Gyrokinetic simulations of reconnection – an update

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Simulation models: AstroGK and GENE

- *Nonlinear gyrokinetic equations for both electrons and ions*
- *5D (3 spatial but 2D for now, 2 velocity)*
- *Trapped particles and EM effects*
- *Valid even for large $k_\perp\rho_i$ and $k_\perp\rho_e$*
- *Collision operator in AGK consistent with Spitzer resistivity*
- *Magnetosonic wave ordered out:* $\delta p_\perp + B_{z0}\delta B_z/(4\pi) \simeq 0$
- *Implementation of* δB_z *in GENE in progress*

When is the AGK model applicable to reconnection?

- *Low frequency:* $$\frac{d}{dt} \ll \Omega_{ci}$$

- *Perturbations generated by reconnection must be small:*

$$\frac{\tilde{n}}{n_0} \ll 1\,, \quad \frac{\tilde{T}}{T_0} \ll 1\,, \quad \frac{\delta B_{\parallel}}{B} \ll 1 \ldots$$

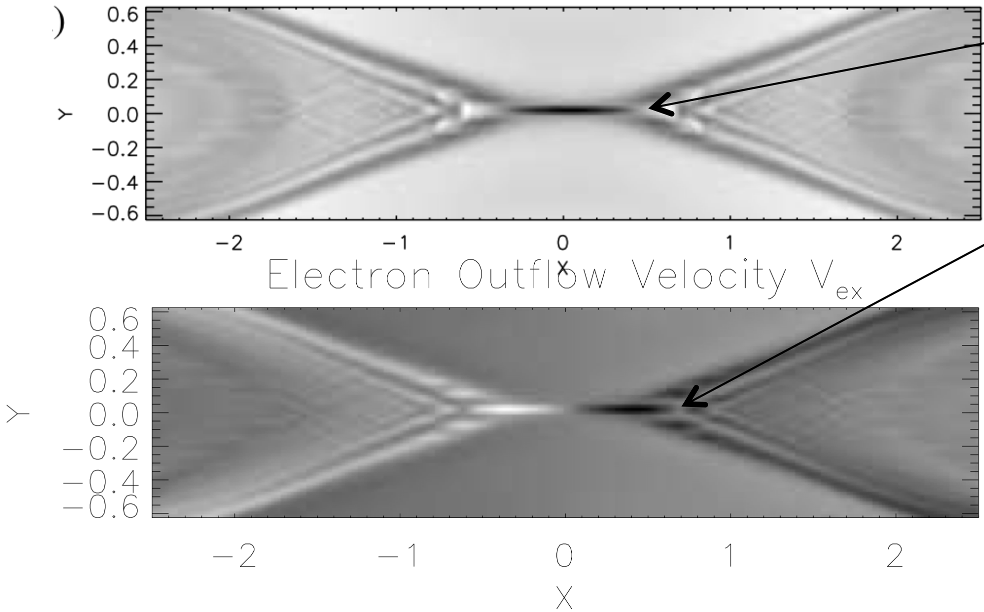
- δB_z *given by* $\delta p_{\perp} + B_{z0}\delta B_z/(4\pi) \simeq 0$

For fixed $\beta,\ \rho_i,\ T_i/T_e,\ m_i/m_e$, *these can usually be satisfied if the guide field* B_{z0} *is sufficiently large.*

But: *(1) the required* B_{z0} *may be very large*
(2) important parameter restrictions may apply

How strong must B_{z0} be?

Two-fluid simulation with weak guide field:



$$B_y \sim (0.2) B_x \sim B_x$$

$$V_{ex} \sim B_x / \sqrt{4\pi n m_e}$$

Modeling the electron layer as a standing wave, expect

$\delta p_\perp + B_{z0} \delta B_z / (4\pi) \simeq 0$ *to be valid when*

$$\boxed{\begin{aligned} &C_m^2 = C_A^2 + C_s^2 > B_x^2/(4\pi n m_e) \quad \text{or} \\ &B_z/B_x > \sqrt{m_i/m_e}/\sqrt{1+\beta/2} \end{aligned}}$$

More generally: $\partial_t \tilde{B}_z = -\hat{z} \cdot \nabla \times \vec{E}$

Parameter restrictions?

Example:

- For $\beta \ll 1$ and large B_{z0} typically:

$$\frac{\tilde{n}}{n_0} \sim \rho_s^2 \nabla_\perp^2 \frac{e\tilde{\phi}}{T} \sim \frac{k_\perp V_E}{\Omega_{ci}} \quad \text{where} \quad \rho_s = \frac{c_s}{\Omega_{ci}}$$

$$\text{With} \quad k_\perp \sim 1/\rho_s \quad \text{and} \quad V_E \sim V_{Ax} \sim B_x/\sqrt{4\pi\rho} \quad \text{where} \quad B_x = B_{rec}:$$

