THE UNIVERSITY OF TOKYO

Nonlinear Explosive Magnetic Reconnection in Collsionless System

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Magneto-luminescence:

Magnetic Energy Dissipation in Astrophysics

Blandford+ Space Sci. Rev. 2017

◎ **Pulsars and their nebulae:**

γ-ray flares in Crab Nebula (AGILE/Fermi observation, e.g., Tavani+11,Abdo+11)

σ-problem ($\sigma >> 1$ in magnetosphere, whereas $\sigma <<1$ in nebula)

◎ **Blazars:**

jets from a massive black hole (10^6-$10^{10}M_{sun}$), bulk Lorentz factor $\Gamma \sim 10$

energy supply by gas accretion or BH spin-up

rapid time variable GeV/TeV flares (e.g., Albert+07, Aharonican+ 07, Aleksic+ 11)

◎ **Gamma Ray Bursts:** (e.g., Kouveliotou+12 for a review)

short bursts (neutron star binary), long bursts (core-collapse supernovae)

relativistic jests with bulk Lorentz factor $\Gamma \sim 100$-1000

◎ **Magnetars:** (e.g., Kaspi & Beloborodov 17 for a review)

a minority of neutron stars/born with millisecond pulsars

B ~ 10-100 GT @ surface, flare observations (e.g., Evans+ 80)

Time Scale of Magnetic Reconnection

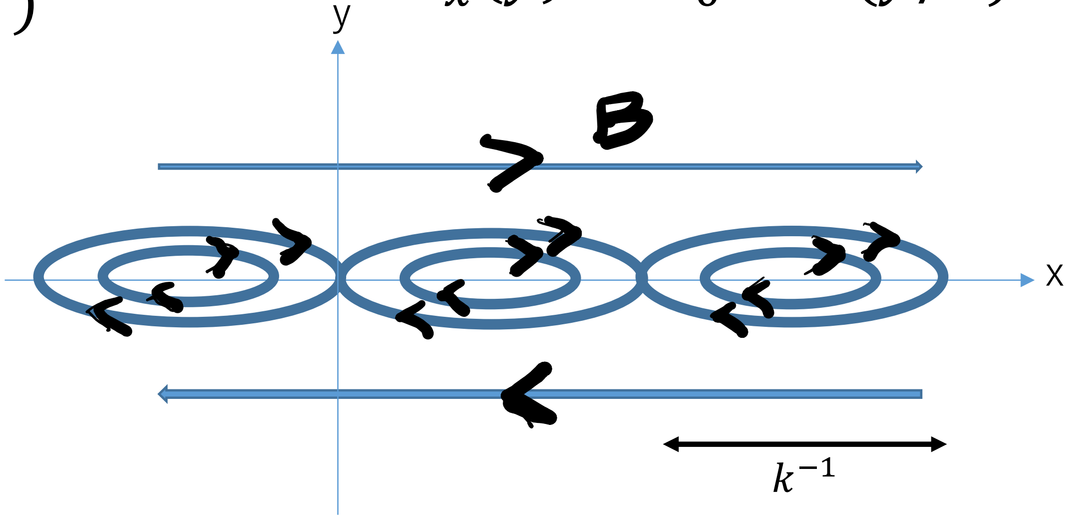
Collisionless tearing-mode instability

$$\gamma_L \tau_A \approx (r_g/\lambda)^{\frac{3}{2}} \left(1 + \frac{T_i}{T_e}\right)\left(1 - k^2\lambda^2\right)$$

$\tau_A = \lambda / V_A$: Alfven transit time r_g: gyro-radius

Coppi+ 1966, Hoh 1966

$$B_x(y) = B_0 \tanh(y/\lambda)$$



Open question:

very slow growth rate for $r_g << \lambda$

This Talk=>

Nonlinear tearing-mode instability

$$\gamma \tau_A \approx O(0.1) - O(1)$$

cf. MHD tearing-mode instability

$$\gamma_{FKR} \tau_A \approx R_m^{-3/5} \left(\frac{1 - k^2\lambda^2}{k\lambda}\right)^{4/5}$$

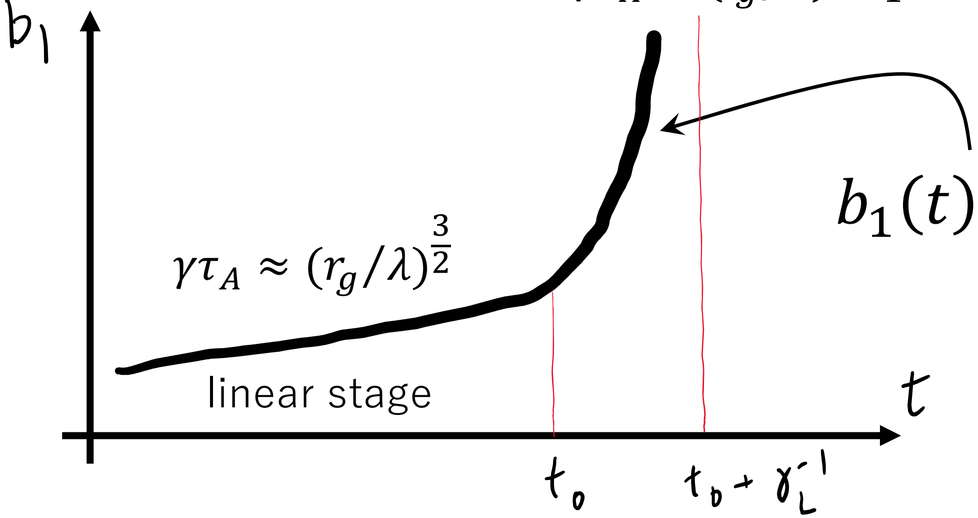
Furth, Killeen & Rosenbluth 1963

Explosive Reconnection by Galeev

$$\gamma_G \tau_A \approx (r_g/\lambda)^{\frac{1}{2}}\ b_1\left(1+\frac{T_i}{T_e}\right)(1-k^2\lambda^2)$$

