Reconnection in Relativistic Plasma

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Workshop on Opportunities in Plasma Astrophysics
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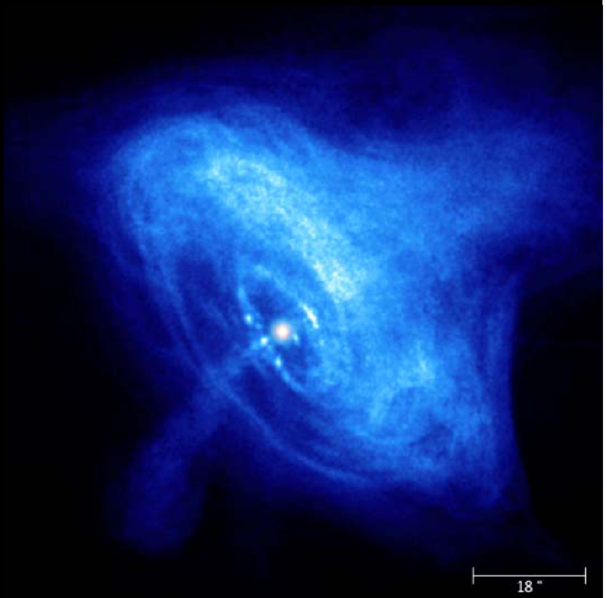
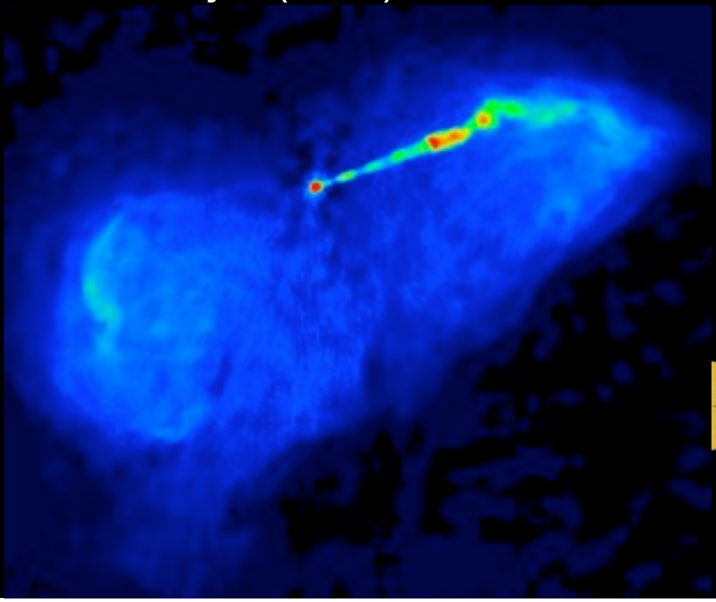
Relativistic Reconnection in Astrophysics

- Relativistic Plasmas in Astrophysics:
  - Pulsars & Winds ($\gamma \sim 10^{6\text{-}7}$)
  - Extragalactic radio source ($\gamma \sim 10$)
  - Gamma ray bursts ($\gamma > 100$)

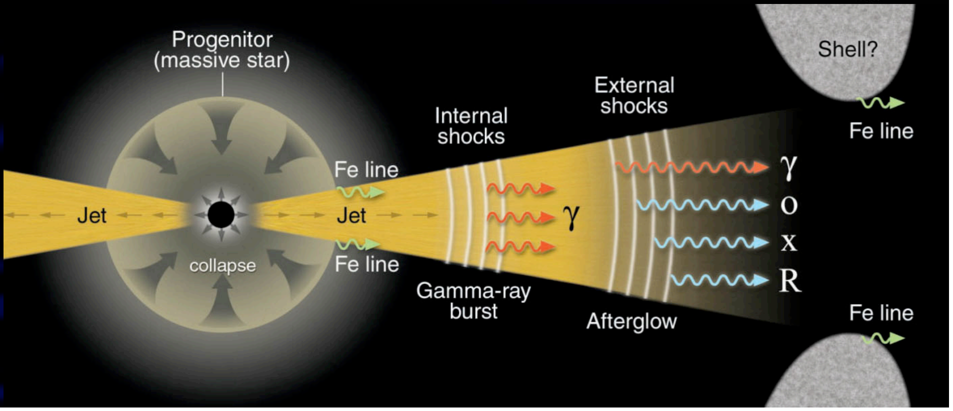
Crab Nebula



AGN jet (M87)



γ-ray burst



Progress of Relativistic Reconnection

1995 2000 2005 2010

Blackman & Field (1994)

Lyutikov & Uzdensky (2003)

Lyubarsky (2005)

Watanabe & Yokoyama (2006)

Zenitani et al (2009)

MHD modeling (fast reconnection)

MHD simulation

Zenitani & MH (2001)

Jaroschek et al (2004)

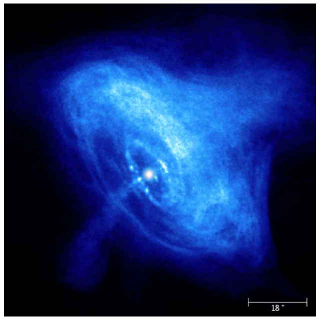
Bessho & Battacharjee (2007)

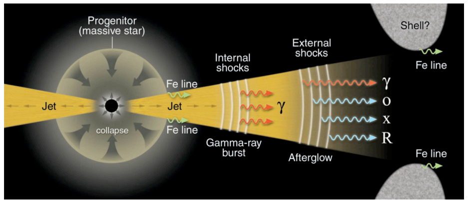
PIC simulation (strong particle acceleration & heating)

Jaroschek & MH (2009)

(radiation cooling)