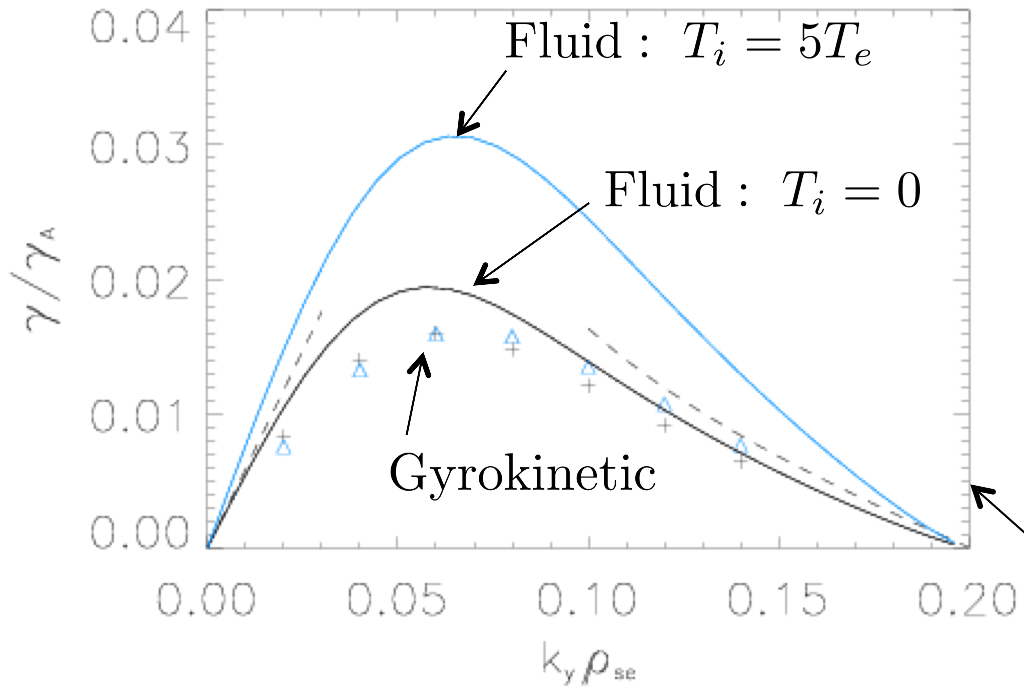
$$\frac{\tilde{n}}{n_0} \sim \frac{k_\perp V_E}{\Omega_{ci}} \sim \frac{V_{Ax}}{c_s} \sim \sqrt{\frac{2}{\beta_x}} \quad \text{where} \quad \beta_x = \frac{8\pi p_0}{B_x^2}$$

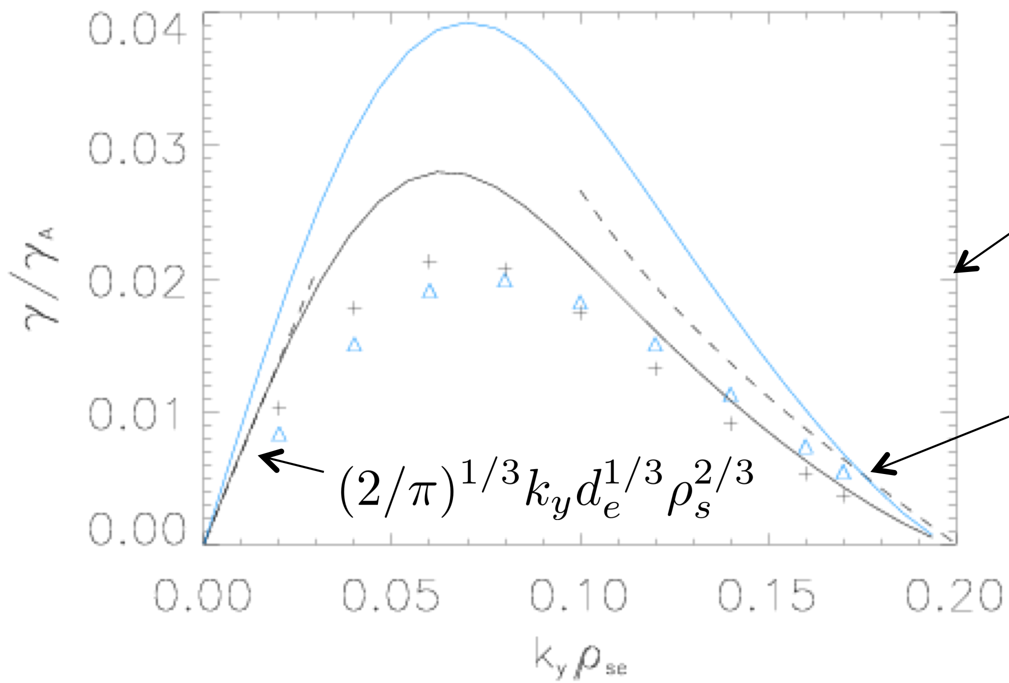
- *Thus* $\quad \dfrac{\tilde{n}}{n_0} \ll 1 \quad \Rightarrow \quad \boxed{\beta_x \gg 1}$ *(or worse)*

- *The same condition results from:*

$$\omega \ll \Omega_{ci} \quad \text{with} \quad \omega \sim k_{||} V_A \sim k_x V_{Ax} \quad \text{and} \quad k_x \sim 1/\rho_s$$

Collisionless limit:





$$\vec{B} = B_{y0}\sin(k_x x)\hat{y} + B_{z0}\hat{z}$$

$$k_x\rho_{se} = 0.2\ ,\quad L_x = 10\pi\rho_{se}$$

$$\rho_{se} = \sqrt{T_e/m_i}/\Omega_{ci}\ ,\ \gamma_A = k_x V_{Ay0}$$

$$\Delta' = 2k_x\tan(\pi D/2)$$

$$D = \sqrt{1-(k_y/k_x)^2}$$

$$\boxed{m_i/m_e = 100\ ,\ \beta_e = 0.2}$$

$$\boxed{m_i/m_e = 25\ ,\ \beta_e = 0.3}$$

$$(1/\pi)k_y\rho_s d_e\Delta'$$

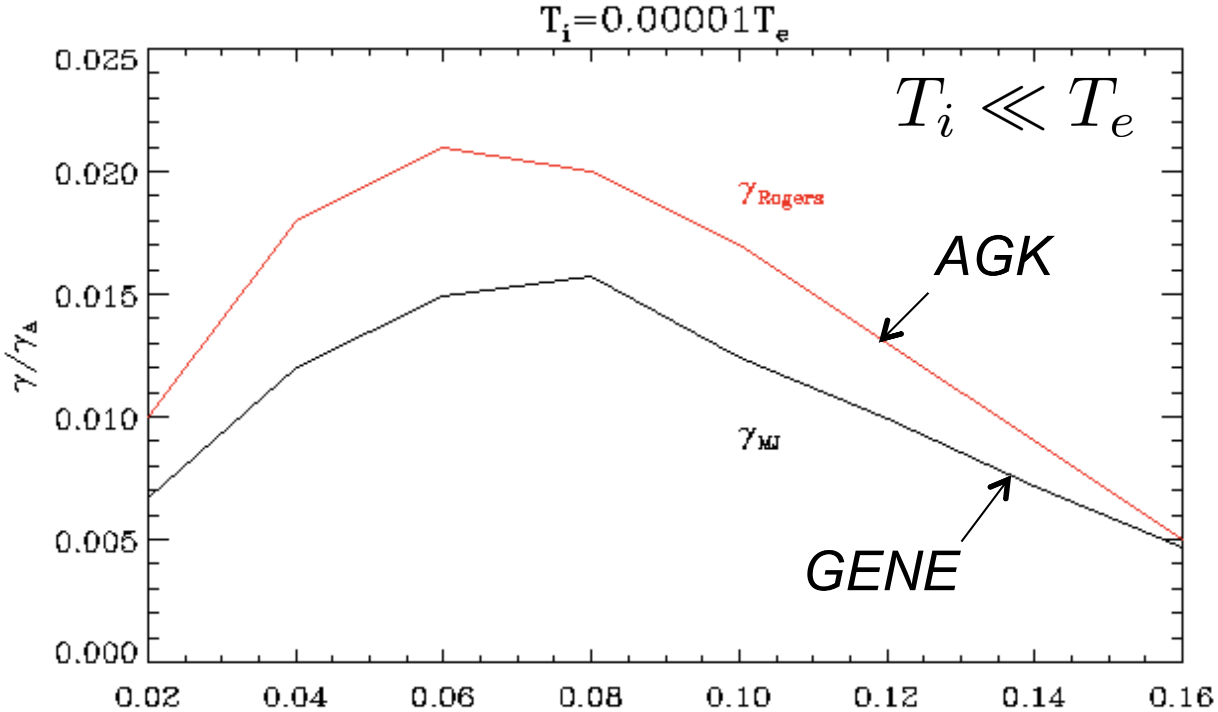
$$\rho_s = \sqrt{(T_e+T_i)/m_i}/\Omega_{ci}$$

$$d_e = c/\omega_{pe}$$

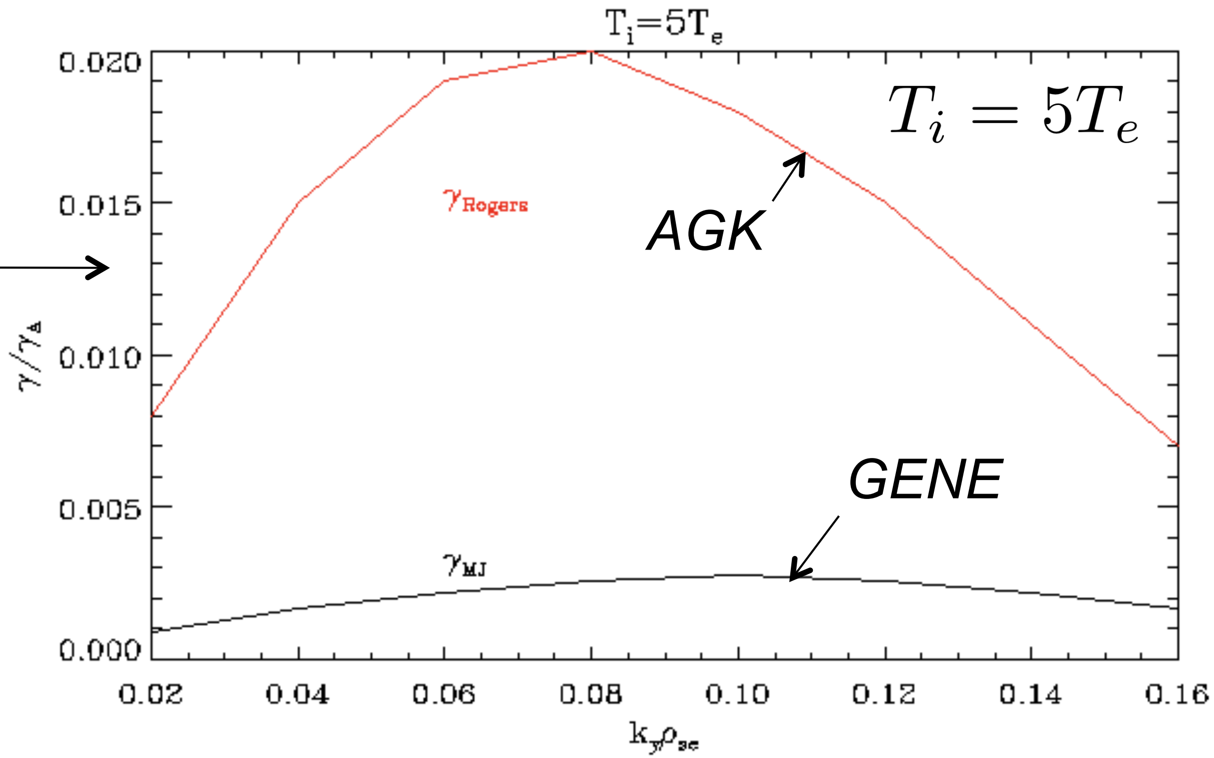
AGK vs GENE

(M. Pueschel, F. Jenko work in progress)

Same system as before.
No $\delta B_{\|}$ yet in GENE.



In GENE, growth rate strongly reduced by Ti



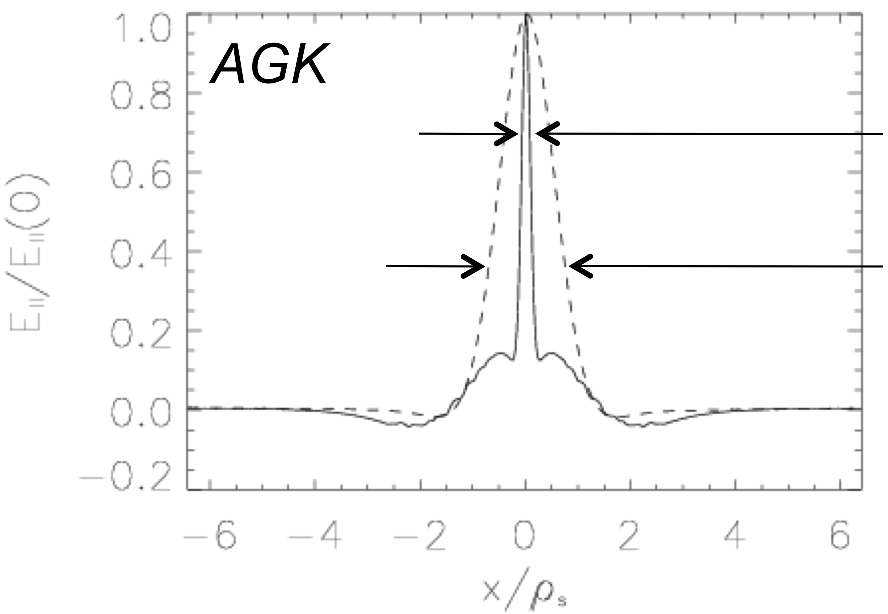
In fluid calculations, the T_i dependence comes from:

$$\nabla_\perp \cdot \frac{d}{dt}\nabla_\perp(\phi + p_{i\perp}) = \nabla_\parallel J$$