Galeev + 1978

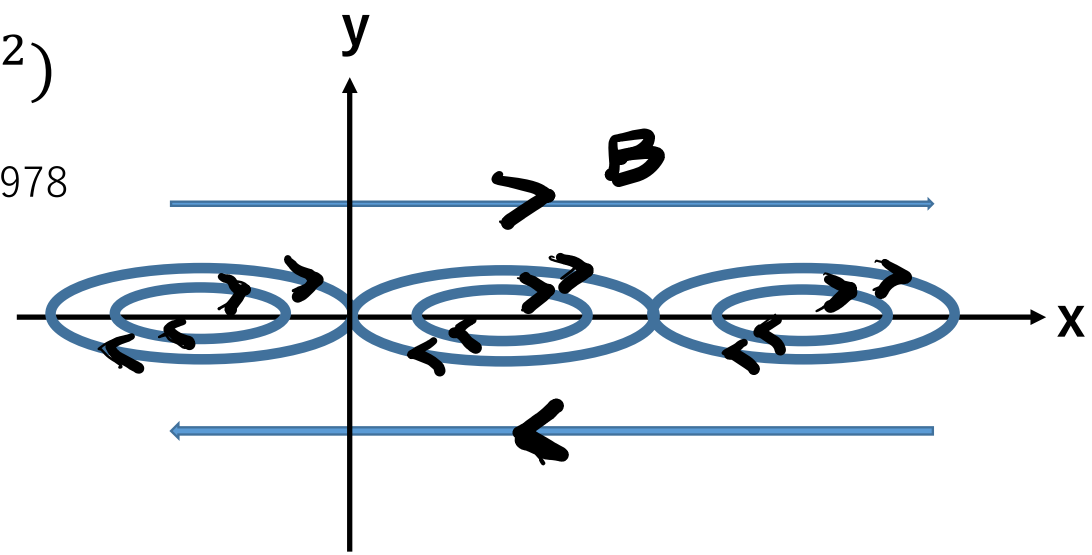
$b_1 \equiv \delta B_y/B_0$
amplitude of reconnecting B



$\gamma\tau_A \approx (r_g/\lambda)^{\frac{1}{2}} b_1$

$\gamma\tau_A \approx (r_g/\lambda)^{\frac{3}{2}}$

linear stage



$$b_1(t) = b_1(t_0)/(1-(t-t_0)\gamma_L)$$

$$\gamma_G \equiv d\log(b_1)/dt$$

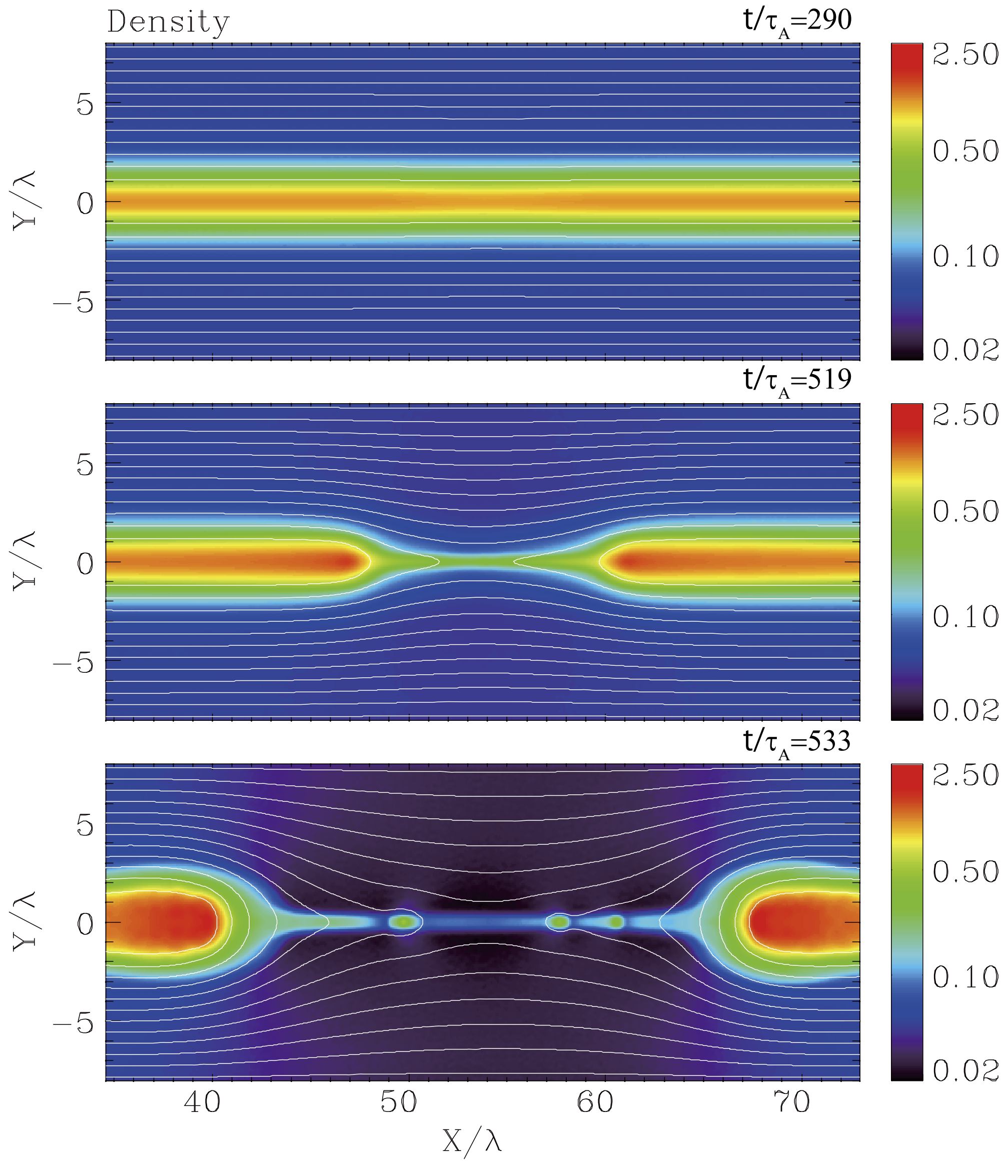
Simulation study: Terasawa 1981

PIC Simulations (particle-in-cell)