In astrophysical context





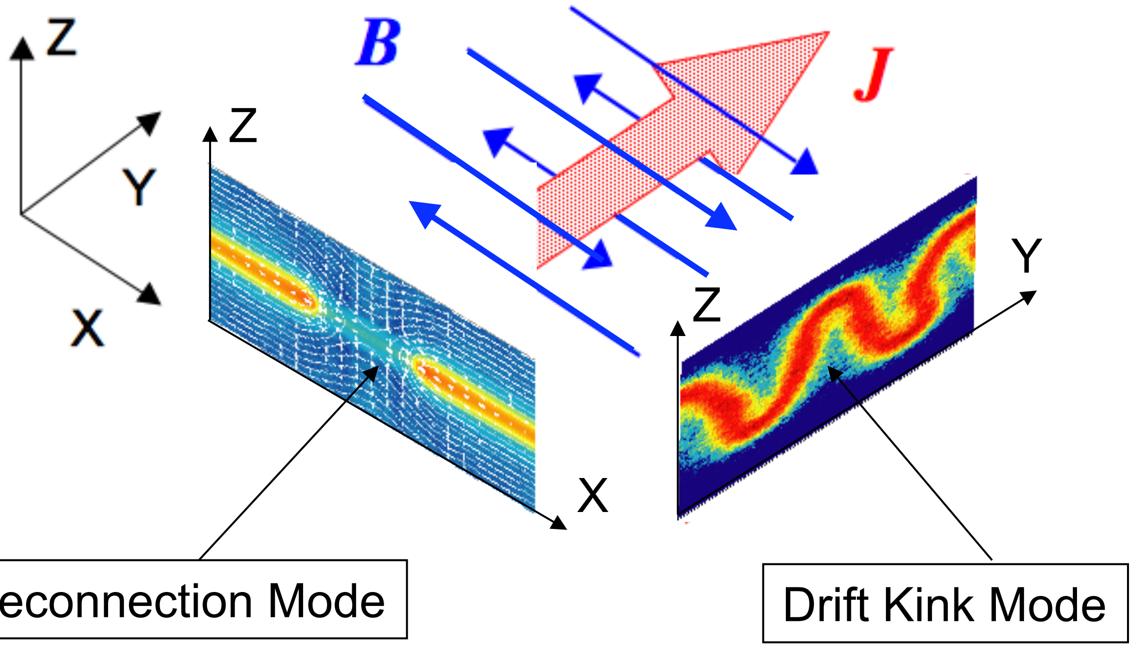
Coroniti 1990, Kirk et al. 2003

Relativistic Current Sheet Instabilities

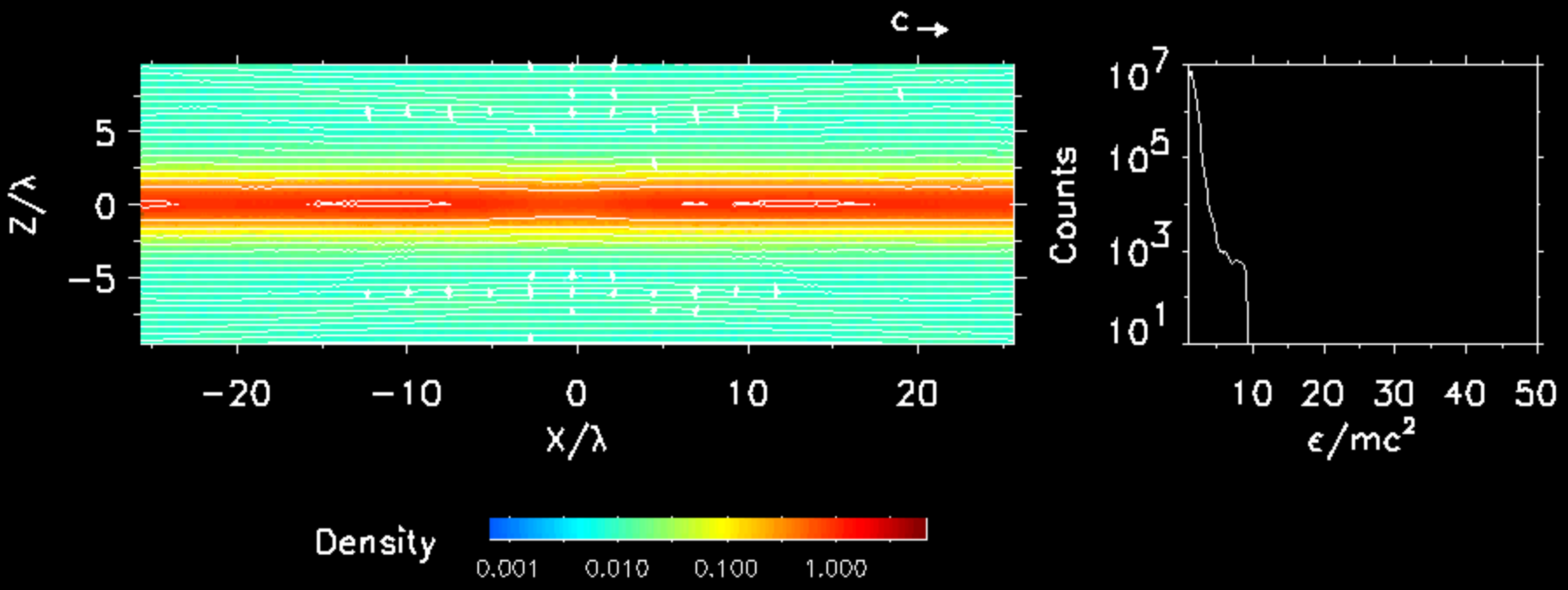
Relativistic Temperature: $T/mc^2 > 1$
Plasma Sheet: $B^2 = nT$

→ $V_A^2 = B^2/nm > c^2$

Electron and Positron Plasmas



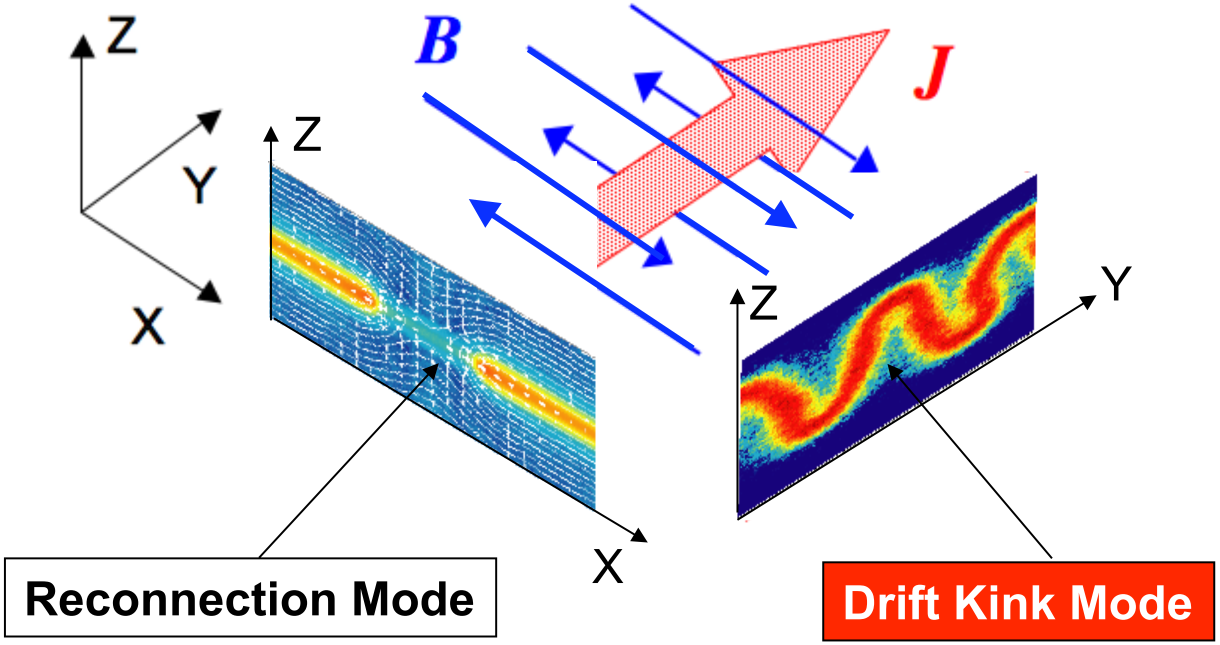
Relativistic Reconnection
(Particle-in-Cell simulation)



Non-thermal particle acceleration

Drift Kink Instability

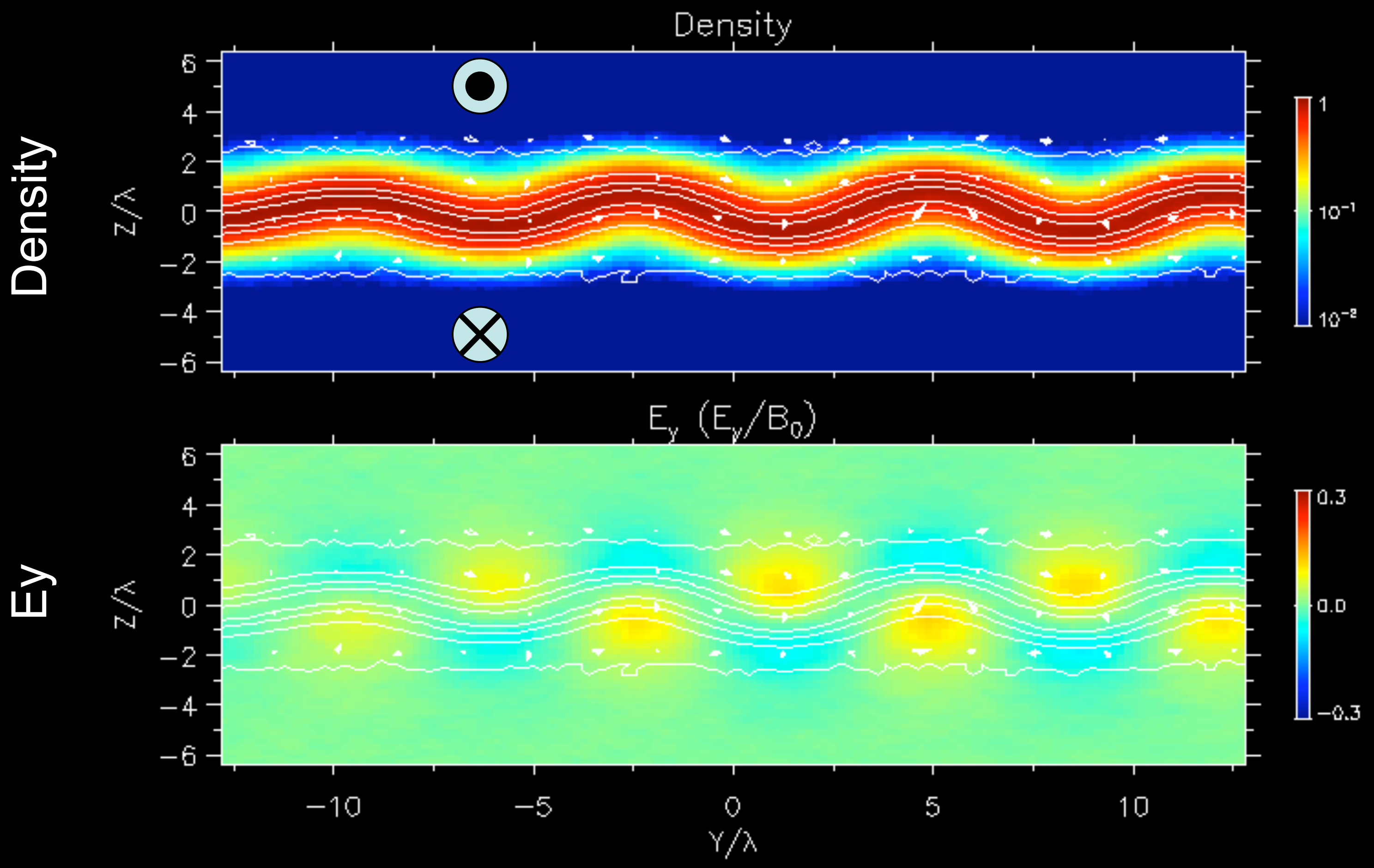
(Current Driven Instability)