In kinetic calculations:

$$\tilde{n}_e = \tilde{n}_i \ , \quad \tilde{n}_i = \frac{n_0 e}{T_i}\left[\Gamma_0(b) - 1\right]\phi \ , \ b = -\rho_i^2 \nabla_\perp^2$$

In either case, same physics as: $\omega^2 = k_\parallel^2 V_A^2 (1 + k_\perp^2 \rho_s^2)$



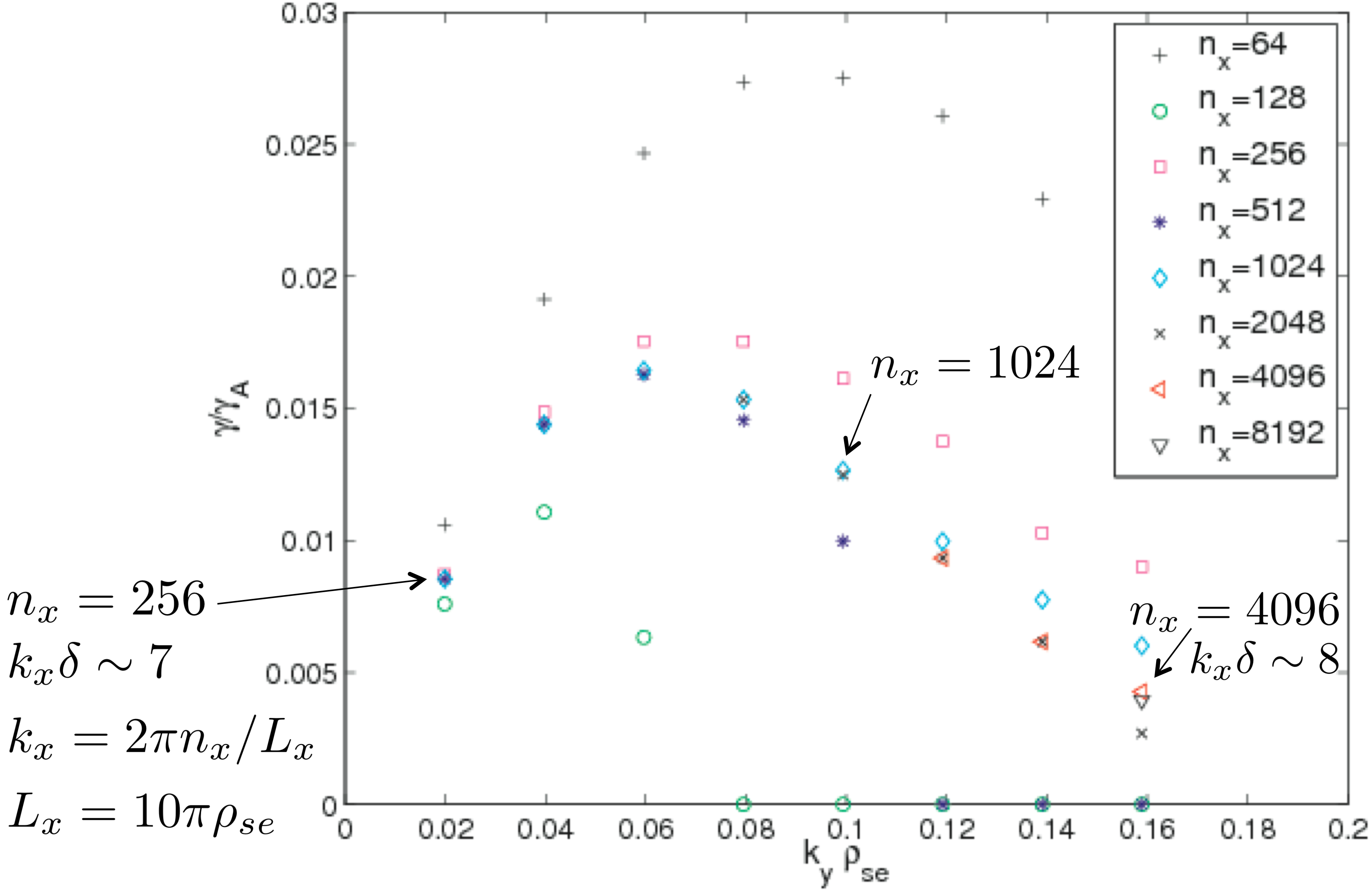
$\delta = (\gamma/\gamma_A)d_e/(k_y\rho_s) \quad (T_i \ll T_e)$