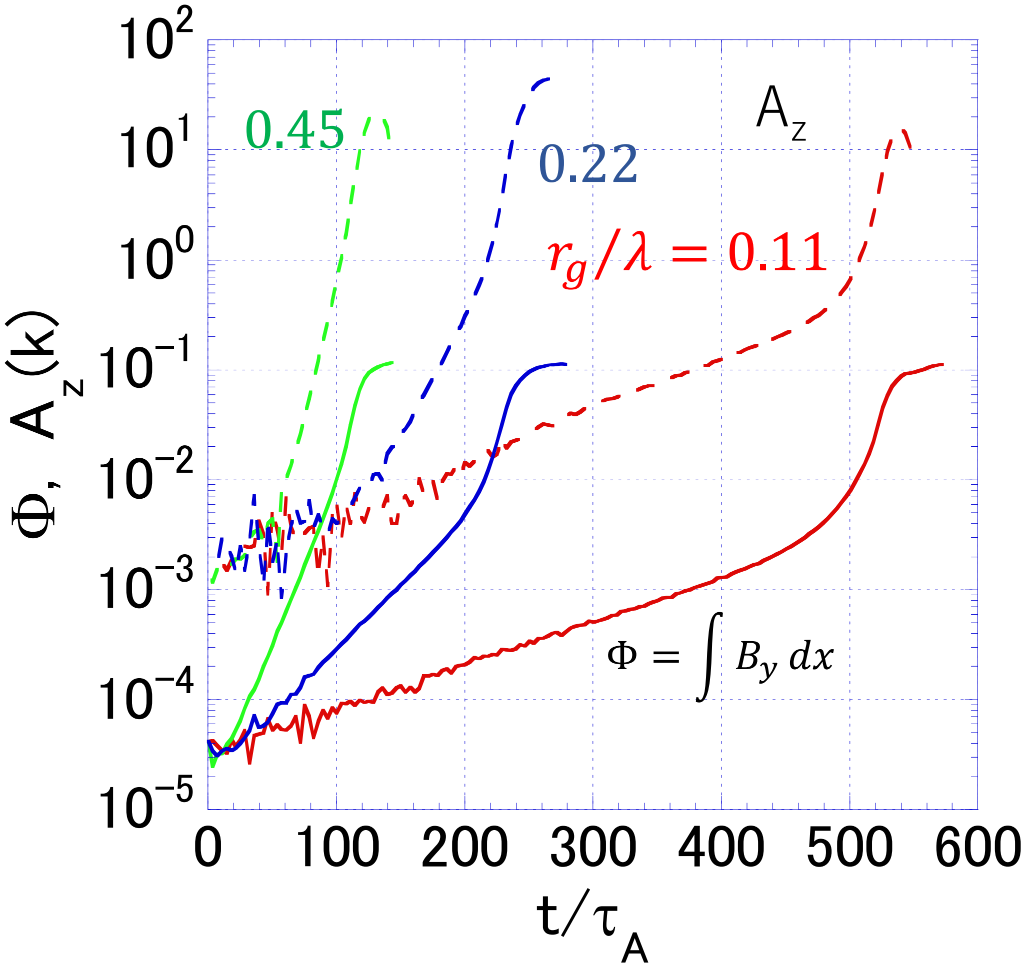
linear stage:
Harris equilibrium,
for simplicity, pair plasma

early nonlinear stage:
shrinkage of current
sheet @ maximum
growth rate

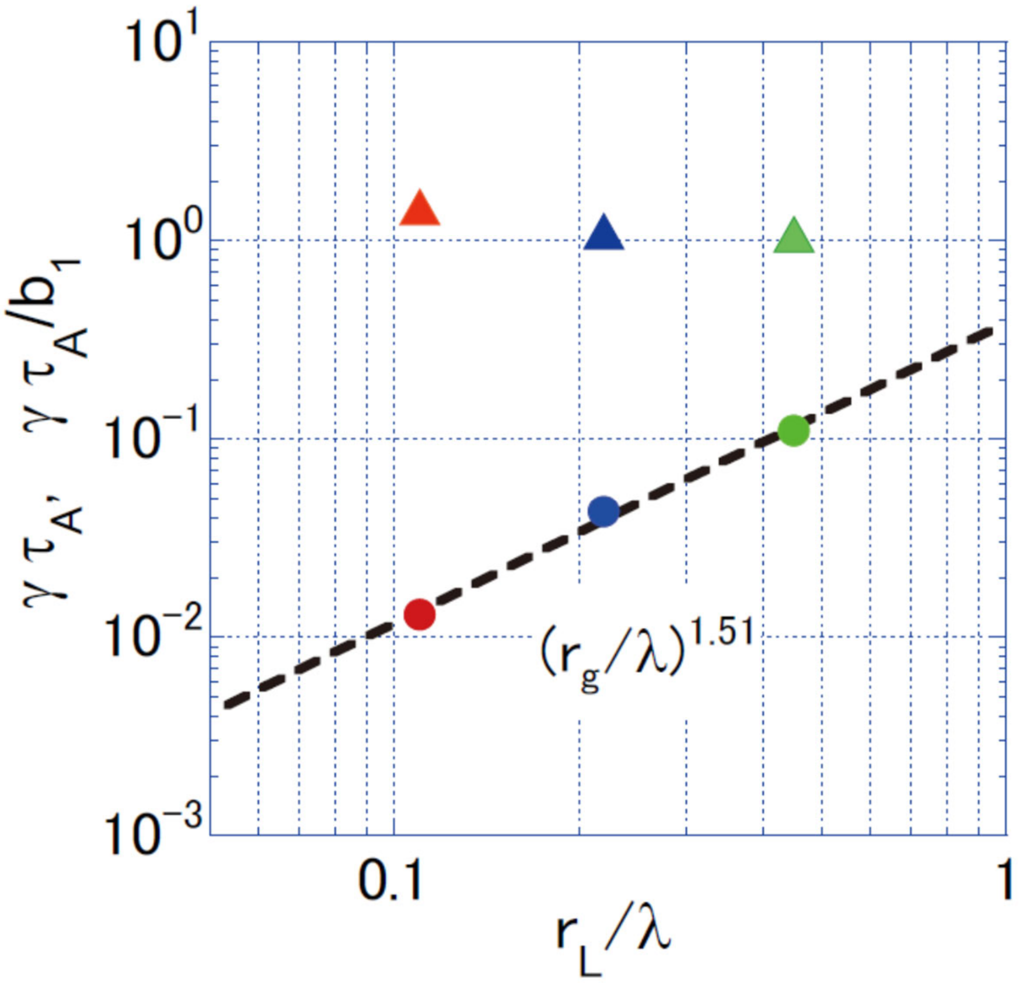
late nonlinear stage:
elongated current
sheet with several
plasmoids/turbulence