Reconnection Mode

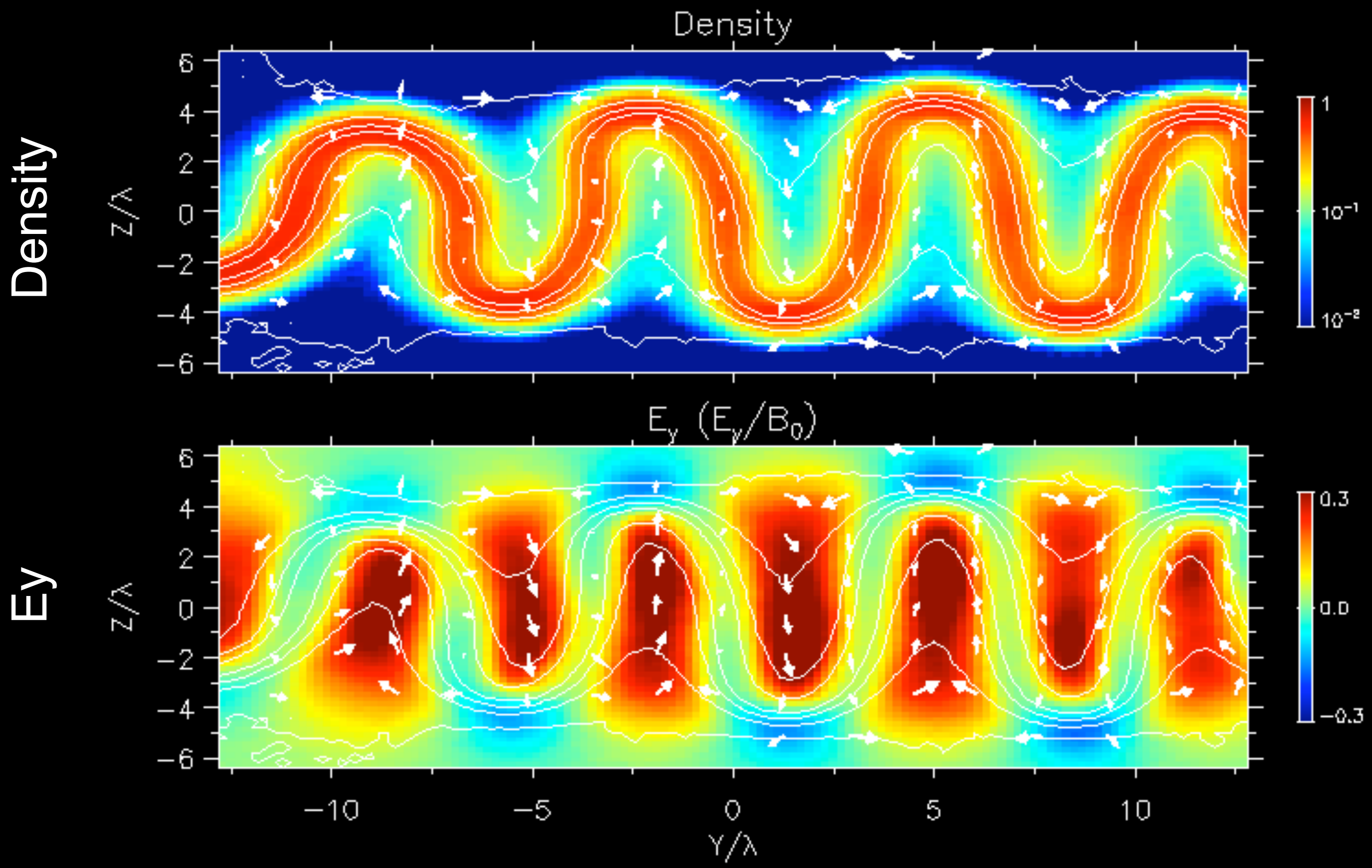
Drift Kink Mode

Drift-Kink Mode (early stage)

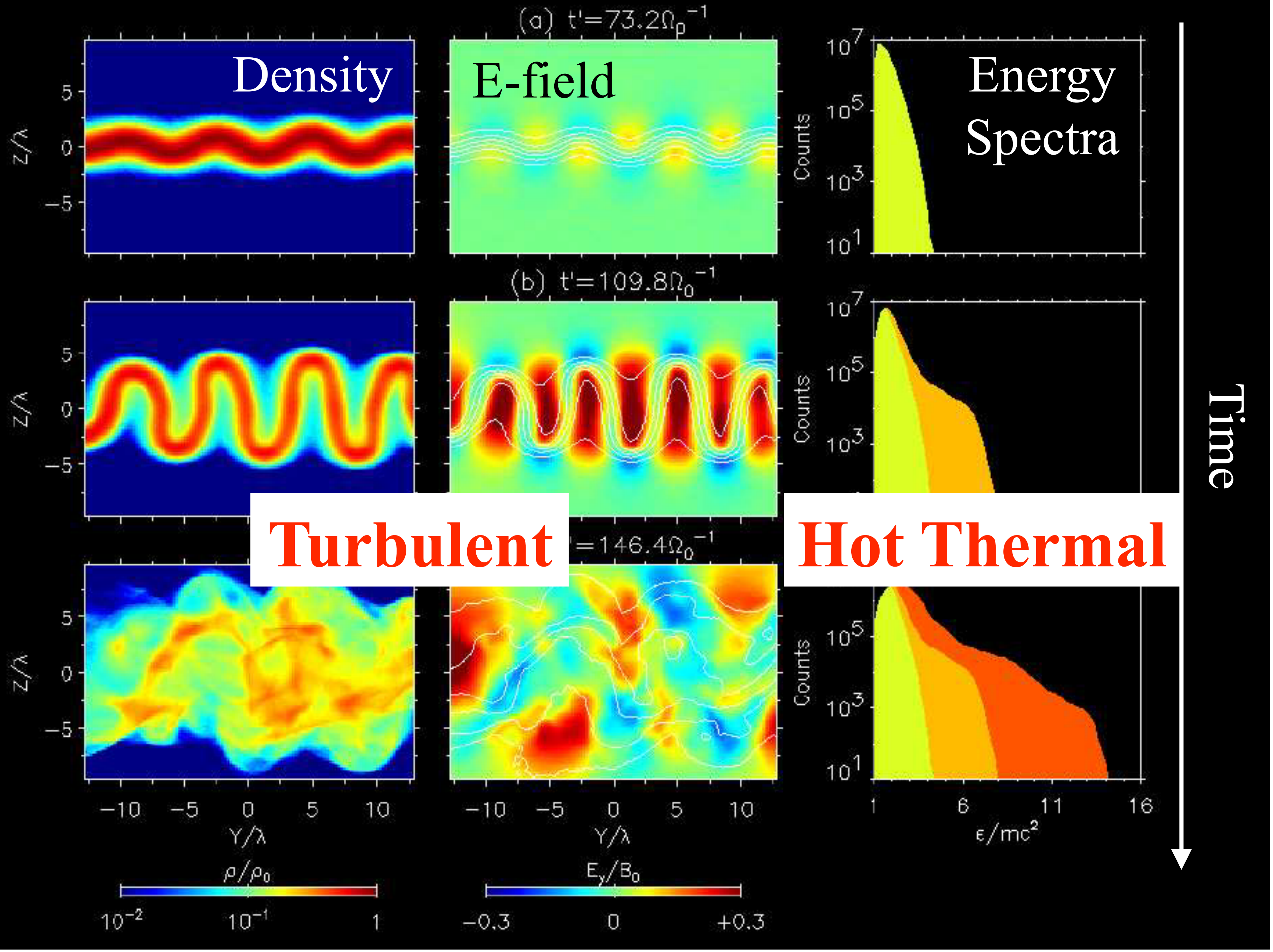


Initial condition: relativistic Harris solution

Drift-Kink Mode (nonlinear stage)