$\rho_s \simeq \rho_i \quad (T_i \gg T_e)$

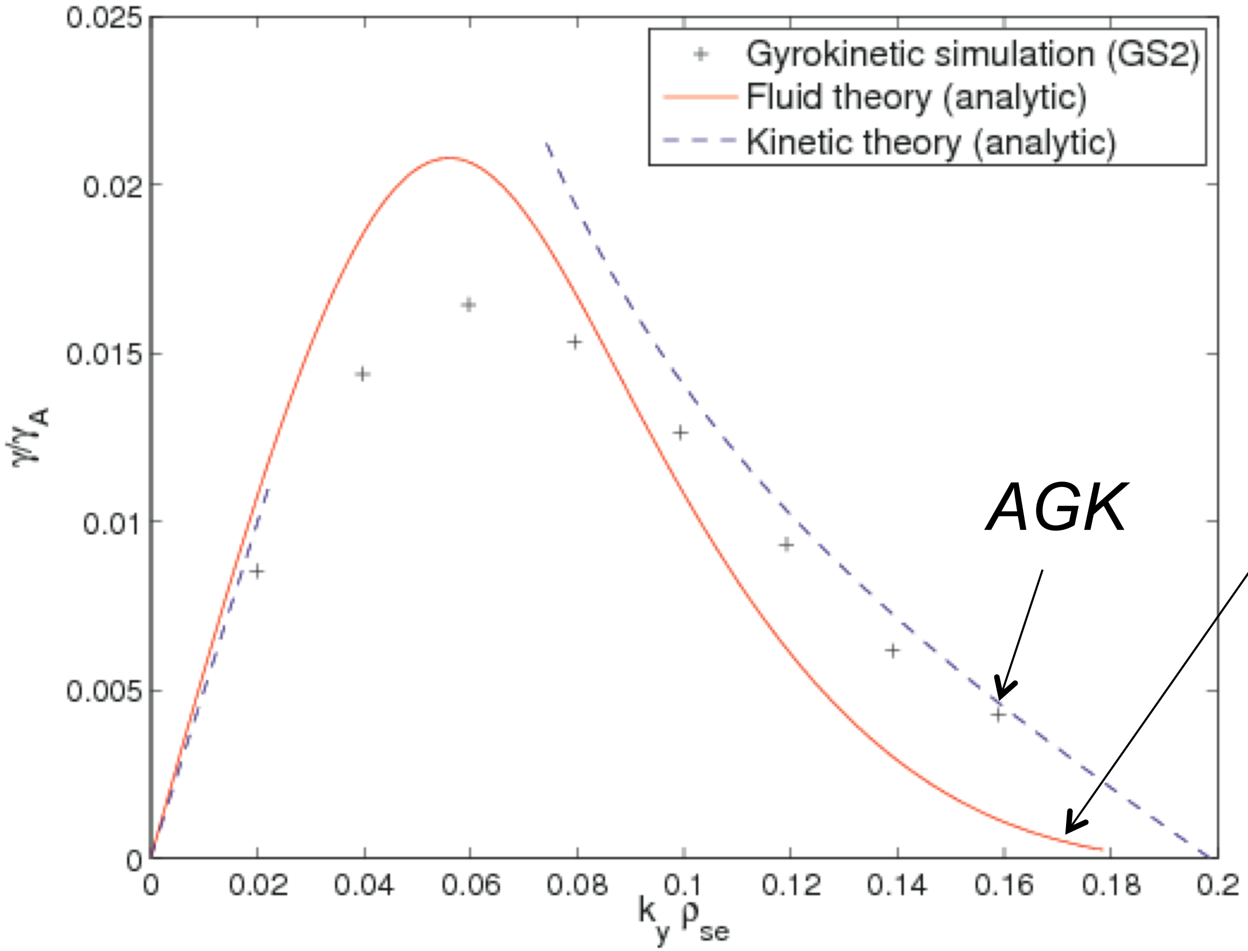
Behavior of eigenfunction seems consistent with theory

High resolution required for small Δ'

Collisionless electron scale length: $\delta = (\gamma/\gamma_A) d_e / (k_y \rho_s)$



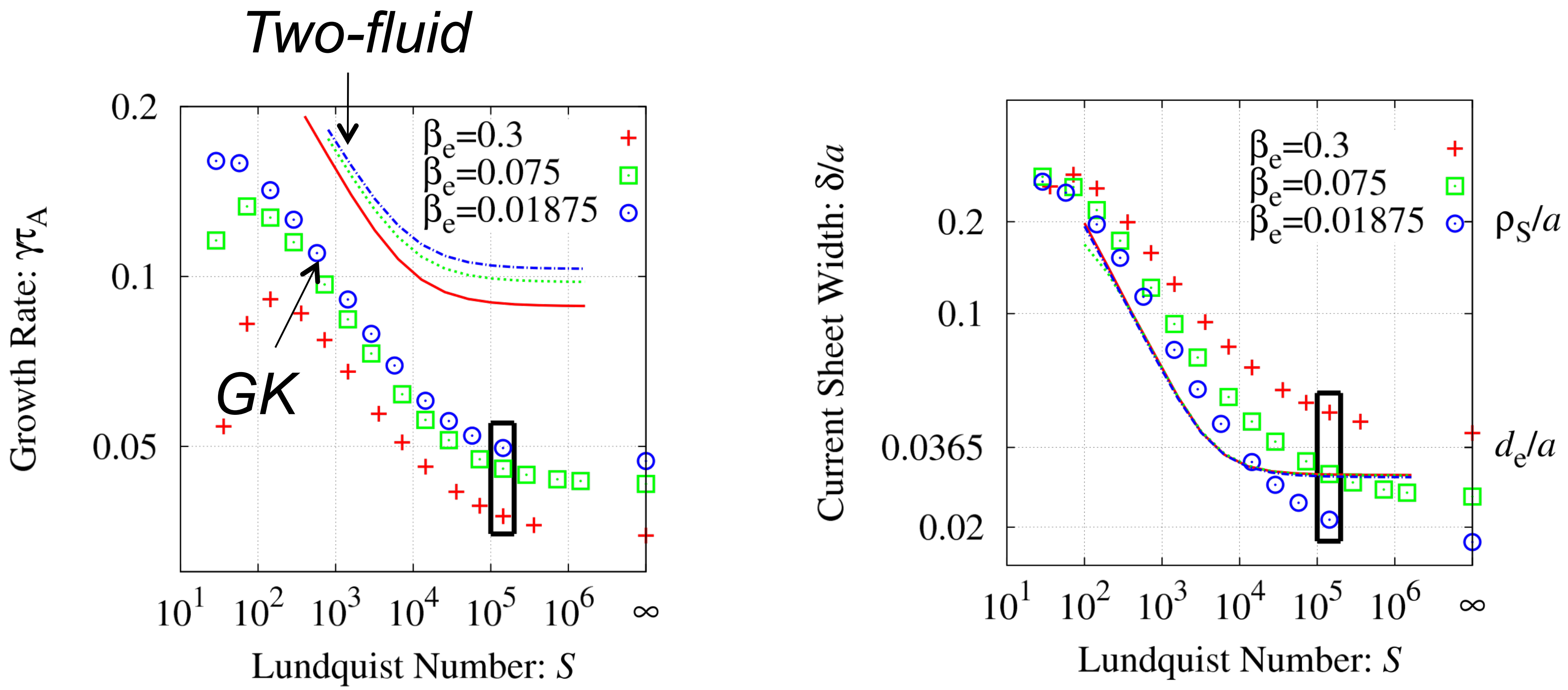
Ongoing debate: is electron gyroviscous cancellation complete or partial?



