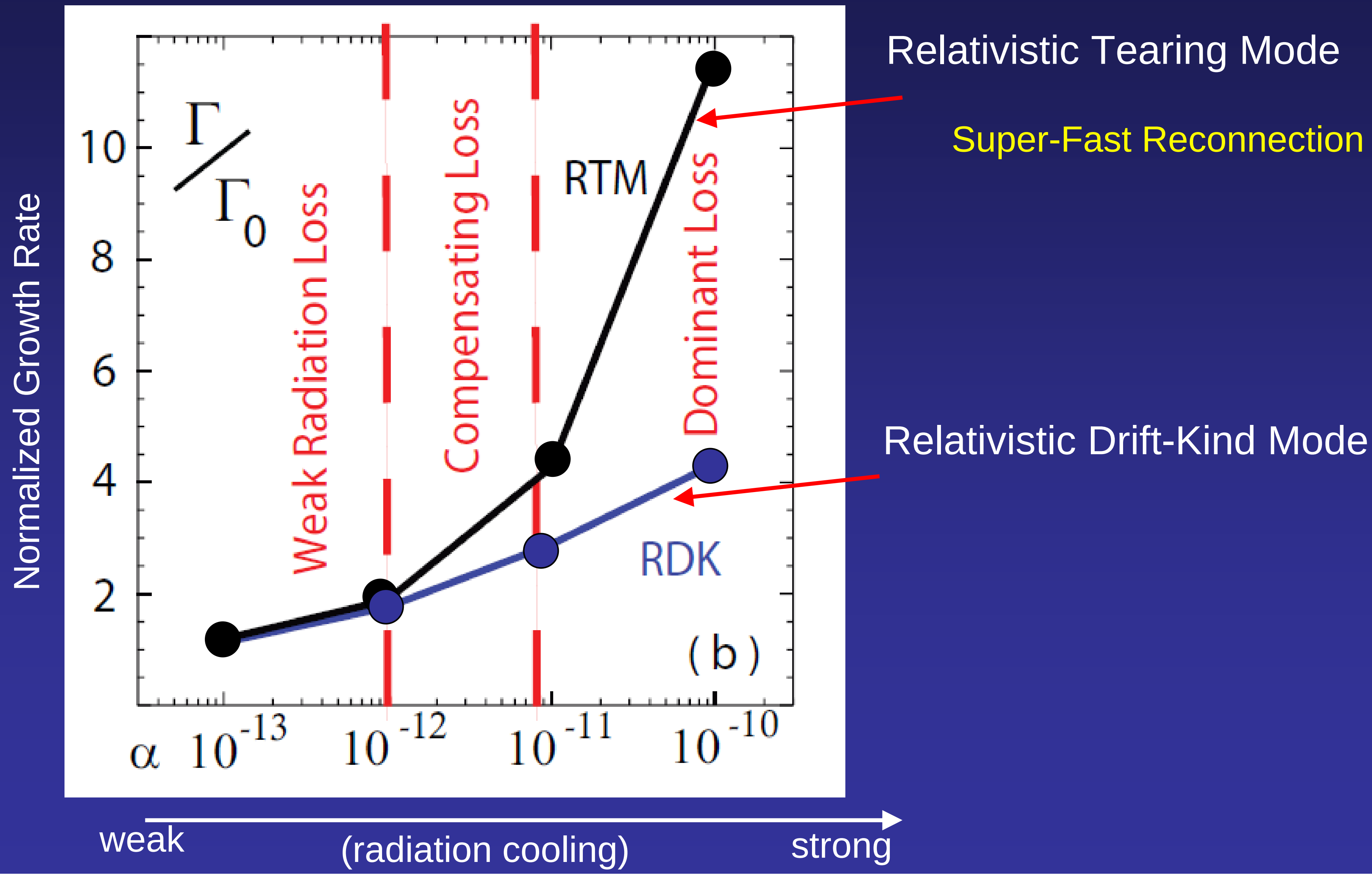
α : radiation loss coefficient
(α =0 : No radiation loss, α =10^{-10} : Strong radiation loss)

Drift-Kink Mode

Tearing Mode (Reconnection)