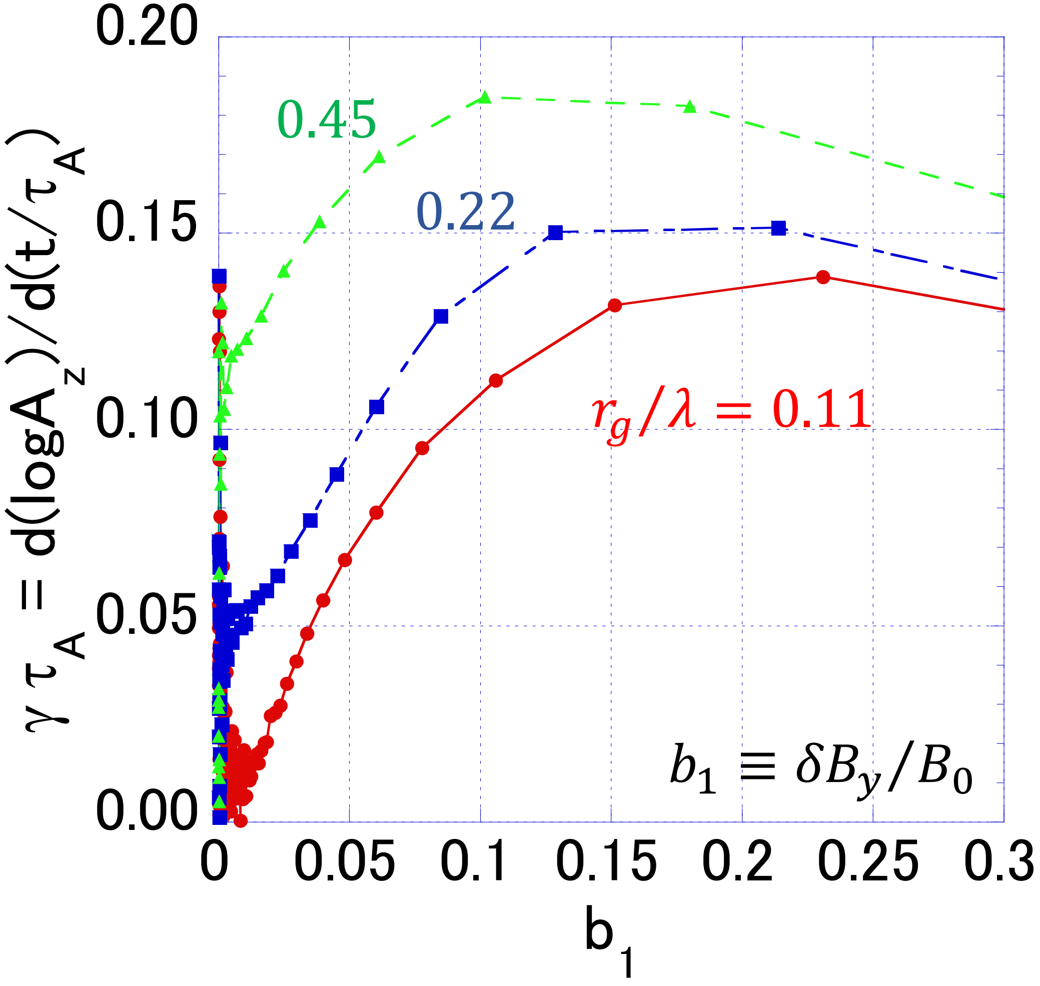
time history: growth curve



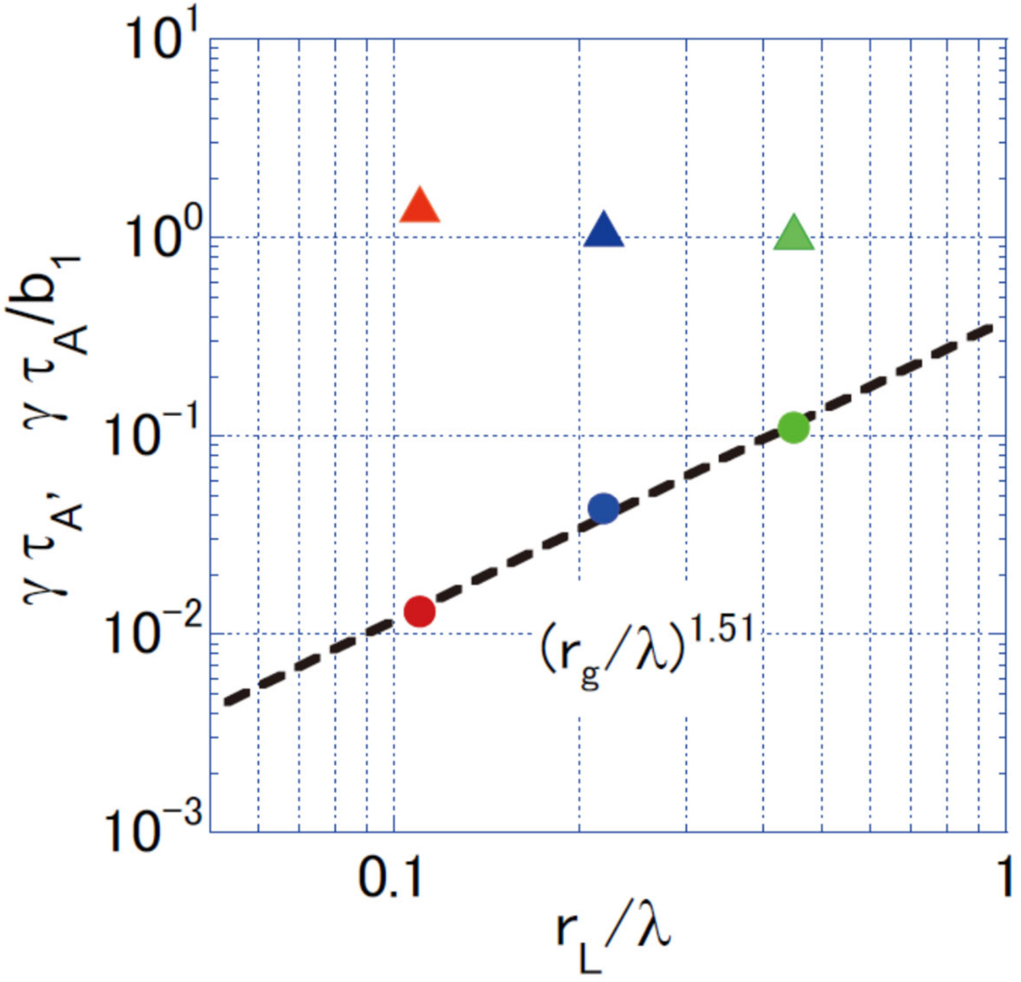
growth rates for linear & nonlinear



“instantaneous” growth rates



growth rates for linear & nonlinear



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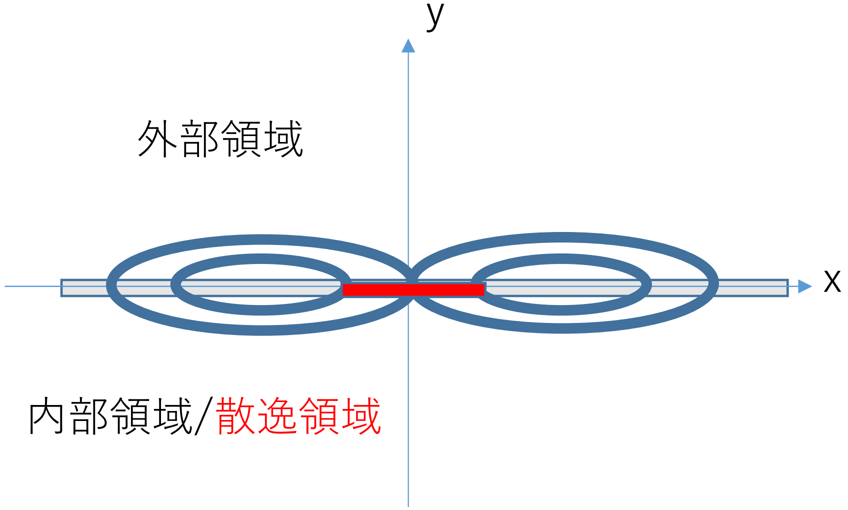
Theory of tearing instability (1/3)

$$\frac{1}{8\pi}\frac{\partial}{\partial t}\left(\vec{B}^2+\vec{E}^2\right)=-\frac{c}{4\pi}\nabla\cdot\left(\vec{E}\times\vec{B}\right)-\vec{E}\cdot\vec{J}$$

$$\vec{B}=\nabla\times A\vec{e}_z \qquad A(x,y)=A_0(y)+A_1(y)\cos(kx)$$

$$\frac{\partial}{\partial t}\iint\frac{B_1^2}{8\pi}dxdy+\iint E_1\cdot J_1^{ad}dxdy=-\iint E_1\cdot J_1^{res}dxdy$$



内部領域の電流

$$J_1^{res}=\sigma E_1 \qquad \sigma=\left(\frac{ne^2}{m}\right)\left(\frac{d_x}{v_{th}}\right)$$

外部領域の電流・ベクトルポテンシャル A

$$B_{0x}(y)=B_0\tanh(y/\lambda)$$

$$A_1(y)=A_1(0)\left(1+\frac{\tanh(|y|/\lambda)}{k\lambda}\right)\exp(-k|y|)$$

Theory of tearing instability (2/3)

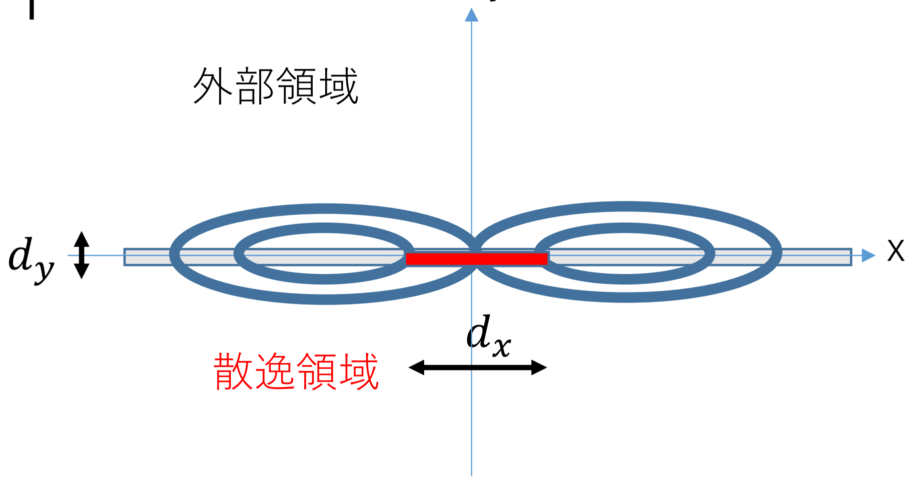