Including electron polarization drift, without electron gyroviscous cancellation in two-fluid model

AGK: Collisional Case

(R. Numata et al 2010)

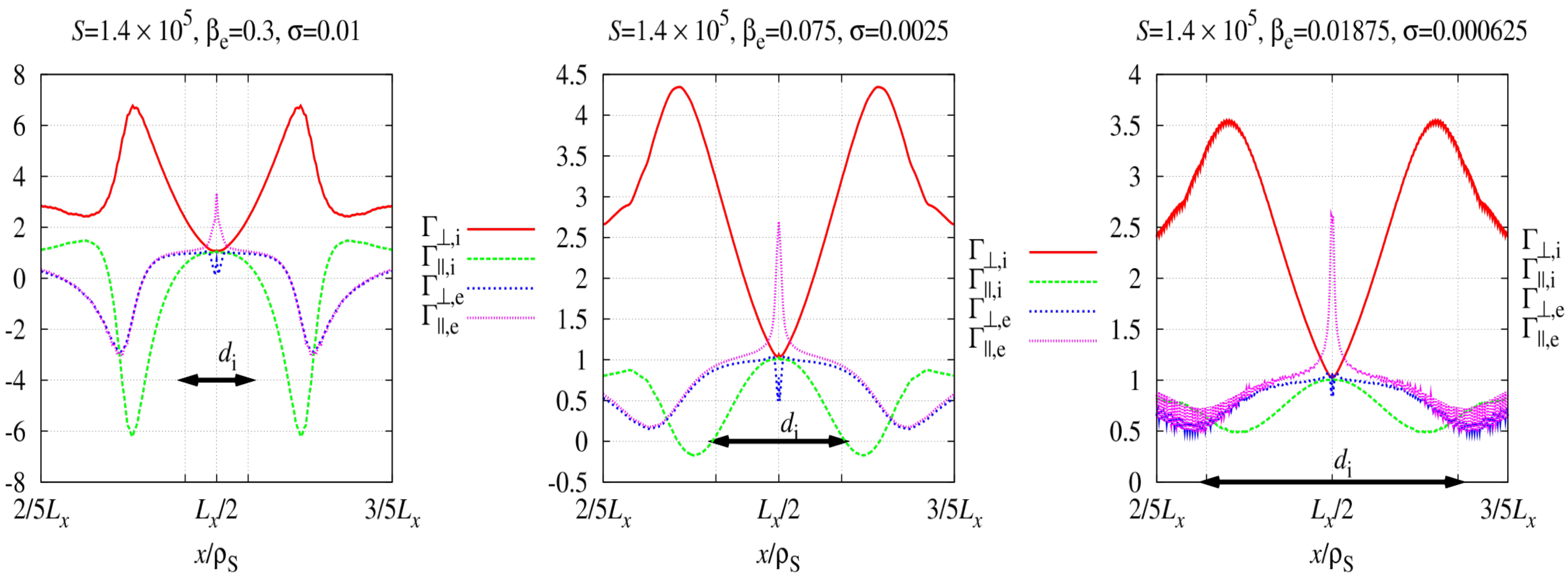


$$A_{\|0}(x) = A_{\|00} \cosh^{-2}\left(\frac{x - L_x/2}{a}\right) S_{\mathrm{h}}(x), \quad B_{y0} = \partial_x A_{\|0}$$

$$\rho_{se}/a = 0.2 \ , \ T_i = T_e \ , \ m_i/m_e = 100$$

Relationship of p to n more complex than simple isothermal or adiabatic equation of state

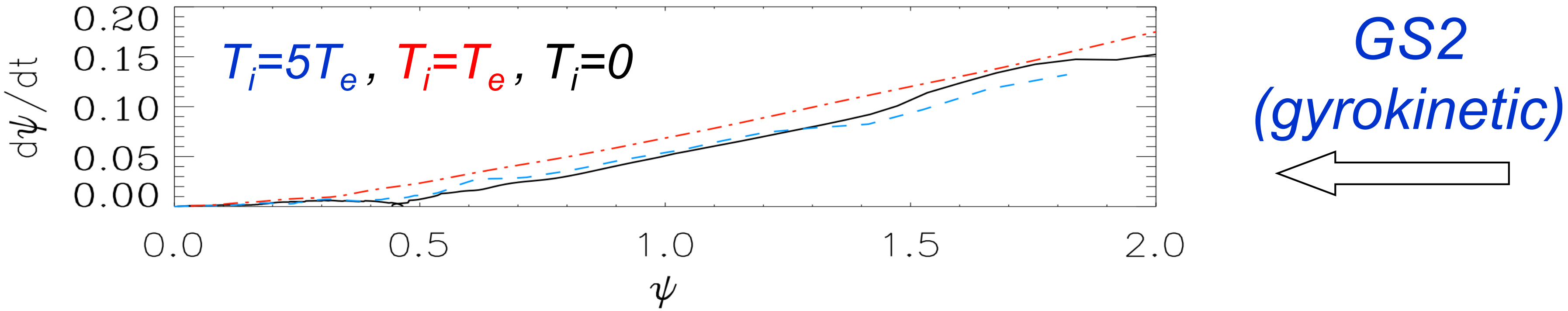
Polytropic Eqn. of State $p \propto (n_0 m)^\Gamma$ leads to $\tilde{p} = \Gamma T_0 \tilde{n}$ or $\tilde{T}/T_0 = (\Gamma - 1)\tilde{n}/n_0$