Comparison of Growth Rate



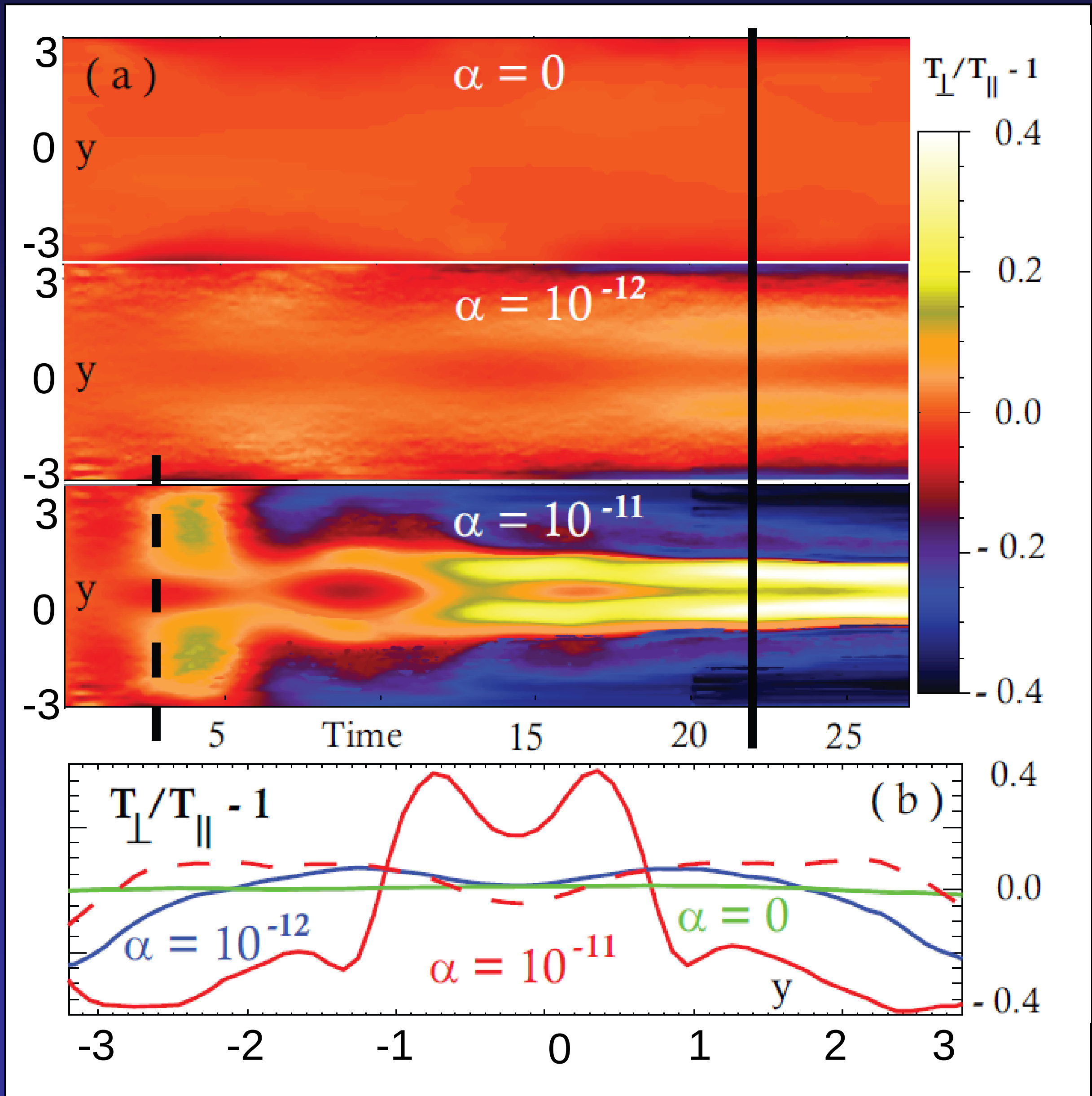
Reason for Fast Growth

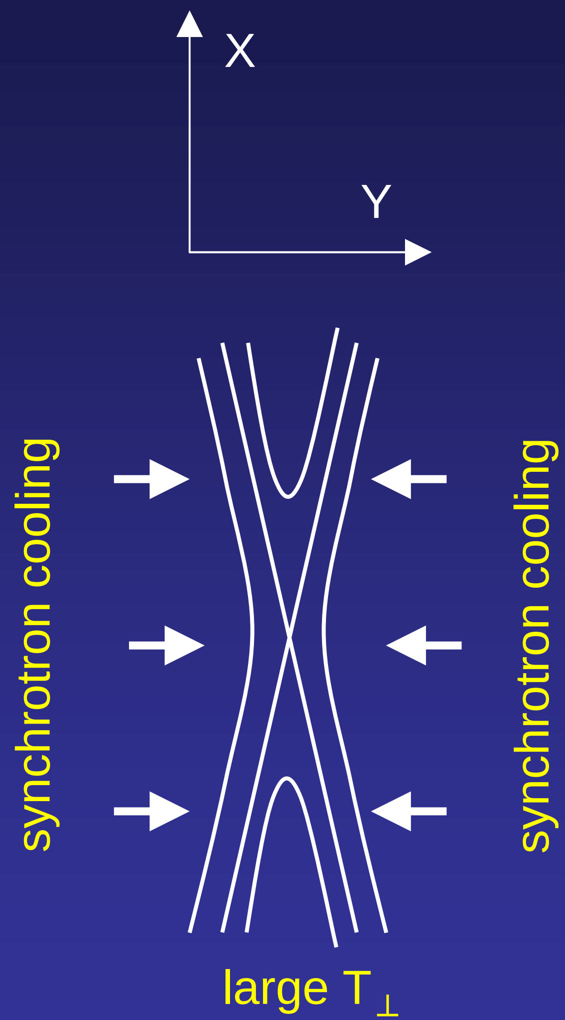
- Decrease of gas pressure by radiation loss
- Shrink of plasma sheet & thin plasma sheet

Why reconnection has super-fast growth?

- Temperature Anisotropy $T_{//} \neq T_{\perp}$