外部領域

$$\frac{\partial}{\partial t}\iint \frac{B_1^2}{8\pi} dxdy + \iint E_1 \cdot J_1^{ad} dxdy = \frac{\partial}{\partial t}\left[\frac{1}{4\pi}\frac{(k^2\lambda^2 - 1)}{k^2\lambda^2}|A_1(0)|^2\right]$$

内部領域/散逸領域/Ohm拡散領域

$$-\iint E_1 \cdot J_1^{res} dxdy = -2\sigma|E_1|^2 d_x d_y = -\frac{1}{2\pi}\frac{\omega_p^2}{c^2}\frac{d_x}{v_{th}}\left|\frac{\partial}{\partial t}A_1(0)\right|^2 d_x d_y$$

$$J_1^{res} = \sigma E_1 \qquad E_1 = -\frac{1}{c}\frac{\partial}{\partial t}A_1 \qquad \sigma = \left(\frac{ne^2}{m}\right)\left(\frac{d_x}{v_{th}}\right)$$



（外部領域のエネルギー）=（散逸領域のエネルギー）

$$\frac{\pi}{k}\frac{(1 - k^2\lambda^2)}{k\lambda^2} = \gamma \frac{\omega_p^2}{c^2}\frac{d_x}{v_{th}} d_x d_y$$

Theory of tearing instability (3/3)

Master Equation（外部領域のエネルギー)=(散逸領域のエネルギー）

$$\frac{\pi}{k}\frac{(1-k^2\lambda^2)}{k\lambda^2}=\gamma\frac{\omega_p^2}{c^2}\frac{d_x}{v_{th}}d_x d_y$$

Linear Tearing Instability e.g. Coppi+ 1966, Hoh 1966

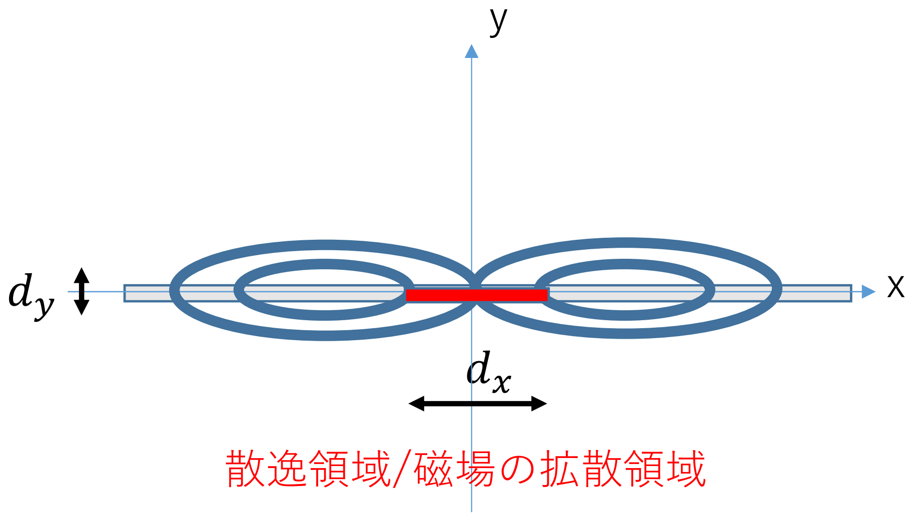
$$d_x=k^{-1},\quad d_y=\sqrt{r_g\lambda}$$

