相対論的ドリフト電流をもつ磁気リコネクション：パルサー風でリコネクションは起きるか

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current starvation

$$J = \frac{c}{4\pi\lambda} B = env, \qquad B \propto \frac{1}{r}, \qquad n \propto \frac{1}{r^2}$$

$$\frac{v}{c} = \frac{B}{4\pi\lambda en} = \left(\frac{B_{lc}}{4\pi\lambda}\frac{1}{en_{GJ}\kappa}\right)\left(\frac{r}{r_{lc}}\right) > \frac{1}{2\kappa}\frac{r}{r_{lc}}$$

$$\frac{B_{lc}}{4\pi\lambda}\frac{1}{en_{GJ}\kappa} \approx \frac{c}{2\lambda\Omega\kappa} > \frac{1}{2\kappa}$$

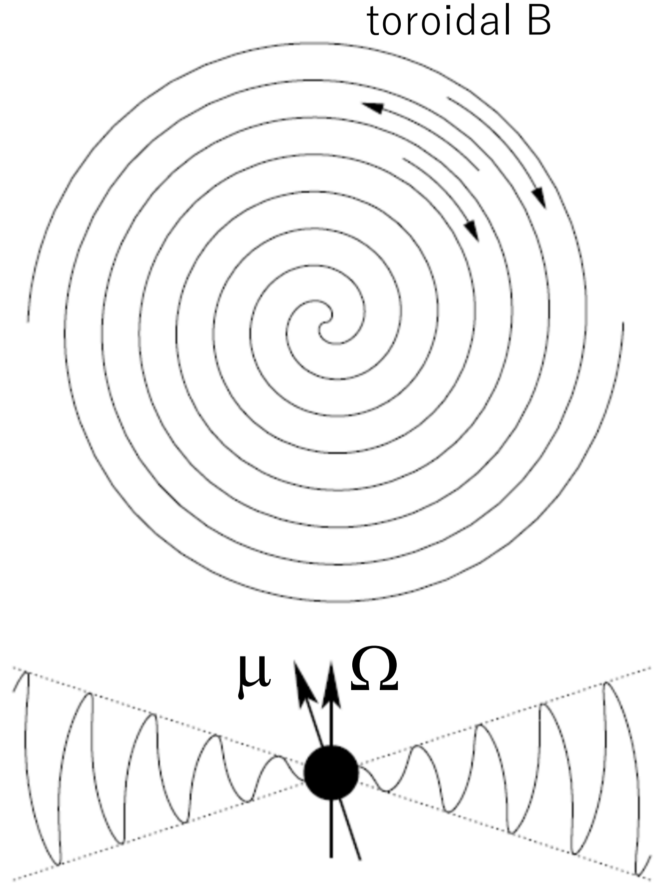
$n_{GJ} = \frac{\Omega \cdot B}{2\pi ec}$ Goldreich-Julian density

$\kappa = 10^3 - 10^4$ multiplicity (Arons 1983)