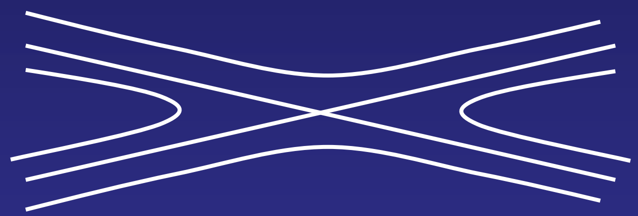
Temperature Anisotropy (Early Stage)





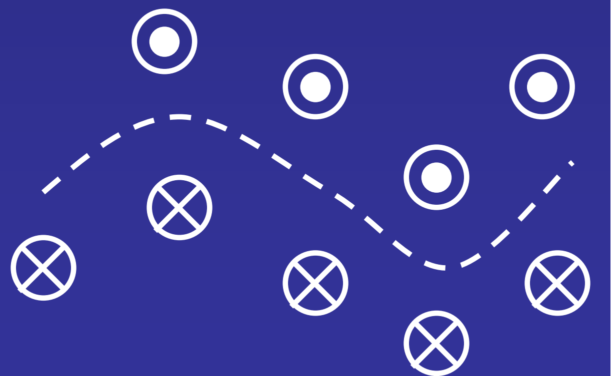
Linear Growth Rate (Γ) under Temperature Anisotropy

- Tearing Mode
  - strong dependence on $T_{\perp}/T_{//}$ (e.g. Chen et al., 1984)
  - $T_{\perp} > T_{//}$ → Γ increase
  - $T_{\perp} < T_{//}$ → Γ decrease