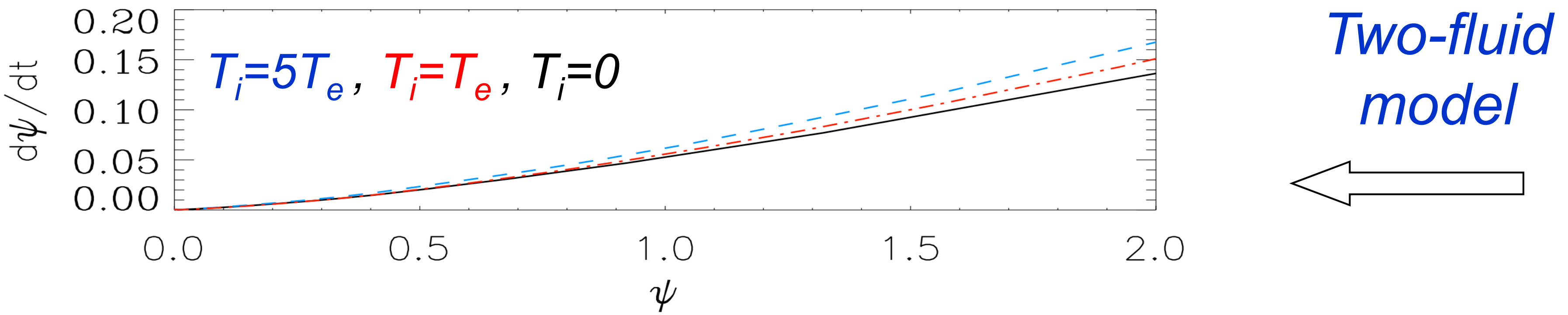


(AGK, R. Numata et al 2010)

Nonlinear Phase

(Phys Plasmas, Sept 2007)