$\lambda < \frac{c}{\Omega}$

$r_{lc} = 10^9 cm, \qquad r_{shock} = 0.1\, pc = 3 \times 10^{18} cm$

Pulsar Wind



e.g. Usov, 1975; Michel 1982; Lyubarsky & Kirk 2001

Relativistic magnetic reconnection

$T/mc^2 > 1$ relativistic hot plasma

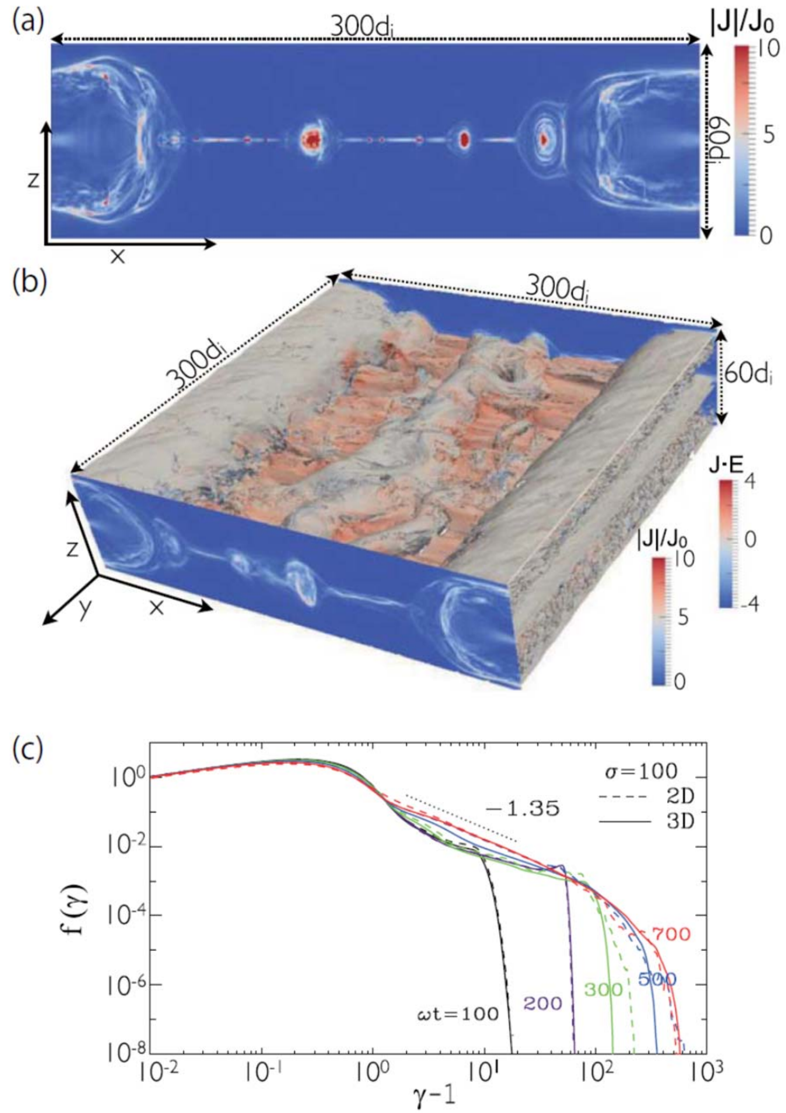
$P + \frac{1}{8\pi}B^2 = const.$ $P = 2nT$ (pair plasma)

$\sigma = B^2/8\pi nmc^2 = 2T/mc^2$

$$v_A = c\sqrt{\sigma/(1+\sigma)} \sim c$$

Non-thermal particle acceleration,
Power-law energy spectrum with a hard spectral index s < 2,
Large reconnection rate (fast reconnection)

e.g. Zenitani &MH, ApJ 2001; Jaroschek+ ApJ 2004;
Sironi & Spitkovsky, ApJ 2014; Guto+ PRL 2014



Relativistic magnetic reconnection

relativistic hot plasma

$$T/mc^2 > 1$$

$$P + \frac{1}{8\pi} B^2 = const.$$

- fast reconnection,
- rapid magnetic energy release

(Theory) Zelenyi & Krasnosel'skihk, Sov. Astron. 1977
(Simulation) Zenitani &MH, ApJ 2001; Jaroschek+ ApJ 2004; Sironi & Spitkovsky, ApJ 2014; Guto+ PRL 2014

relativistic drift velocity

$$v_d \approx c$$

?

$$-\nabla P + \frac{en}{c} v_d \times B = 0$$

So far,

- probably fast reconnection,
- Probably rapid magnetic energy release,

But, not yet investigated..