$T_{\perp}/T_{//}$ → isotropization

- Drift-Kink Mode
  - weak dependence on $T_{\perp}/T_{//}$

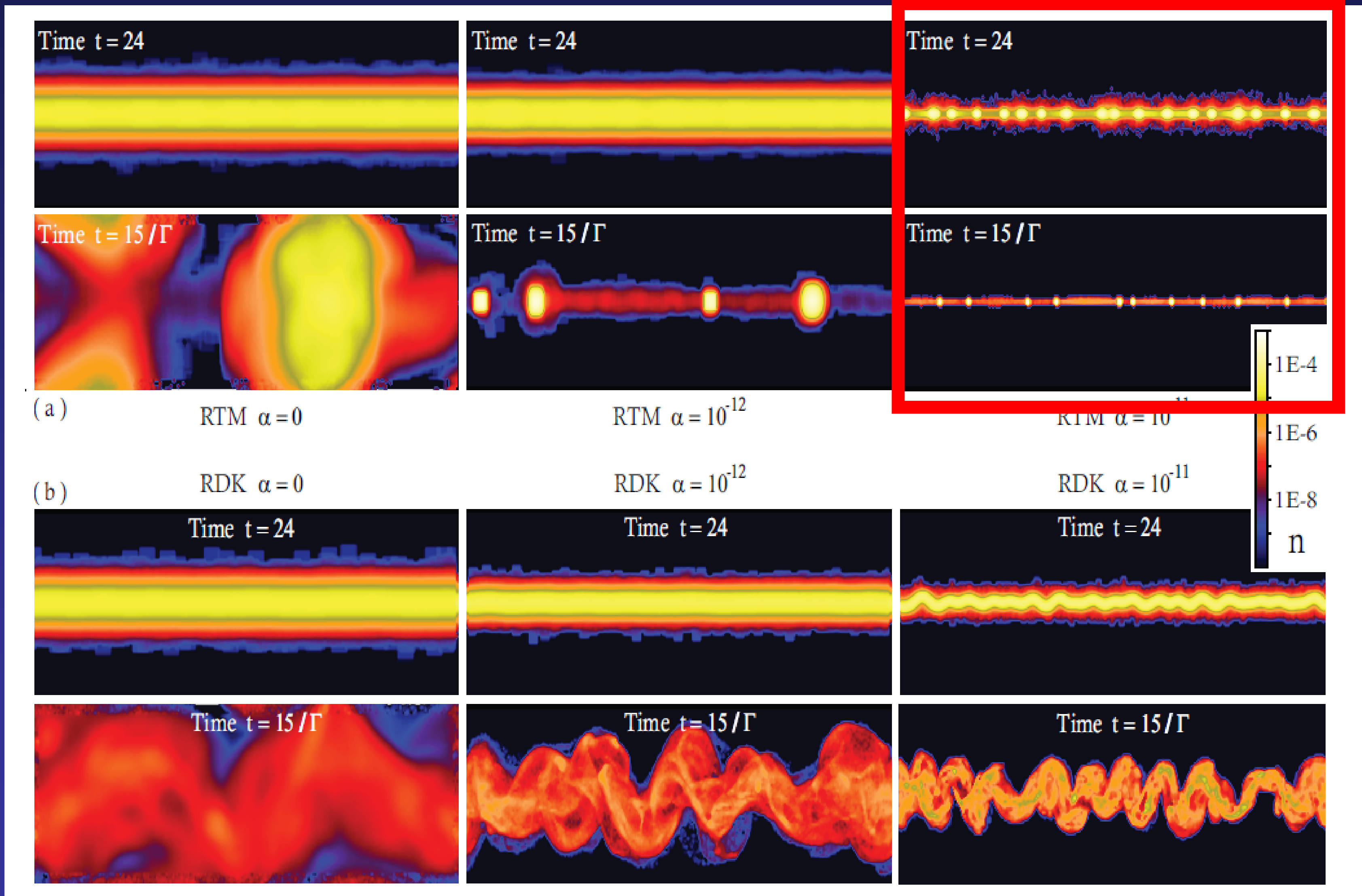