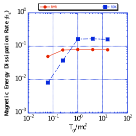


$E \cdot J > 0$ strong magnetic energy dissipation



Turbulent

Hot Thermal



Energy Dissipation Rate

Drift Kink

Reconnection

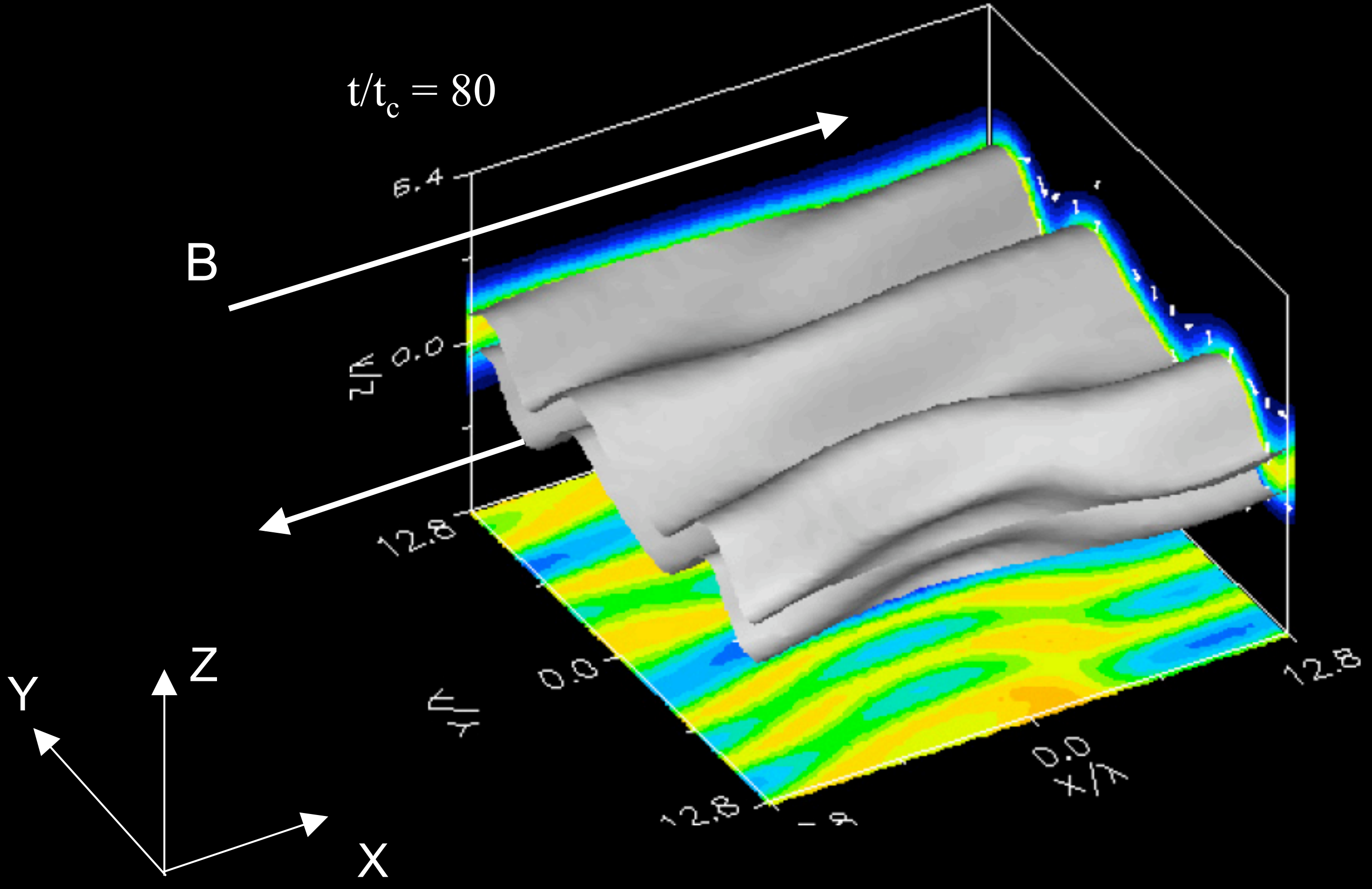
Non-Relativistic Regime

Relativistic Regime

Reconnection in Non-Relativistic, Drift-Kink in Relativistic Regime

3D Current Sheet Evolution

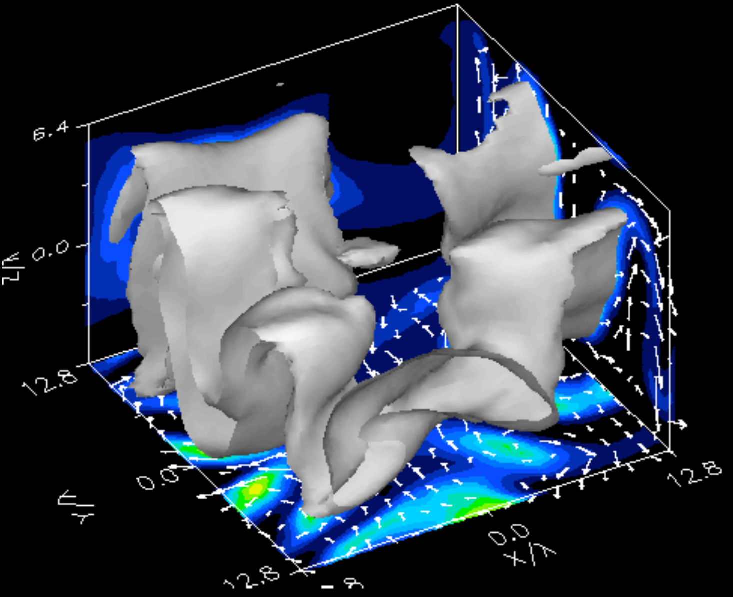
Isosurface of N, Color contour of N at neutral sheet



Drift-Kink grows faster than Reconnection

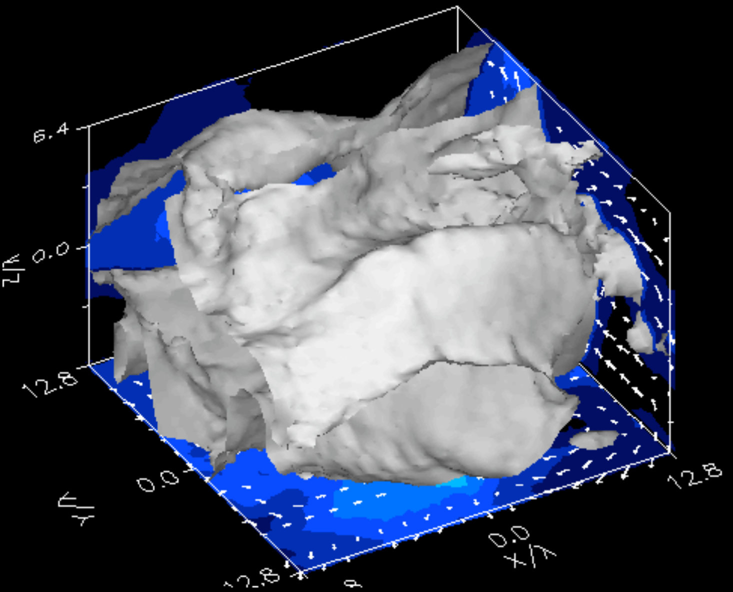
Nonlinear Stage of 3D Current Sheet

$t/t_c = 110$



Drift-Kind Mode
dominates,
No Reconnection.

$t/t_c = 140$

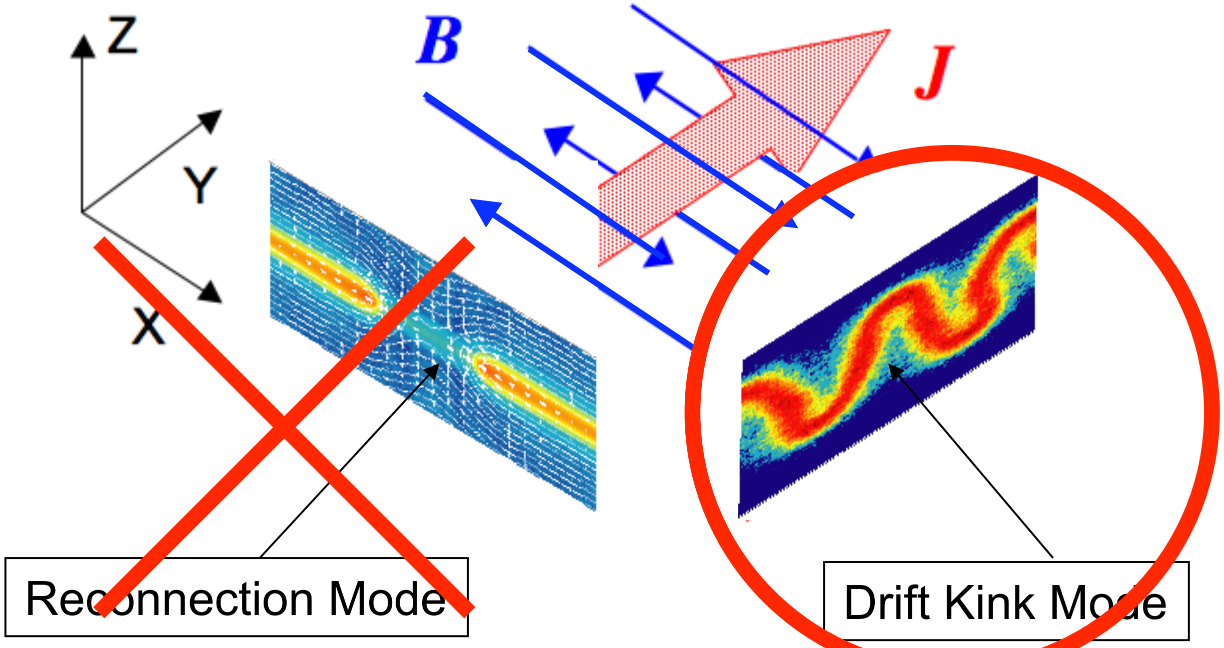


Turbulent Sheet

Transition to
turbulence is fast in
3D than in 2D
plasma mixing

Relativistic Current Sheet Instabilities

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



~~Reconnection Mode~~

Slower Growth Rate

Drift Kink Mode

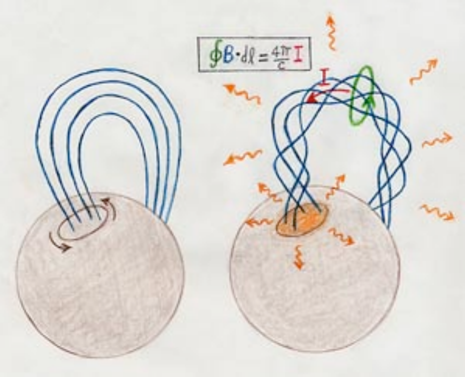
Faster Growth Rate

Radiation Effect in Relativistic Current Sheet

- synchrotron cooling in strong B

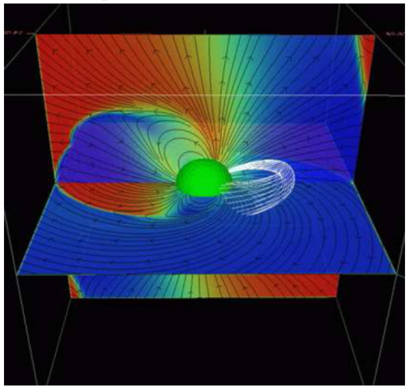
$$\frac{\tau_{loss}}{\tau_{dyn}} \approx \left(\frac{10^2}{\tau_{dyn}\Omega_c}\right)\left(\frac{10^{12}G}{B}\right)\left(\frac{10}{E/mc^2}\right)^2$$