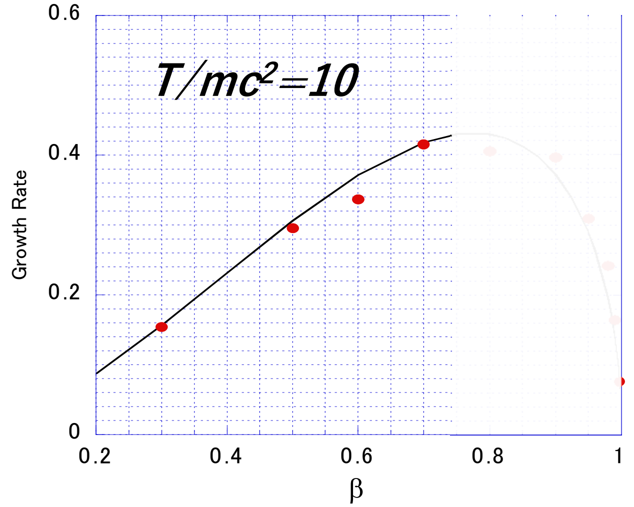
tearing instability

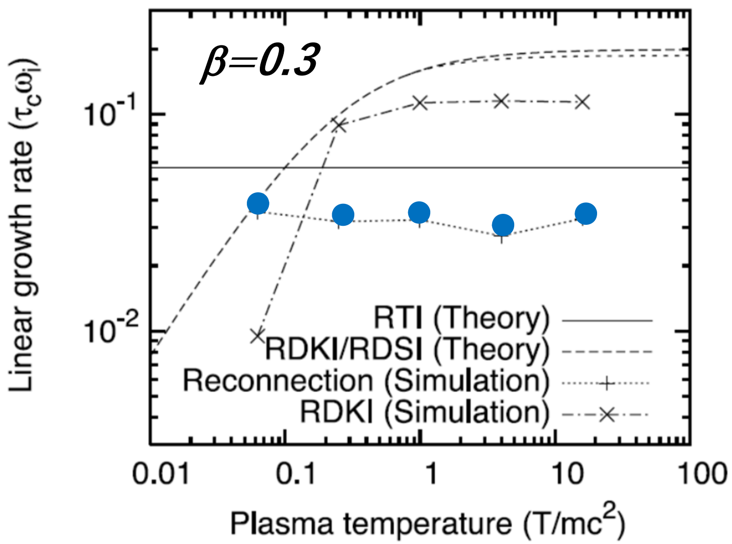
$$\Gamma_\beta = 1/\sqrt{1-\beta^2} \approx O(1)$$

growth rate increases with increasing $\beta = v_d/c$

$$\gamma_{MR}\tau_c = \begin{cases} (1-k^2\lambda^2)\beta^{\frac{3}{2}}\left(\frac{2T}{mc^2}\right)^{-1/2}, & T \ll mc^2 \\ (1-k^2\lambda^2)\beta^{\frac{3}{2}}, & T \gg mc^2 \end{cases}$$

(Zelenyi & Krasnosel'skihk, Sov. Astron. 1977)