Late Nonlinear Stage

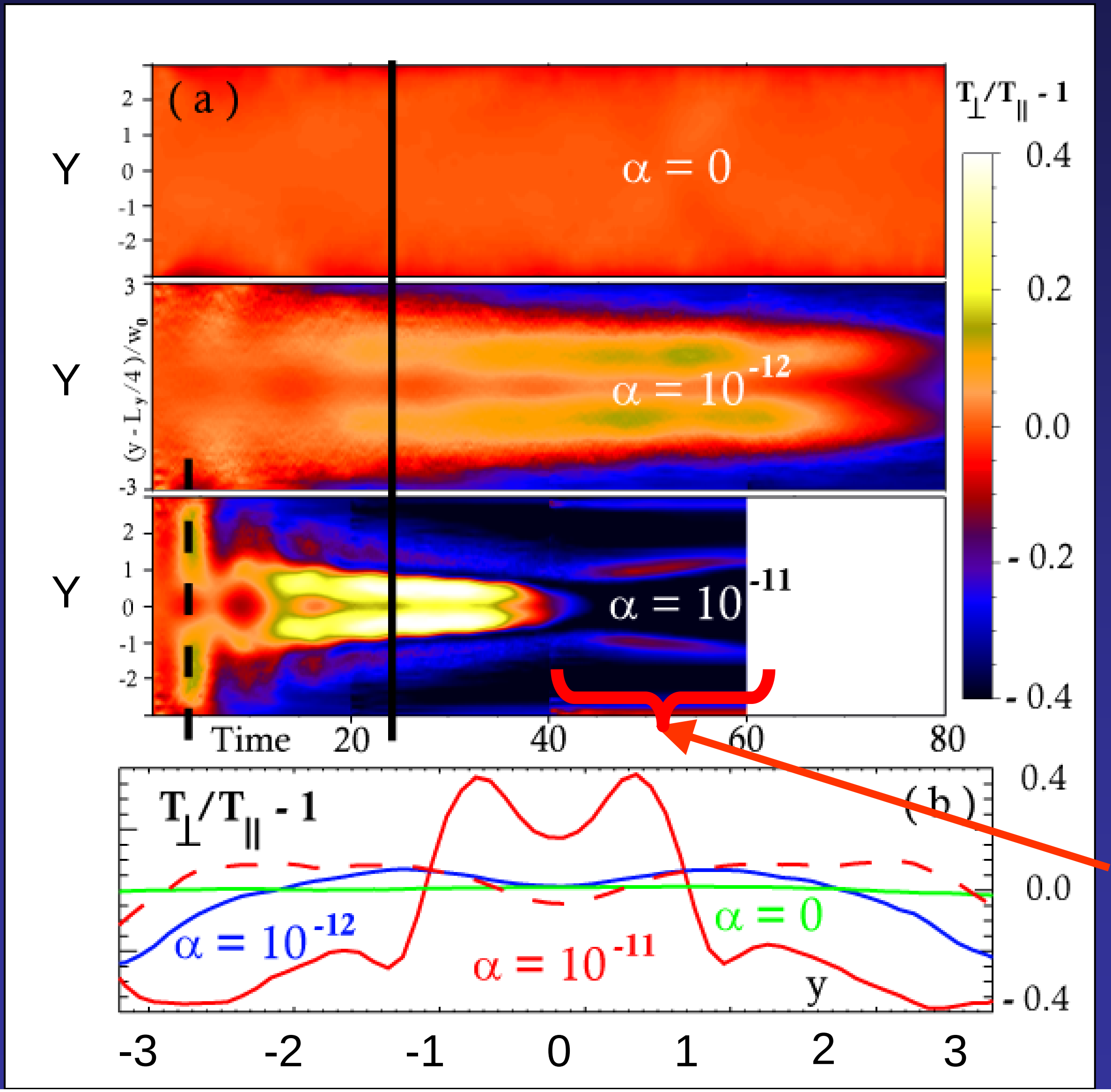
$\alpha = 0$ $\alpha = 10^{-12}$ $\alpha = 10^{-11}$