$$\Rightarrow \gamma\tau_A \approx (r_g/\lambda)^{\frac{3}{2}}$$

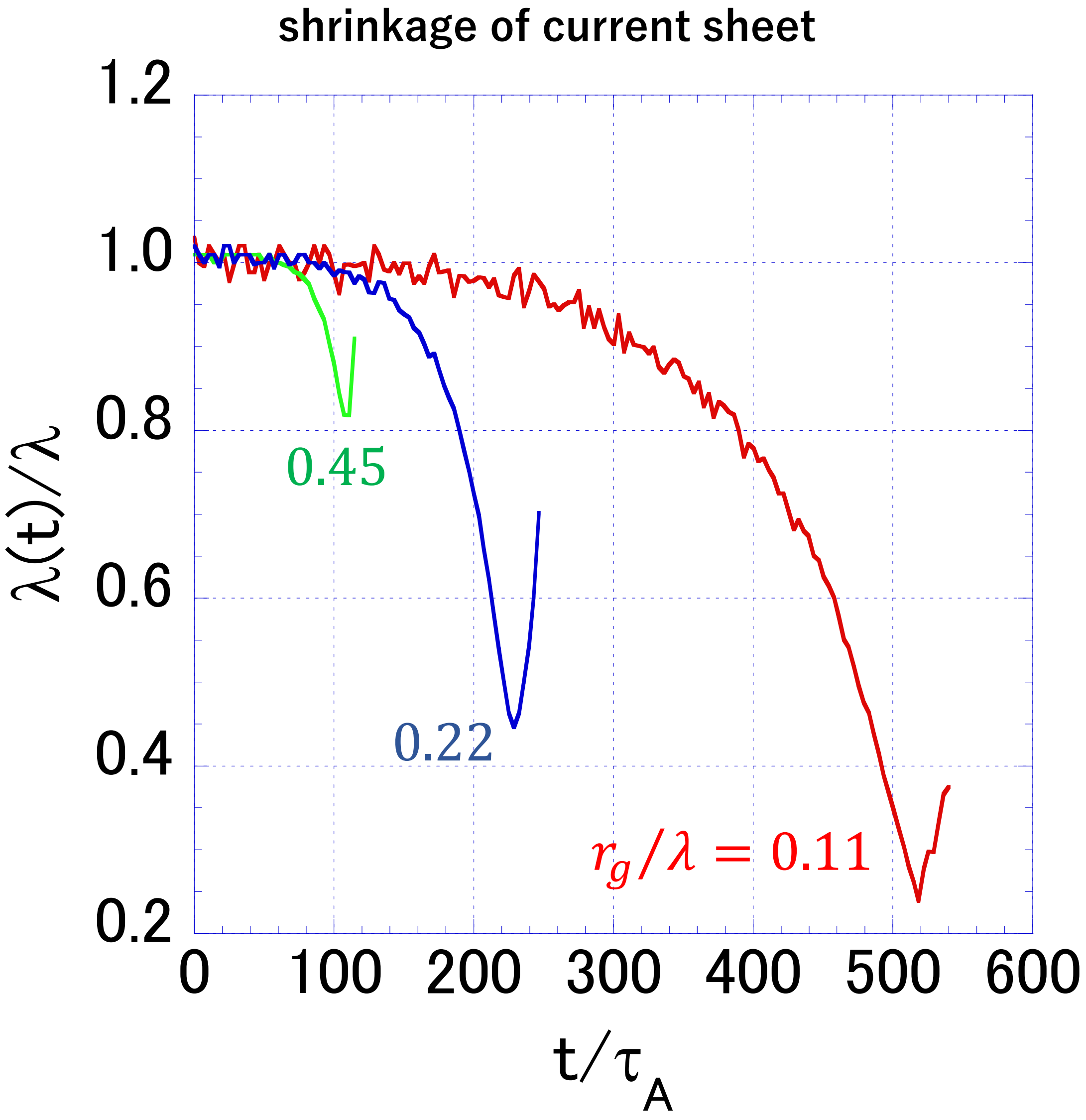
Galeev's tearing instability Galeev + 1978