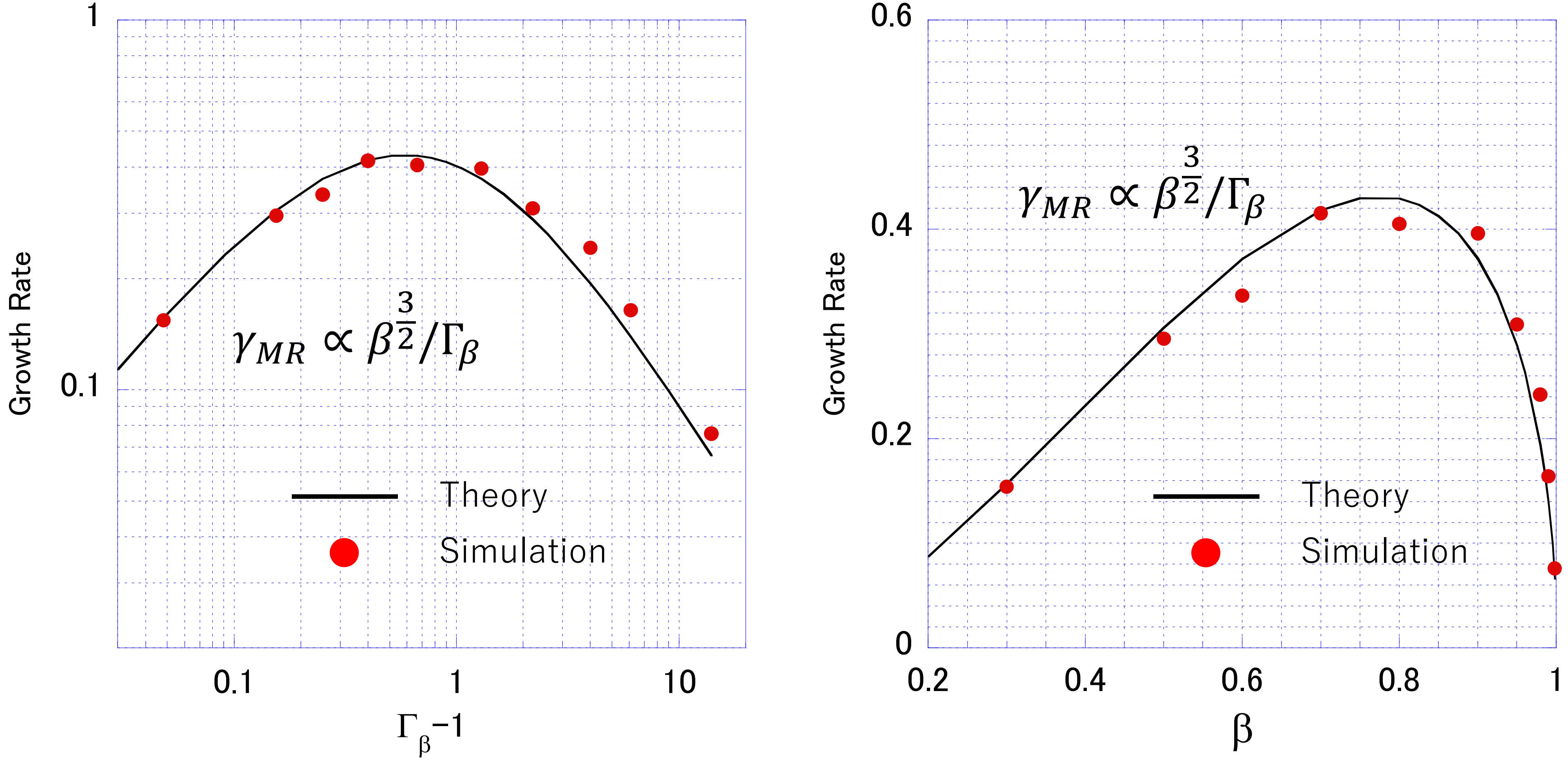


(Zenitani & MH, ApJ, 2007)

reconnection with relativistic drift velocity ($\beta=v_d/c$): PIC simulation

$$T/mc^2 = 10$$

$$\Gamma_\beta = 1/\sqrt{1-\beta^2}$$



collisionless conductivity in Ohm's law (heuristic)

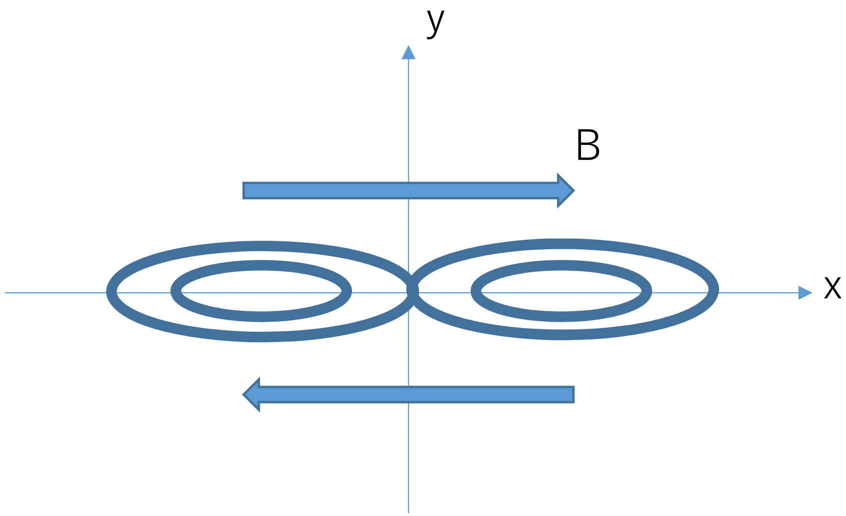
near the neutral sheet, $B \sim 0$

$$m\frac{dv}{dt} = eE - \nu_c m v \approx 0$$

$$\nu_c = k v_{th}$$ Landau resonance around X-point

$$J_z = e n v_z = \sigma E_z$$

$$\sigma = \frac{ne^2}{m}\frac{1}{\nu_c} = \frac{ne^2}{m}\frac{1}{k v_{th}}$$



collisionless conductivity (Landau resonance)

$$f_0 = \frac{\bar{N}}{4\pi m^2 c\Theta K_2(\frac{mc^2}{\Theta})} \exp\left[-\frac{\Gamma_\beta}{\Theta}(E + c\beta p_z)\right]$$