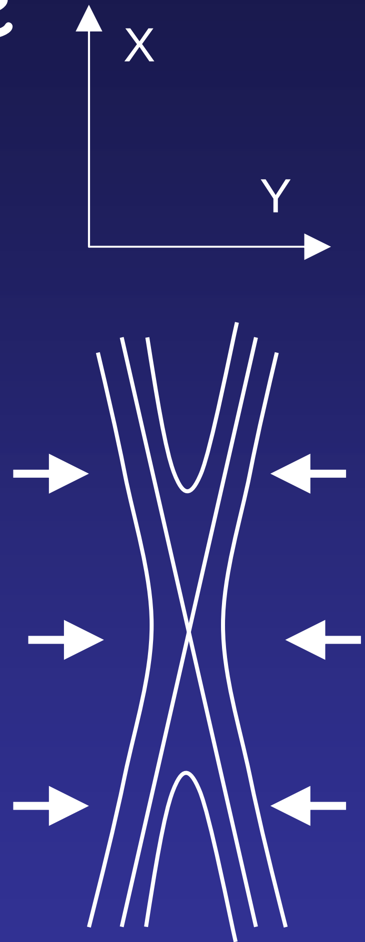
Tearing

Drift-Kink



Temperature Anisotropy in Late Nonlinear Stage

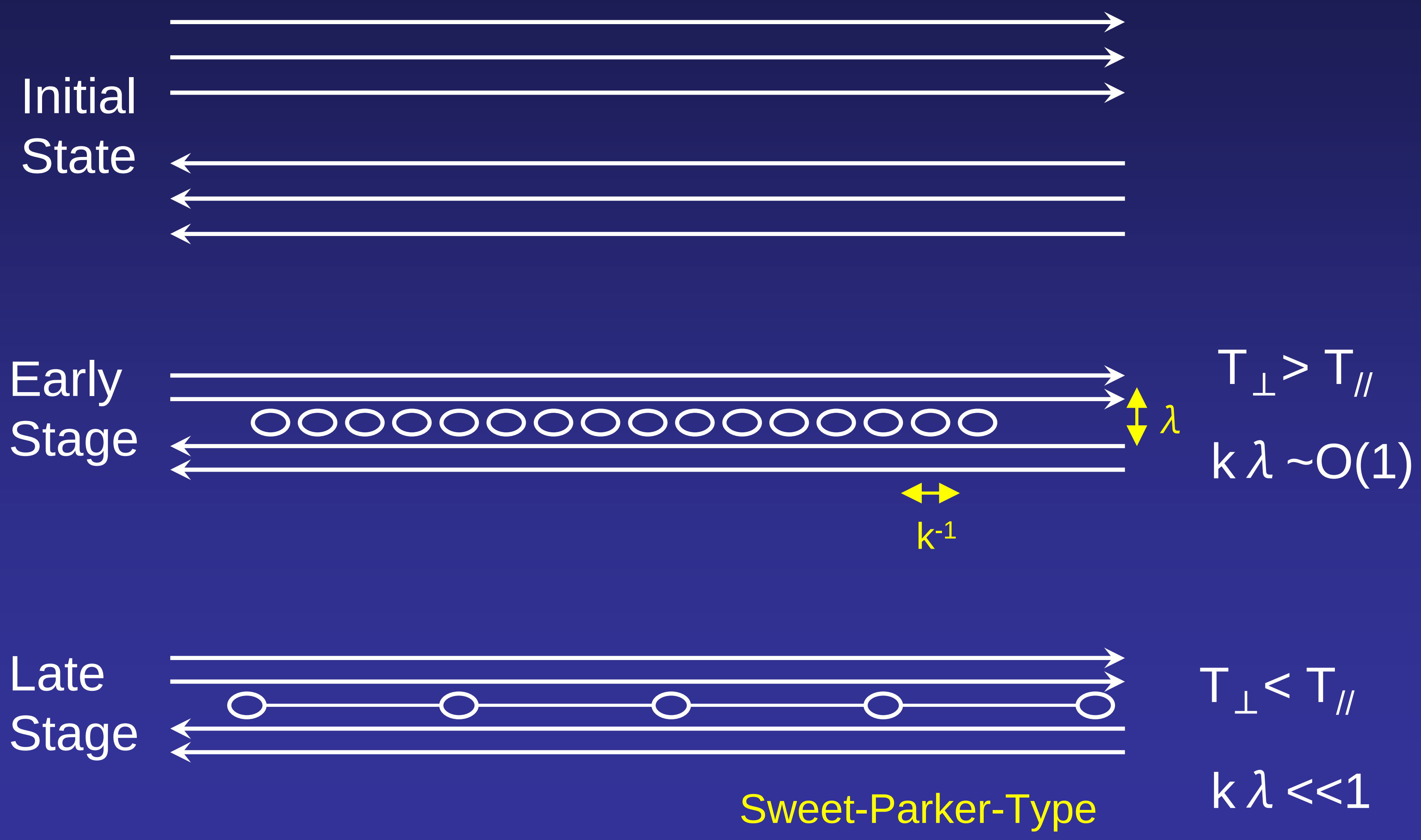




$T_\perp < T_{//}$

reconnection suppressed, shifted to small k mode

Relativistic Reconnection under Synchrotron Cooling



Summary

- Relativistic Reconnection with Radiation Cooling
  - thin current sheet due to radiation cooling
  - fast growth of reconnection/drift-kink instability

- Nonlinear Evolution of Reconnection/Drift-Kink
  - Early Stage: $T_{\perp} > T_{//}$
    - Super-Fast Reconnection
    - Fast Drift-Kink Instability (weak effect of Temp. Anisotropy)
  - Late Nonlinear Stage: $T_{\perp} < T_{//}$
    - Transition to Sweet-Parker Reconnection