$$d_x=\sqrt{r_g/(b_1 k)},\quad d_y=\sqrt{r_g\lambda}$$

$$\Rightarrow \gamma\tau_A \approx (r_g/\lambda)^{\frac{1}{2}}\, b_1$$



散逸領域/磁場の拡散領域



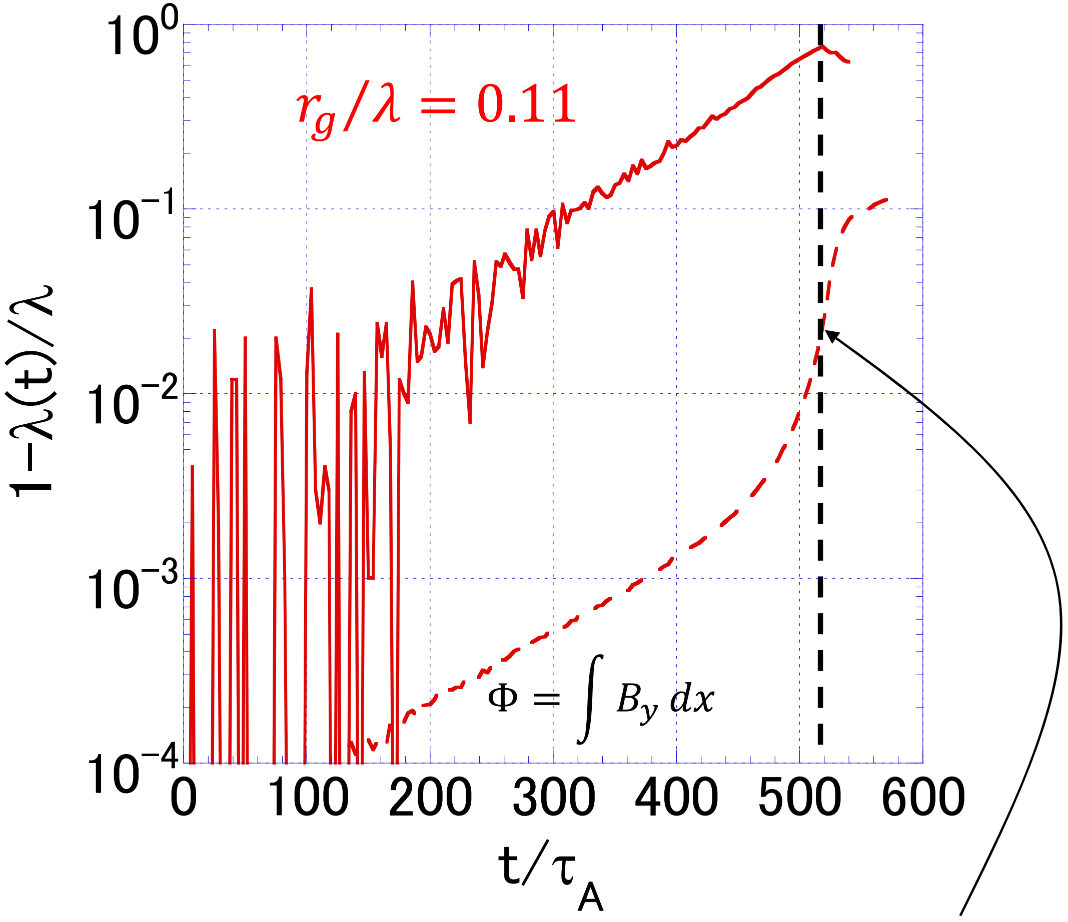
fitting of current sheet

$J_z(y) \propto \mathrm{sech}^2(y/\lambda(t))$

thickness of shrinkage

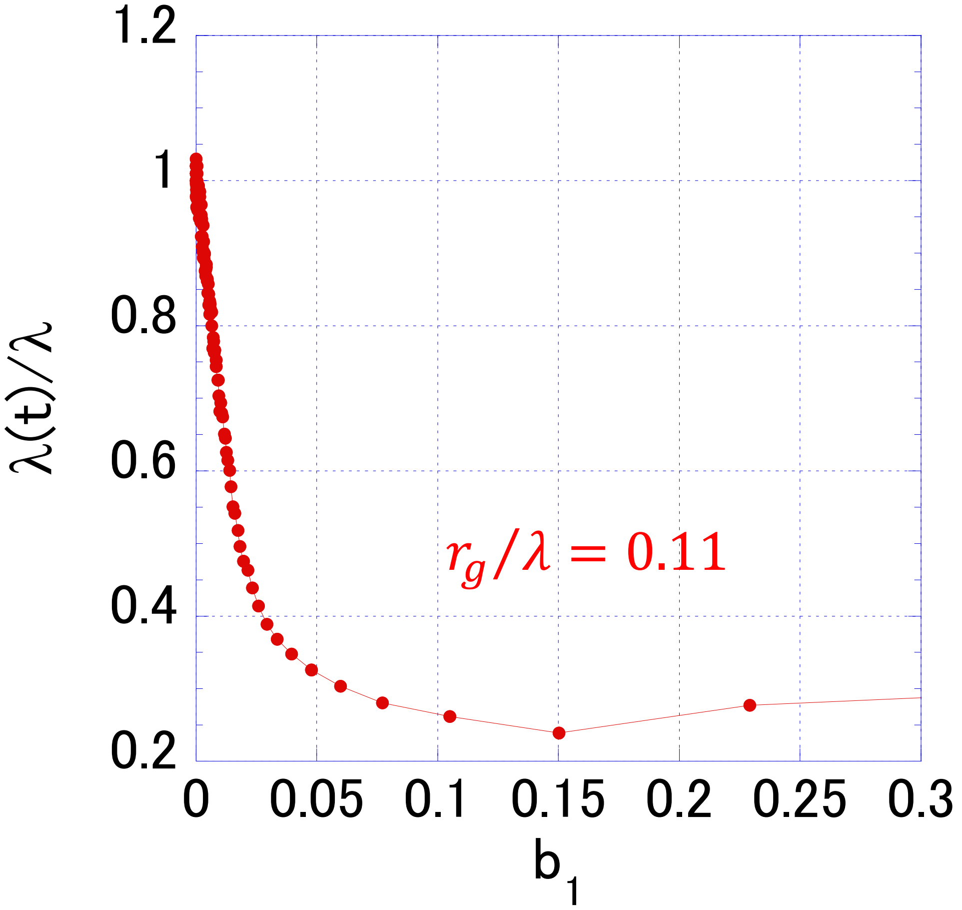
$\lambda_{min} \approx 2r_g$ for any r_g/λ

time history of current sheet & reconnecting flux Φ



minimum thickness = maximum growth rate

shrinkage of current sheet as function b_1



Nonlinear explosive magnetic reconnection

Master Equation（外部領域のエネルギー)=(散逸領域のエネルギー）

$$\frac{\pi}{k}\frac{(1-k^2\lambda^2)}{k\lambda^2} = \gamma\frac{\omega_p^2}{c^2}\frac{d_x}{v_{th}}d_x d_y$$

Linear Tearing Instability

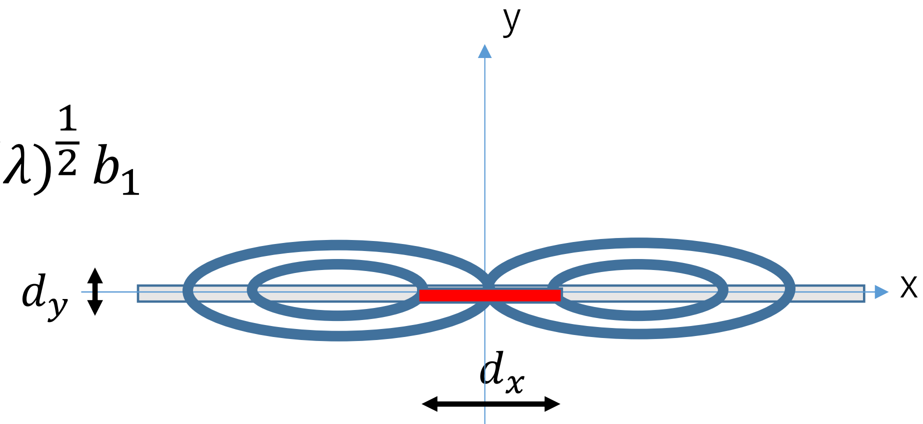
$$d_x = k^{-1},\quad d_y = \sqrt{r_g\lambda} \qquad \Rightarrow \ \gamma\tau_A \approx (r_g/\lambda)^{\frac{3}{2}}$$