$\beta = v_d/c$ $T = \Gamma_\beta \Theta$

$\Gamma_\beta = 1/\sqrt{1-\beta^2}$

$$f_0 \propto \exp\left[-\frac{m}{2\Theta}\left(v_x^2 + v_y^2 + (v_z - v_d)^2\right)\right]$$

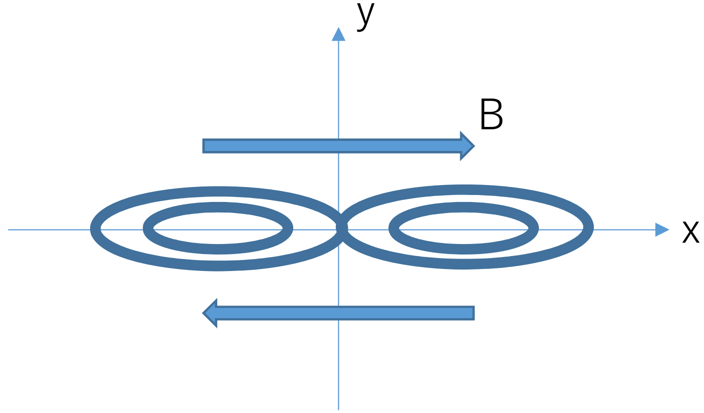
$$\left\{\frac{\partial}{\partial t} + v \cdot \frac{\partial}{\partial x} + e(\frac{v}{c} \times B_0) \cdot \frac{\partial}{\partial p}\right\} f_1 = \left\{e\,(E_1 + \frac{v}{c} \times B_1) \cdot \frac{\partial}{\partial p}\right\} f_0$$

$E_1 = -\frac{1}{c}\frac{\partial}{\partial t} A_1$

$B_1 = \nabla \times A_1$

$$\left\{\frac{\partial}{\partial t} + v \cdot \frac{\partial}{\partial x}\right\} f_1 \approx \frac{ef_0}{cT}\left\{\left(\frac{\partial}{\partial t} + v \cdot \frac{\partial}{\partial x}\right)(v_d A_{1z}) - \frac{\partial}{\partial t}(v_z A_{1z})\right\}$$

$$\frac{\partial}{\partial t} + v \cdot \frac{\partial}{\partial x} = -i(\omega - k v_x)$$



$$f_1 \approx \frac{ef_0}{cT}\left(v_d A_{1z} - \frac{\omega}{\omega - k v_x} v_z A_{1z}\right)$$

collisionless conductivity (non-relativistic)

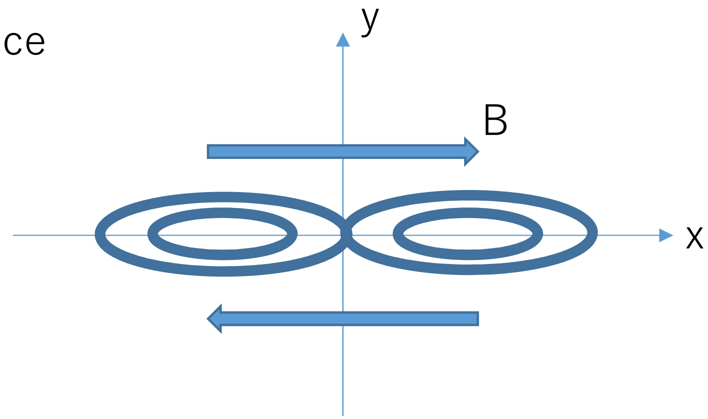
$$f_0 = n\left(\frac{m}{2\pi T}\right)^{3/2} \exp\left[-\frac{m}{2\Theta}\left(v_x^2 + v_y^2 + (v_z - v_d)^2\right)\right]$$

$$f_1 \approx \frac{ef_0}{cT}\left(v_d A_{1z} - \frac{\omega}{\omega - kv_x} v_z A_{1z}\right)$$

$$f_1^{ad} \approx \frac{ef_0}{cT} v_d A_{1z} \qquad f_1^{res} \approx -\frac{ef_0}{cT}\frac{\omega}{\omega - kv_x} v_z A_{1z}$$

$$J_{1z} \approx \iiint ev_z f_1^{res}\, d^3v \approx \frac{ne^2}{m}\frac{1}{kv_{th}} E_{1z}$$