magnetar

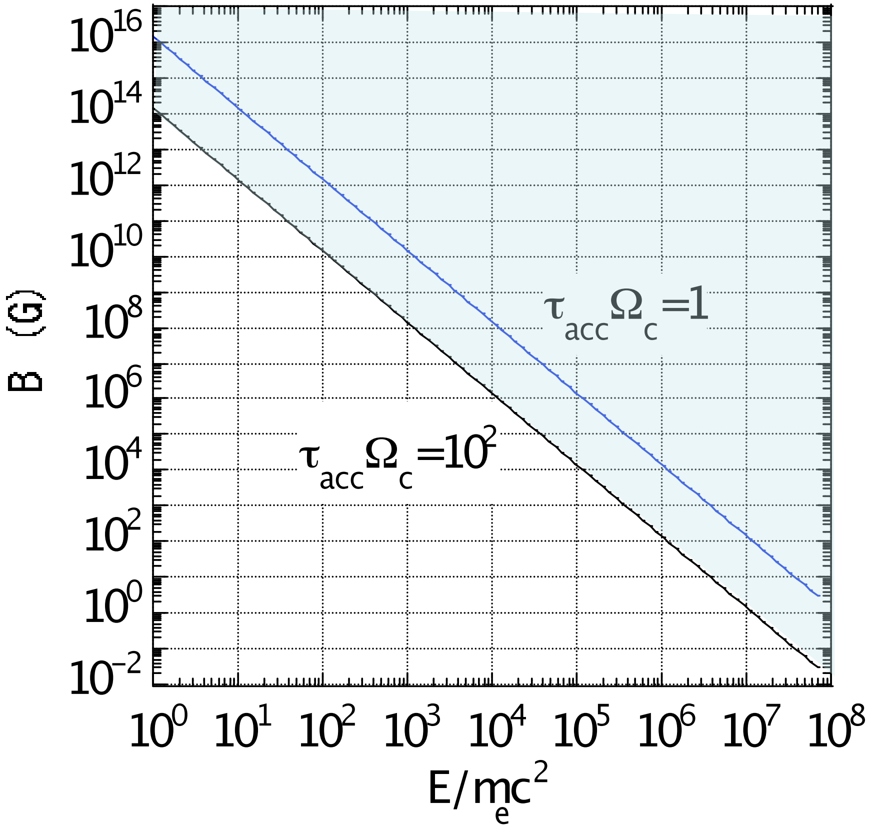


Duncan & Thompson

pulsar



Spitkovsky (2006)



Radiation Loss Effect in PIC Simulation Code

Abraham-Lorentz Formula for Radiation Drag Force

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

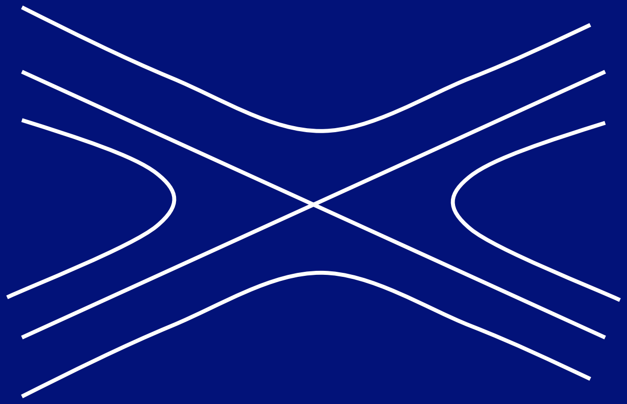
$$\begin{aligned} g^i &= \frac{2e^2}{3c}\left(\frac{d^2\,u^i}{ds^2} + u^i\frac{d\,u^k}{ds}\frac{d\,u_k}{ds}\right) \\ &= \frac{2e^3}{3mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l - \frac{2e^4}{3m^2c^5}F^{ik}F_{lk}u^l + u^i\cdot\frac{2e^4}{3m^2c^5}(F^{kl}u_l)(F_{km}u^m) \end{aligned}$$

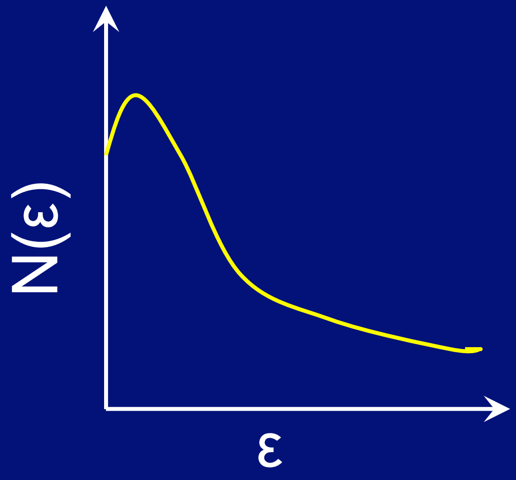
$\alpha \equiv \omega_c\tau_0 = \frac{eB}{mc}\frac{e^2}{mc^3} << 1$ τ_0 : Light crossing time over classical electron radius

(cf. Noguchi & Liang 2006; Koga et al. 2007)