Galeev's Nonlinear Tearing Instability

$$d_x = \sqrt{r_g/(b_1 k)},\quad d_y = \sqrt{r_g\lambda} \qquad \Rightarrow \ \gamma\tau_A \approx (r_g/\lambda)^{\frac{1}{2}}\, b_1$$

Nonlinear Explosive Tearing Instability

$$d_x = \sqrt{r_g/(b_1 k)},\quad d_y = 2r_g \qquad \Rightarrow \ \gamma\tau_A \approx b_1$$



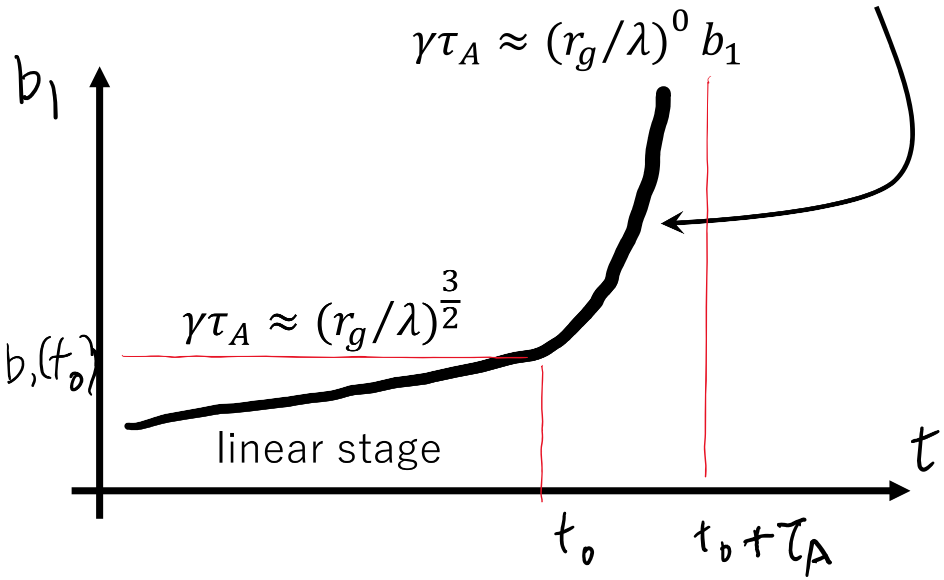
散逸領域/磁場の拡散領域

Summary

nonlinear explosive reconnection

$$\gamma\tau_A \approx b_1$$

$$b_1(t) = b_1(t_0)/(1-(t-t_0)\frac{\pi b_1(t_0)}{k\lambda\tau_A})$$



Onset of nonlinear explosive growth

$$b_1(t_0) = k\, r_g$$

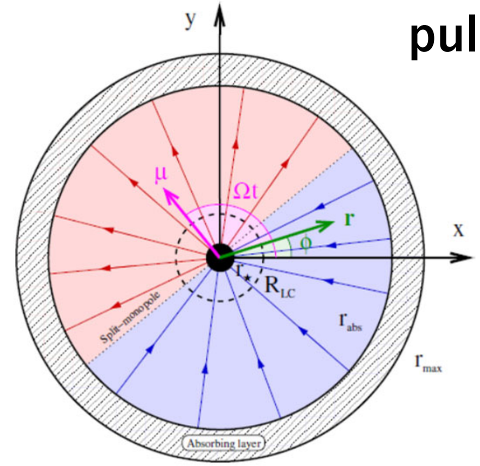
$$k\lambda = O(10^{-1})$$

$$\Rightarrow b_1(t_0) = O(10^{-1})(r_g/\lambda)$$

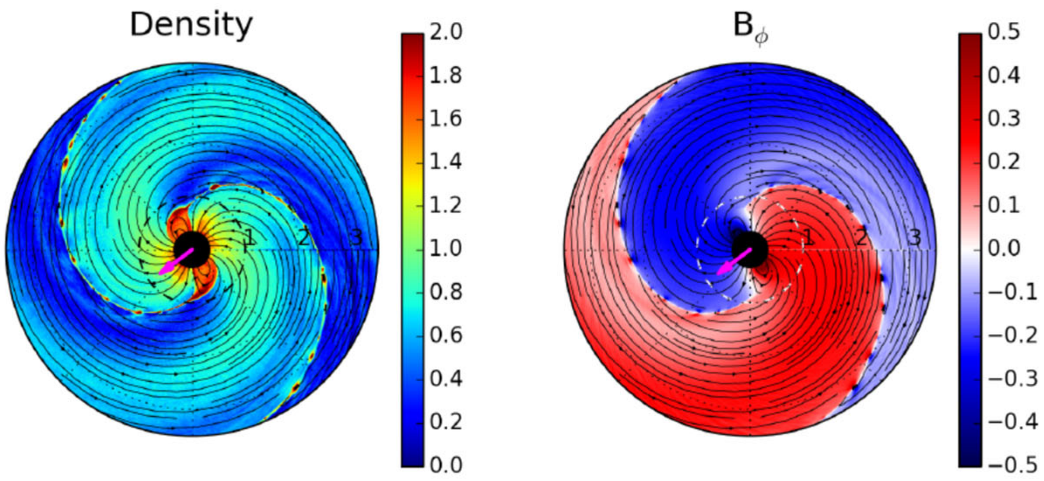
onset appears at very early stage for a thick current sheet with $r_g << \lambda$

Final Remark

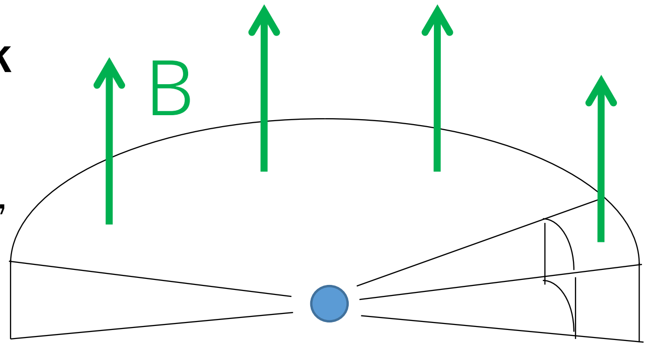
pulsar wind evolution



Split-monopole,
2d & 3d-PIC simulation,
σ problem by reconnection
Cerutti+, 17,20



MRI in accretion disk



2d & 3d-PIC simulation,
particle acceleration
by reconnection,
Hoshino, 13, 15