Landau resonance



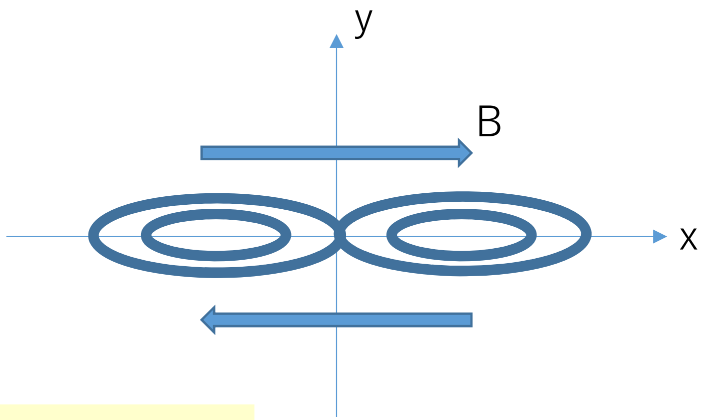
$$\sigma = \frac{ne^2}{m}\frac{1}{kv_{th}}$$

$$E_1 = -\frac{1}{c}\frac{\partial}{\partial t} A_1$$

collisionless conductivity (relativistic)

$$f_0 = \frac{\bar{N}}{4\pi m^2 c\Theta K_2(\frac{mc^2}{\Theta})} \exp\left[-\frac{\Gamma_\beta}{\Theta}(E + c\beta p_z)\right]$$

$$f_1 \approx -\frac{ef_0}{cT}\frac{\omega}{\omega - kv_x}v_z A_{1z}$$



$$J_{1z} \approx \iiint ev_z \frac{ef_0}{cT}\frac{\omega}{\omega - kv_x}v_z A_{1z} d^3p$$

$$\approx \left(\frac{\bar{N}\Gamma_\beta e^2}{m}\right)\left(\frac{\Gamma_\beta}{kc}\right)\left(\frac{\Gamma_\beta mc^2}{\Theta}\right)E_{1z} = \left(\frac{ne^2}{m}\right)\left(\frac{\Gamma_\beta}{kc}\right)\left(\frac{mc^2}{T}\right)E_{1z}$$

$$\sigma^{non-rel} = \frac{ne^2}{m}\frac{1}{kv_{th}}$$

$$\sigma^{rel} = \left(\frac{ne^2}{m}\right)\left(\frac{\Gamma_\beta}{kc}\right)\left(\frac{mc^2}{T}\right)$$

tearing instability $(\Gamma_\beta \gg 1)$

$$\Gamma_\beta \equiv 1/\sqrt{1-\beta^2}$$

$$\gamma_{MR}\tau_c = \begin{cases} (1-k^2\lambda^2)\beta^{\frac{3}{2}}\left(\dfrac{2\Gamma_\beta T}{mc^2}\right)^{-1/2}, & \Gamma_\beta T \ll mc^2 \\ (1-k^2\lambda^2)\dfrac{\beta^{\frac{3}{2}}}{\Gamma_\beta}, & \Gamma_\beta T \gg mc^2 \end{cases}$$

growth rate decreases with increasing Γ_β

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

$$\frac{\partial}{\partial t}\int\frac{B^2}{8\pi}dy + \int E\cdot J^{ad}dy = -\int E\cdot J^{res}dy$$