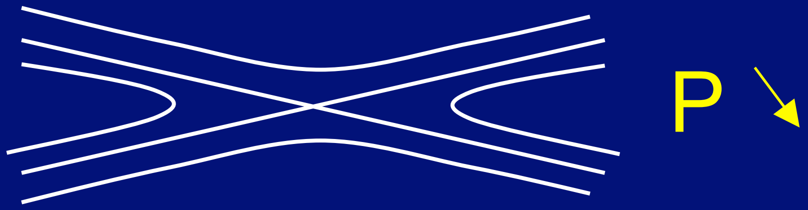
Synchrotron Radiation Effect

Without radiation loss

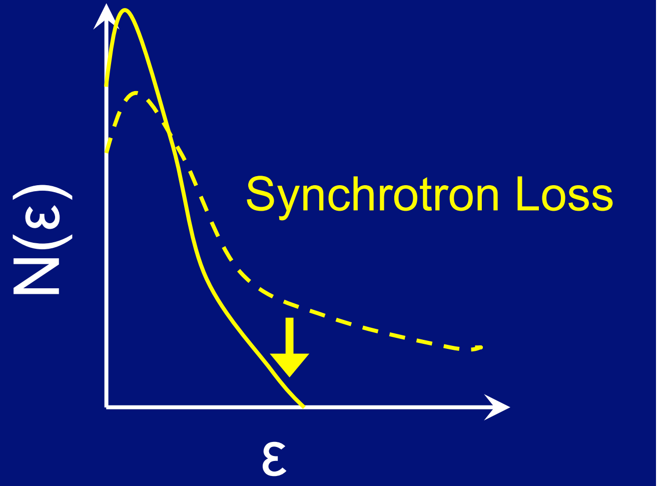




With radiation loss



Fast Reconnection



Time Evolution of MR & DKI

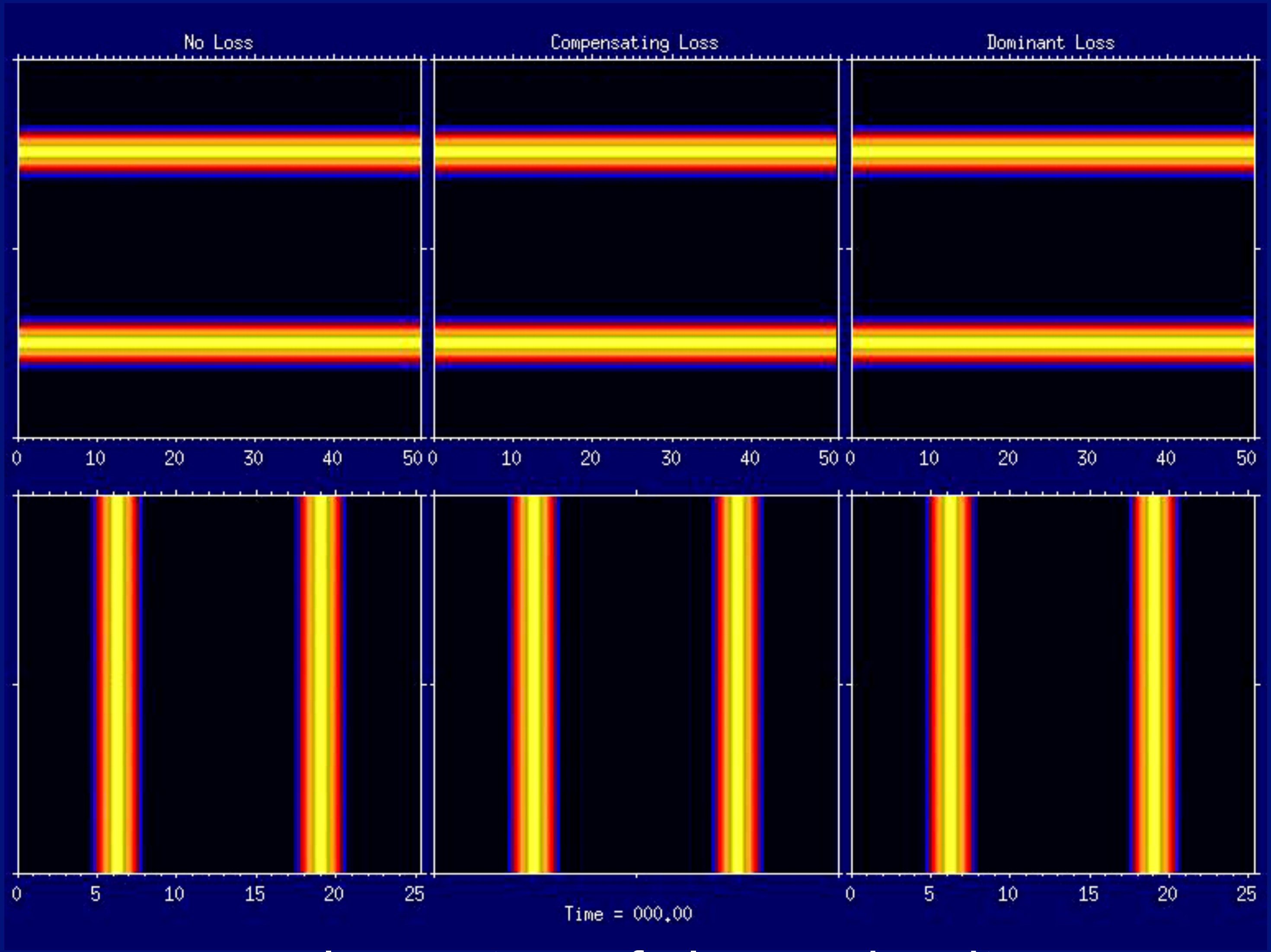
No Radiation Loss

Intermediate

Dominant Radiation Loss

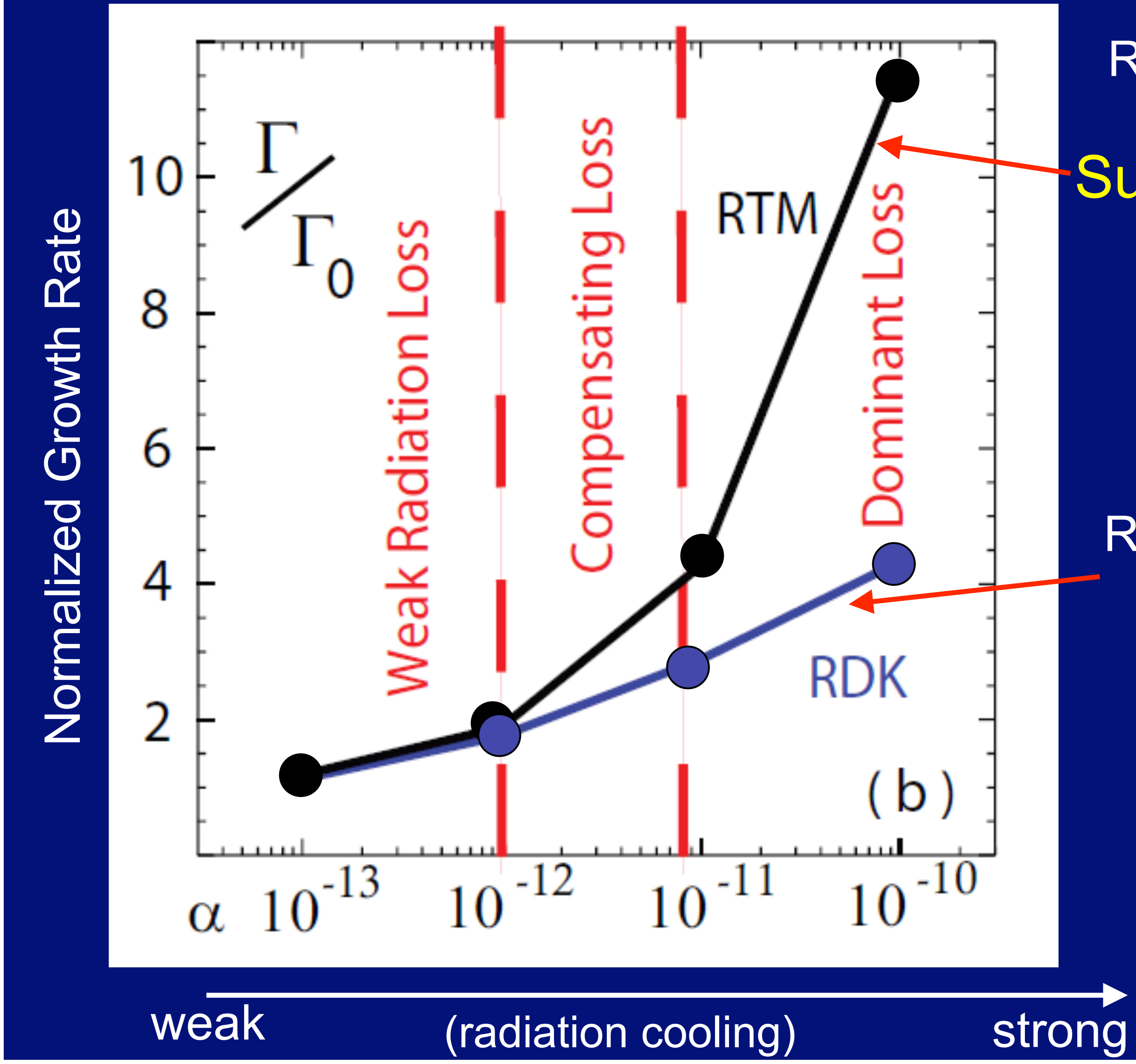
Tearing

Drift-Kink



color contour of plasma density

Comparison of Growth Rate



Relativistic Tearing Mode

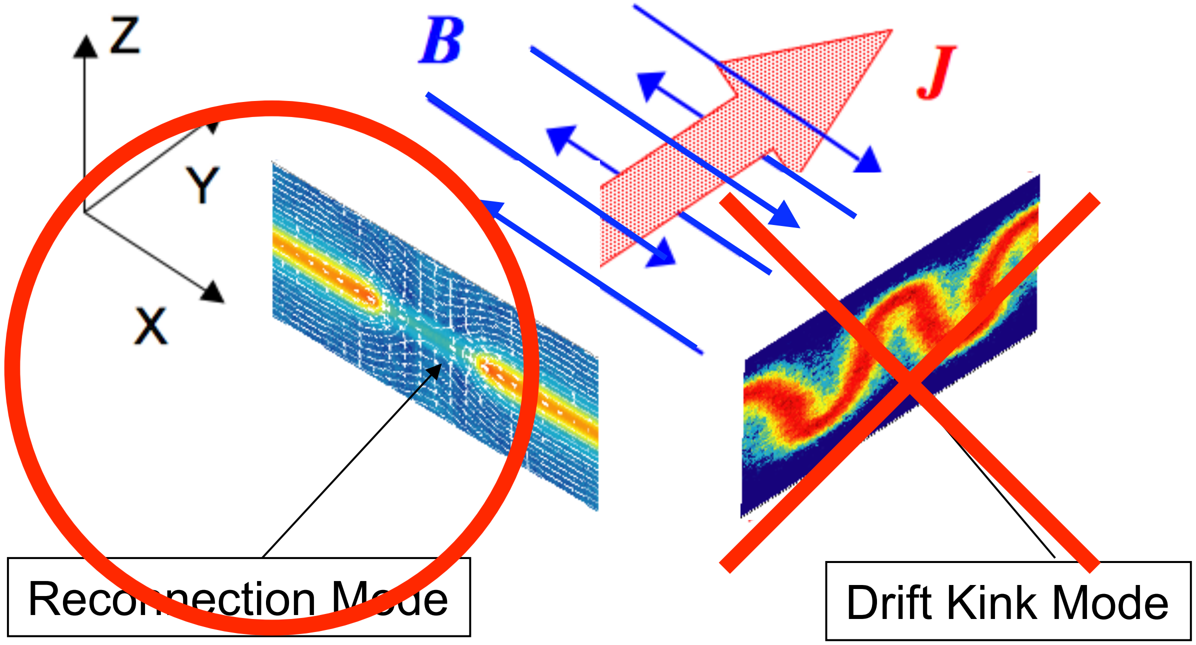
Super-Fast Reconnection

$T_{\perp} > T_{//}$

Relativistic Drift-Kind Mode

Relativistic Current Sheet Instabilities

Radiation Cooling
$V_A/c \sim O(1)$, $T/mc^2 \sim O(1)$,
Electron and Positron Plasmas



Reconnection Mode

Faster Growth Rate

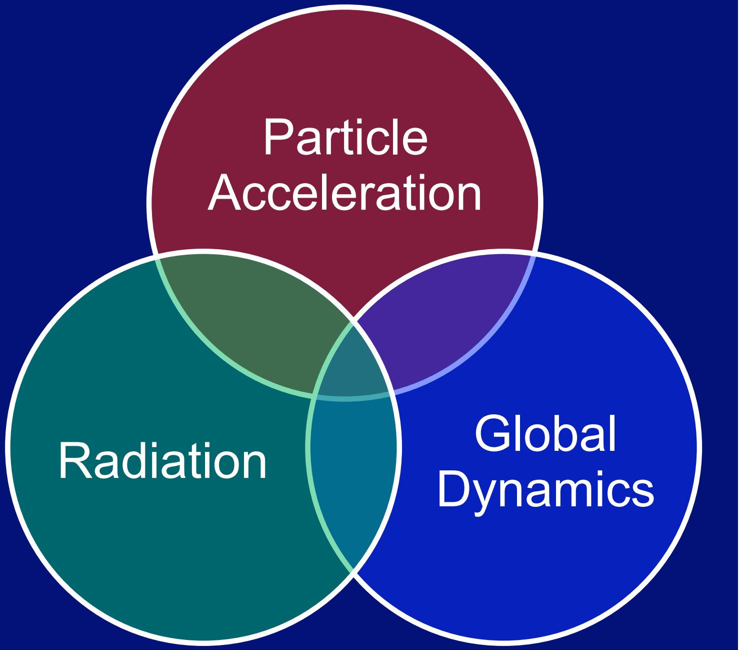
Drift Kink Mode

Fast Growth Rate

Opportunities in Relativistic Reconnection

- Relativistic Plasma Sheet with $T/mc^2 >> 1$
  - "Drift-Kink" > "MRX" without radiation effect
  - "MRX" > "Drift-Kink" with radiation cooling