$$J^{ad} = \frac{c}{4\pi}\frac{A_{1z}}{\lambda^2 cosh^2(\frac{y}{\lambda})}$$

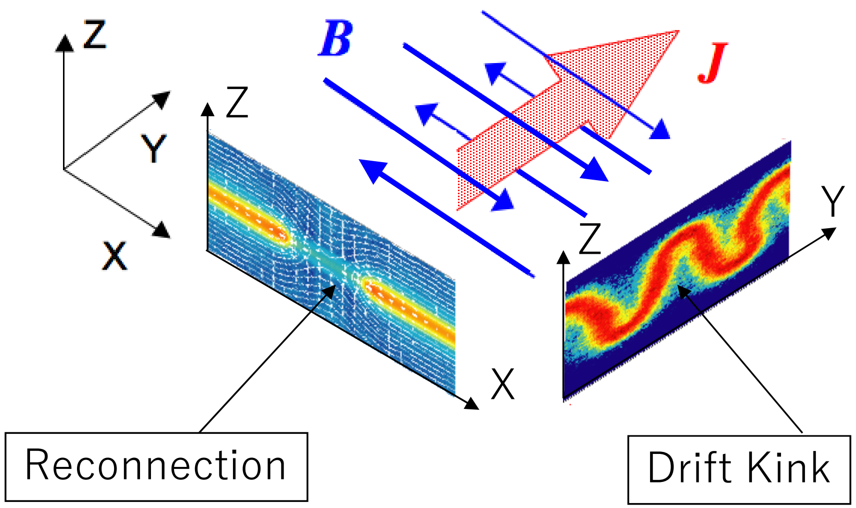
$$J^{res} = \sigma E_{1z} \qquad \sigma = \left(\frac{ne^2}{m}\right)\left(\frac{\Gamma_\beta}{kc}\right)\left(\frac{mc^2}{T}\right)$$

$$\frac{\partial}{\partial t}\left[\frac{1}{8\pi}\int_{-\infty}^{+\infty}\left(\left|\frac{d}{dy}A_{1z}\right|^2 + k^2A_{1z}^2 - \frac{2A_{1z}^2}{\lambda^2 cosh^2(\frac{y}{\lambda})}\right)dy\right]$$

$$= -\int_{-d}^{+d}\sigma E_{1z}^2 dy = \int_{-d}^{+d}\frac{\sigma}{c^2}\left(\frac{\partial}{\partial t}A_{1z}\right)^2 dy$$

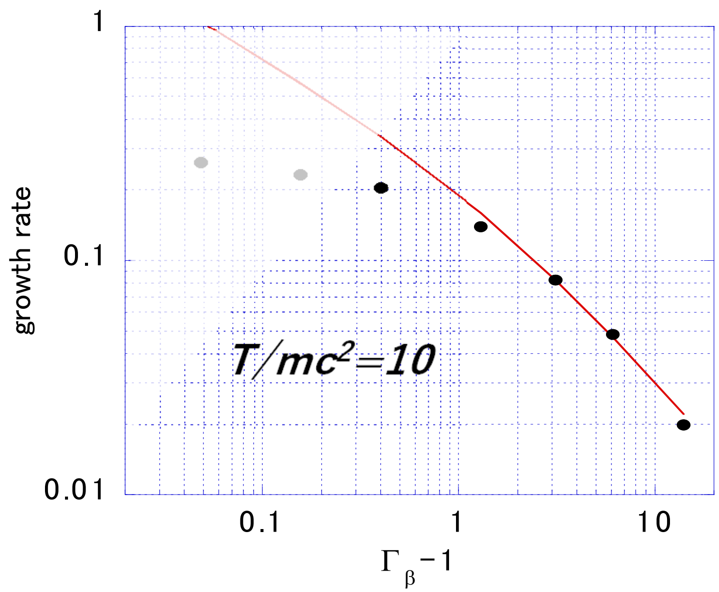
$$E = -\frac{1}{c}\frac{\partial}{\partial t}A \qquad B = \nabla\times A$$

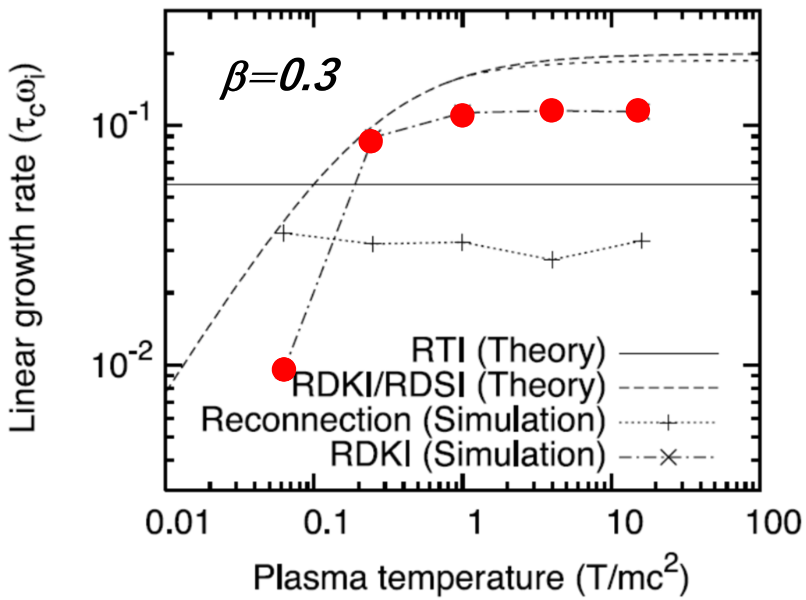
drift kink instability



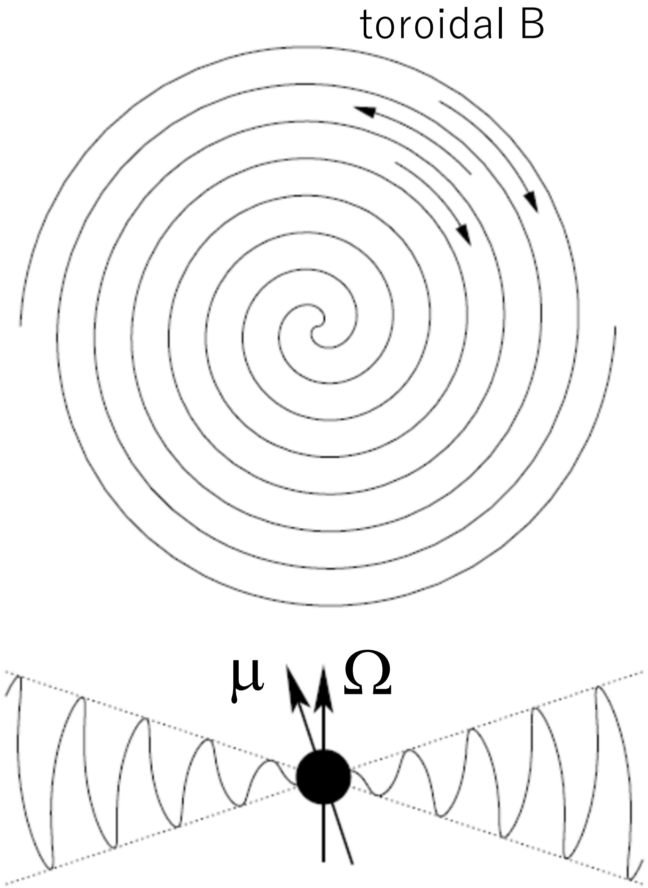
$$\gamma_{DK}\tau_c = \begin{cases} \dfrac{1}{4\Gamma_\beta \beta}\dfrac{T}{mc^2}, & T \ll mc^2 \\ \dfrac{1}{16\Gamma_\beta \beta}, & T \gg mc^2 \end{cases}$$

(Zenitani & MH, ApJ, 2007)





Pulsar Wind



Summary

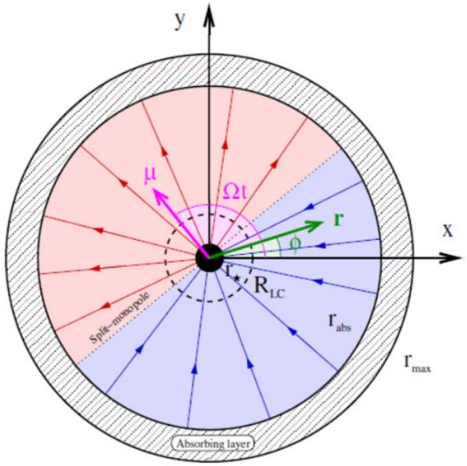
relativistic drift velocity

$$v_d \approx c$$

- slow reconnection & slow drift-kink
- slow magnetic energy release

magnetic energy dissipation is not easy in pulsar wind, and current starvation may happen...

pulsar wind evolution (PIC)



Split-monopole,
2d-PIC simulation,
equatorial plane
(Cerutti & Philippov, A&A 2017)