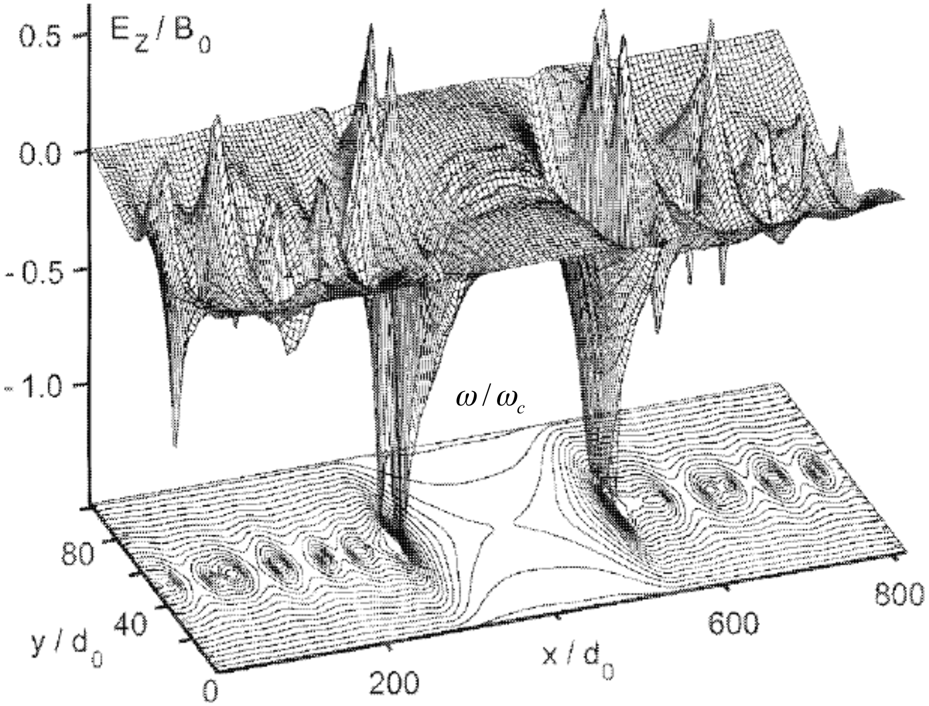
- Laser Produced Reconnection
  - efficiency of particle acceleration as a function of V_A/c


Particle Acceleration

Radiation

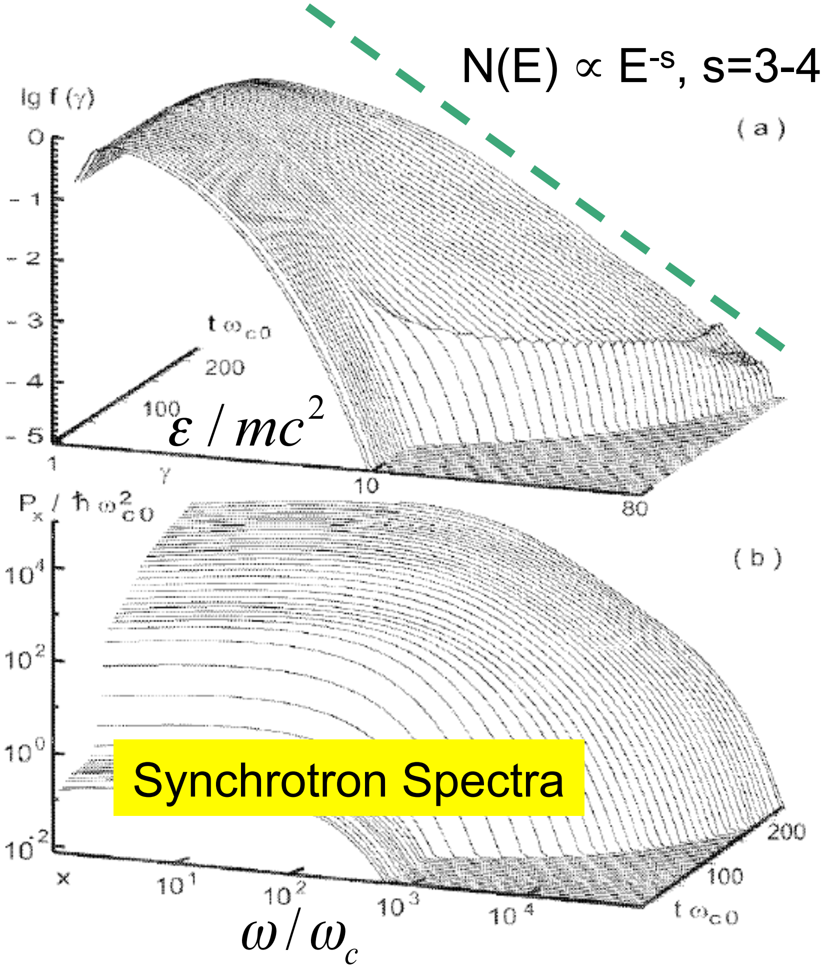
Global Dynamics

Large Scale Relativistic Reconnection



Power-law Energy Spectrum

$N(E) \propto E^{-s}$, s=3-4



Synchrotron Spectra

Jaroschek et al. ApJ 2004

Radiation Loss Effect in PIC Simulation Code

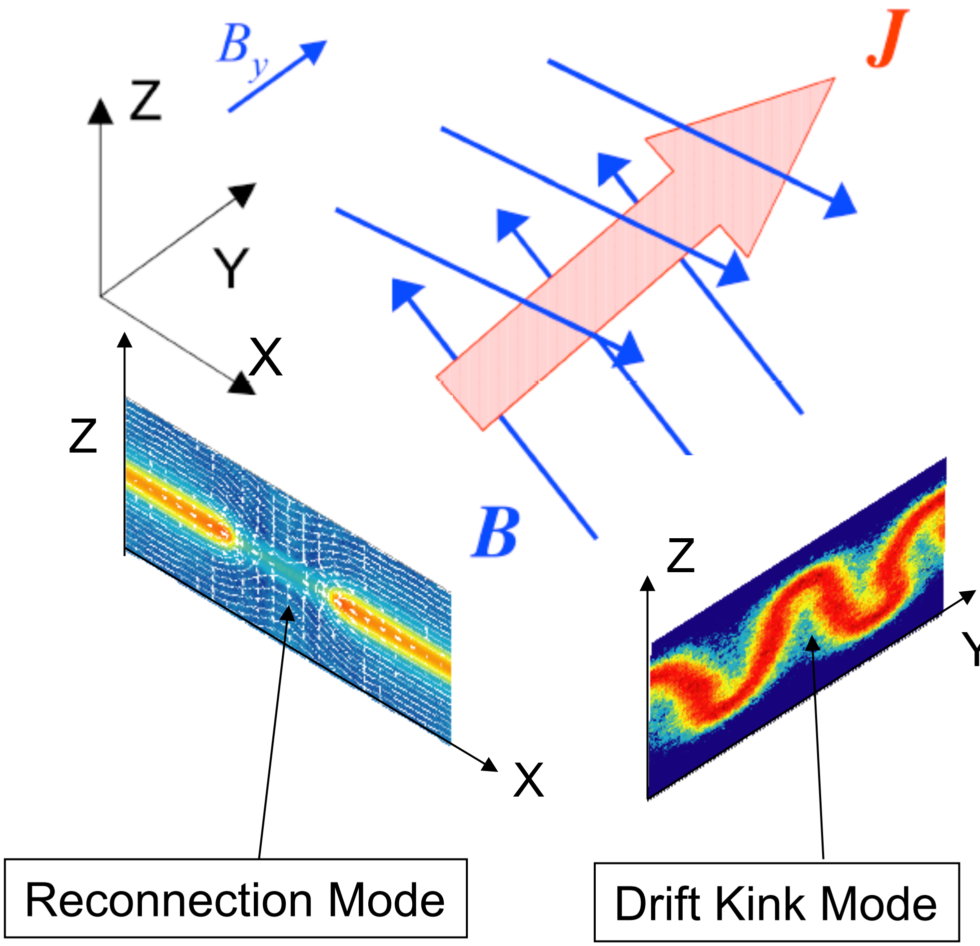
Abraham-Lorentz Formula for Radiation Drag Force

$$
\begin{aligned}
\mathbf{T}_1 &= \frac{2}{3}\gamma \cdot (\omega_{c0}\tau_0) \cdot (mc\omega_{c0}) \cdot \left(\, (\hat{\partial}_t + \hat{\mathbf{v}} \cdot \hat{\nabla})\hat{\mathbf{E}} + \hat{\beta} \times (\hat{\partial}_t + \hat{\mathbf{v}} \cdot \hat{\nabla})\hat{\mathbf{B}} \,\right) \\
\mathbf{T}_2 &= \frac{2}{3} \cdot (\omega_{c0}\tau_0) \cdot (mc\omega_{c0}) \cdot \left(\, \hat{\mathbf{E}} \times \hat{\mathbf{B}} + \hat{\mathbf{B}} \times (\hat{\mathbf{B}} \times \beta) + \hat{\mathbf{E}}(\beta \cdot \hat{\mathbf{E}}) \,\right) \\
\mathbf{T}_3 &= -\frac{2}{3}\gamma^2 \cdot (\omega_{c0}\tau_0) \cdot (mc\omega_{c0}) \cdot \beta \cdot \left(\, (\hat{\mathbf{E}} + \beta \times \hat{\mathbf{B}})^2 - (\hat{\mathbf{E}} \cdot \hat{\beta})^2 \,\right)
\end{aligned}
$$

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

Main Radiation Effect is Synchrotron Radiation

3D Reconnection with Guide Field (By)

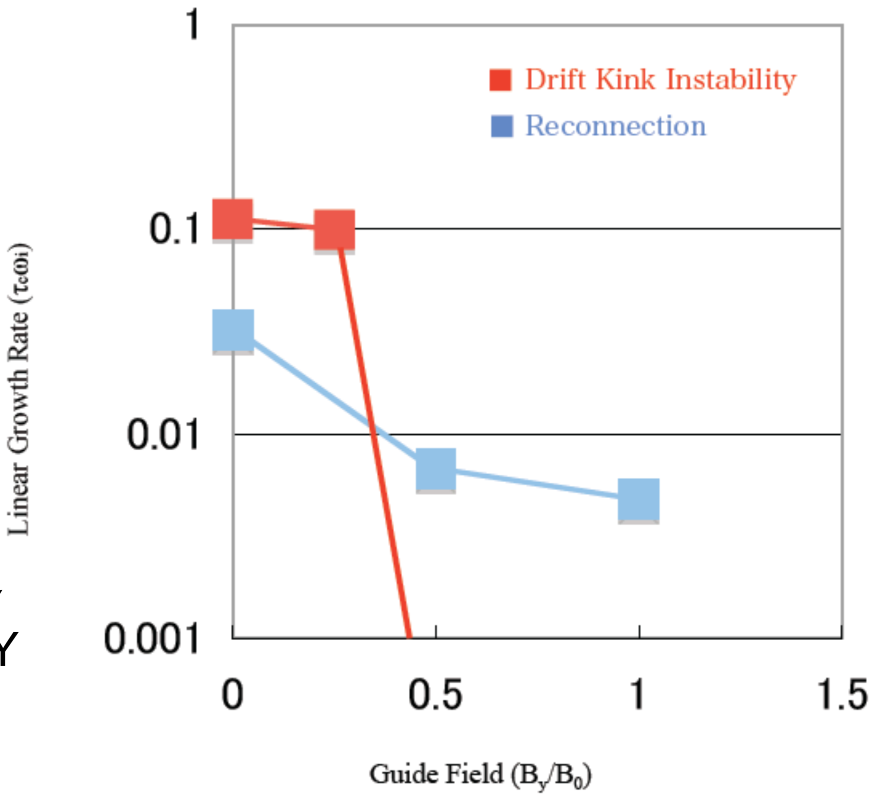


Reconnection Mode

Faster Growth Rate

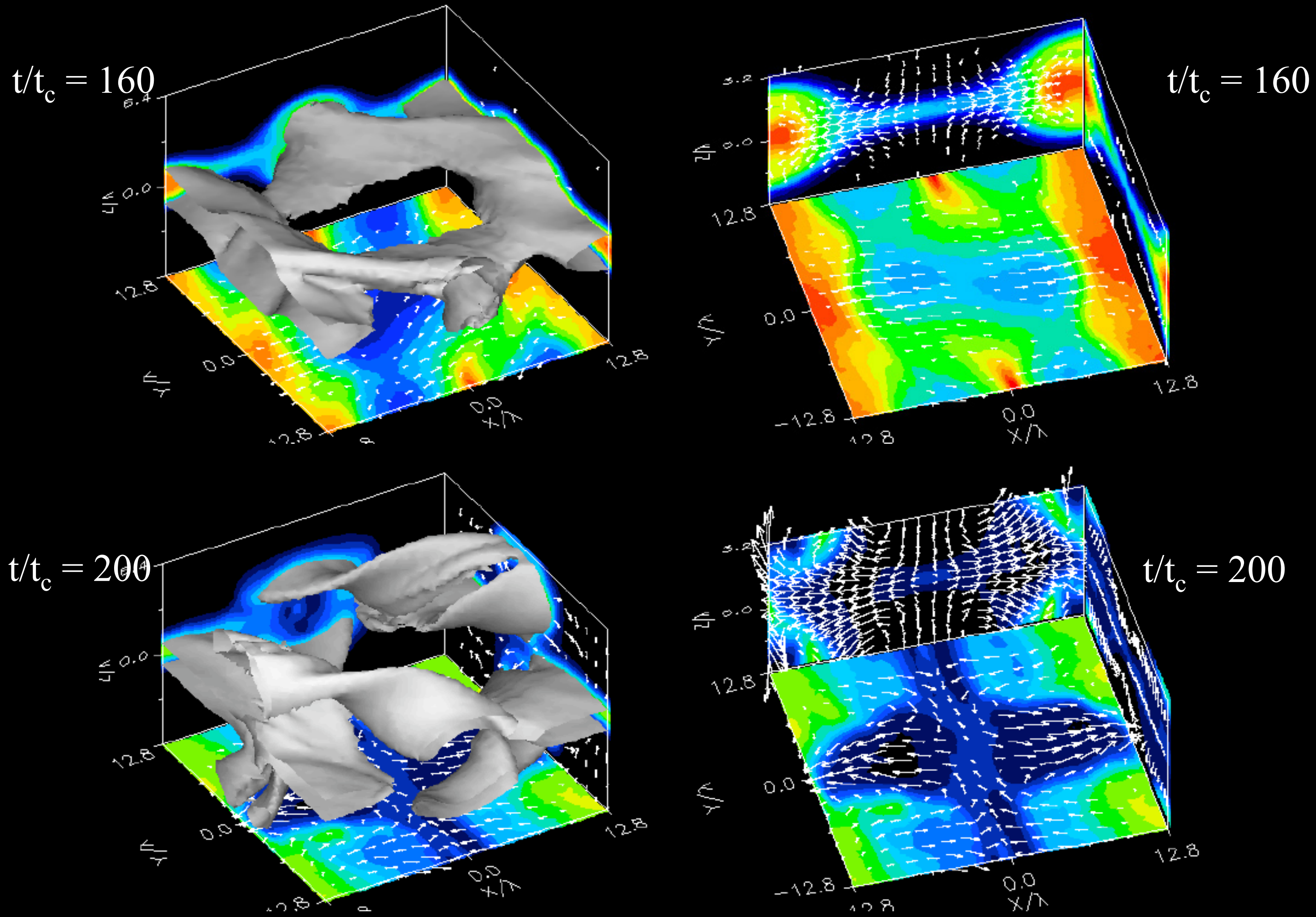
Drift Kink Mode

Slower Growth Rate



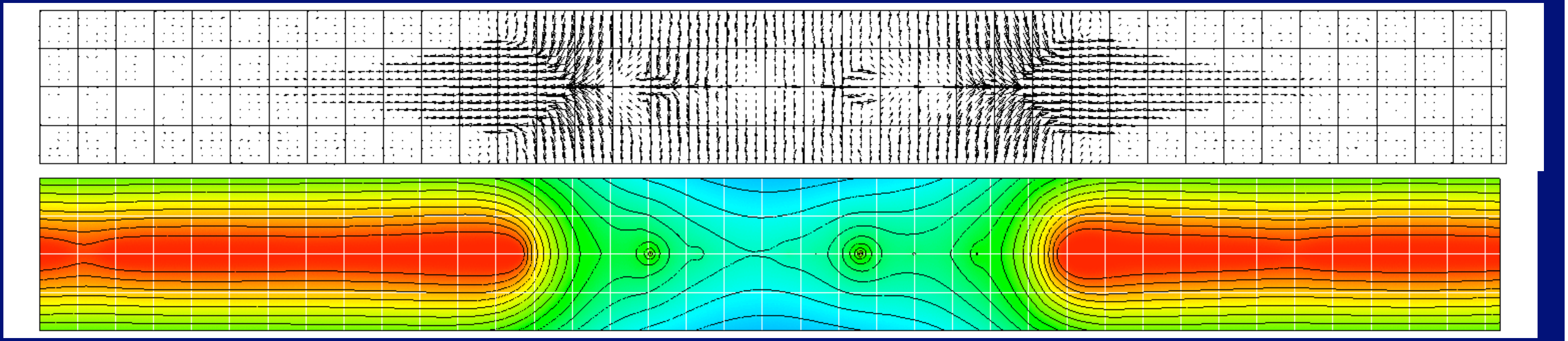
Drift-Kink is suppressed due to magnetic tension force

3D Reconnection with Guide Field

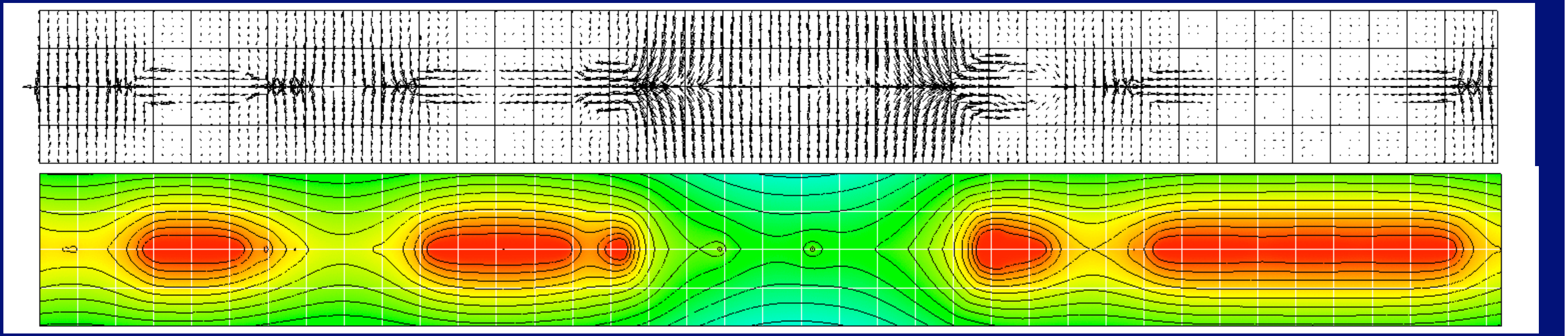


Zenitani & MH, PRL 2005

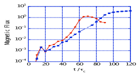
Radiation cooling (OFF)



Radiation cooling (ON)

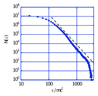


radiation cooling at plasma sheet → pressure decreases →
thin current sheet → fast reconnection with stronger E=-vxB field,
small magnetic islands



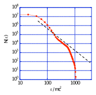
radiation loss

no radiation



no radiation

$$\boxed{N(\varepsilon) \propto \varepsilon^{-3.3}}$$



radiation loss

$$\boxed{N(\varepsilon) \propto \varepsilon^{-2.4}}$$