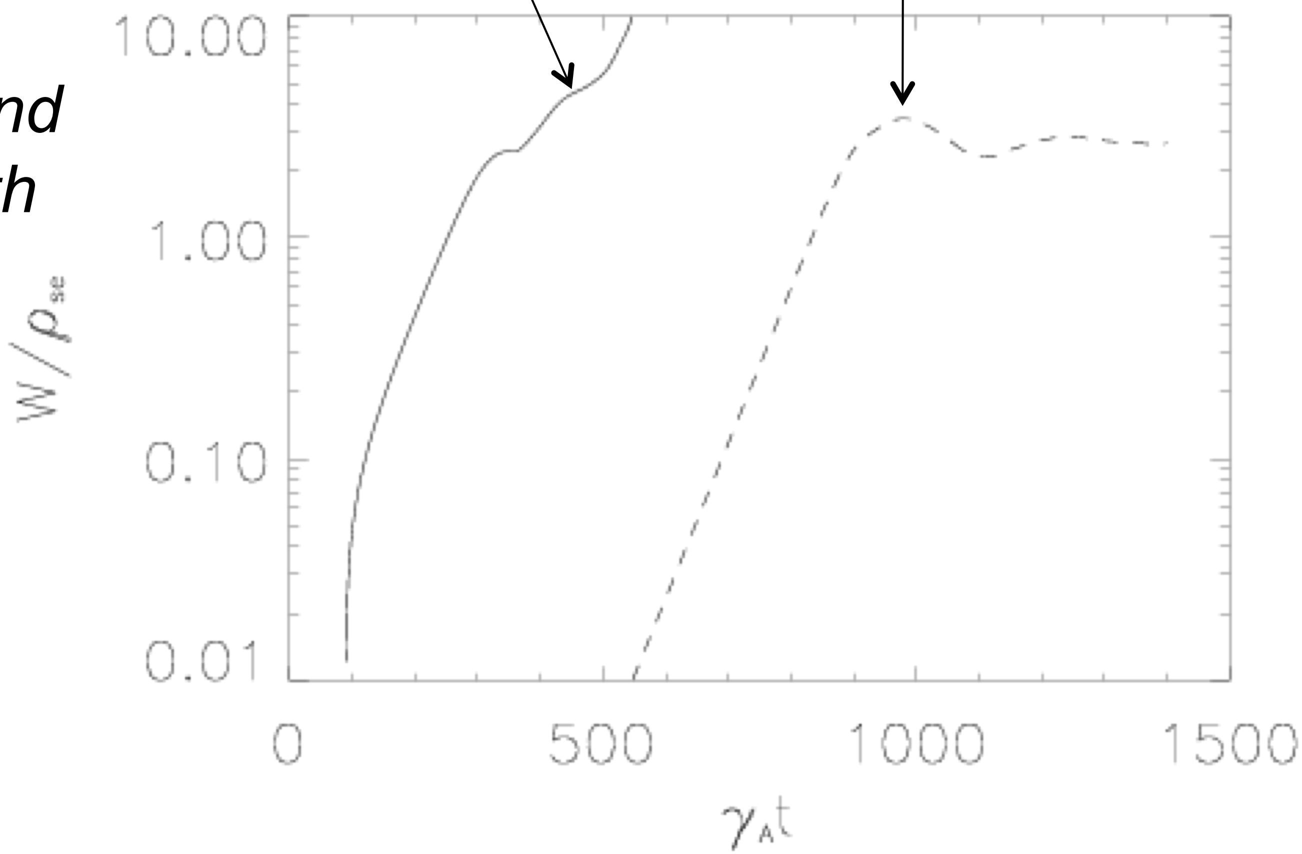


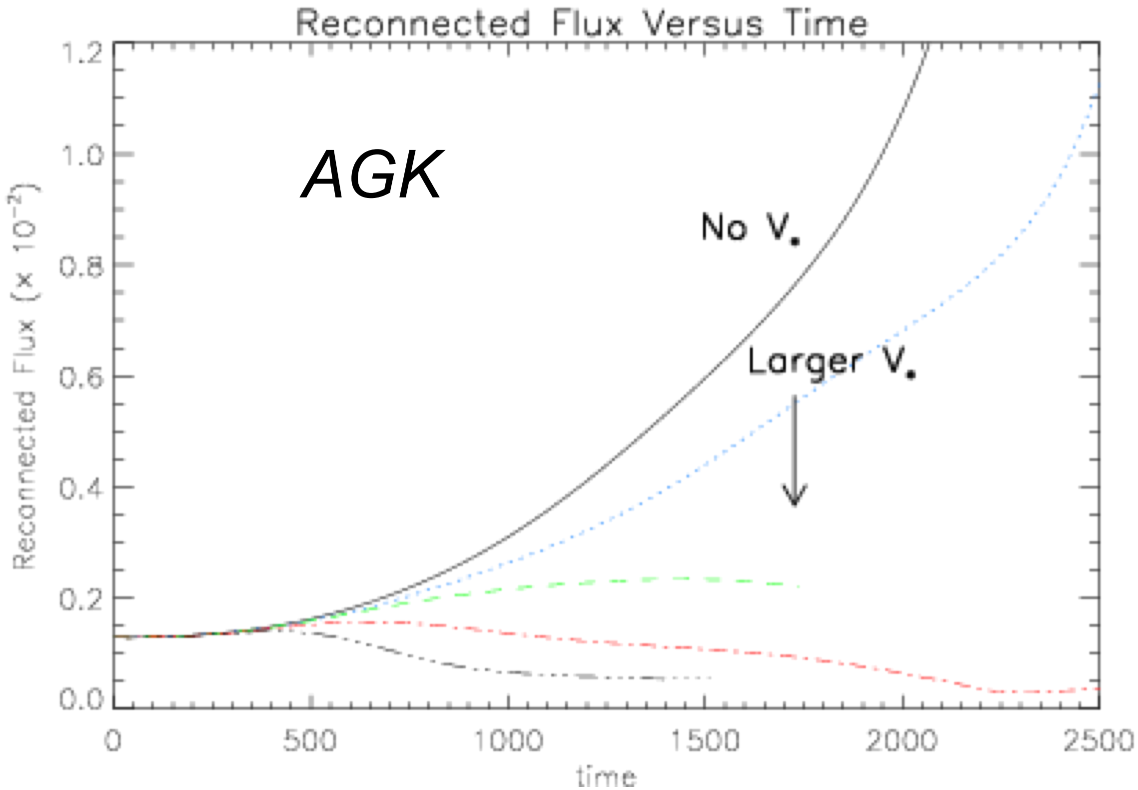
- Nonlinear reconnection rates in simple large-Δ' system very similar to two-fluid model

For Ti>>Te and very low noise, island saturates in early nonlinear stage

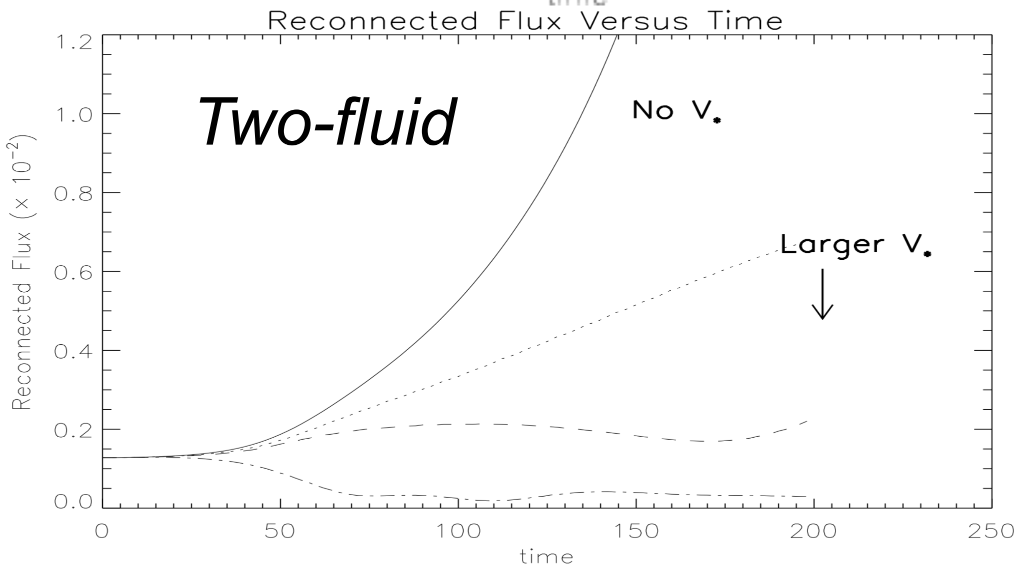
Same run with noise

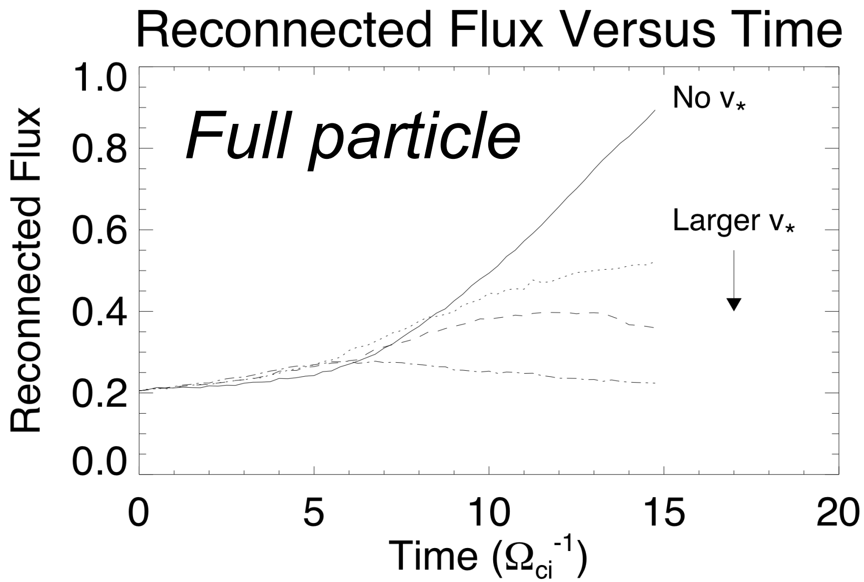
w=island width



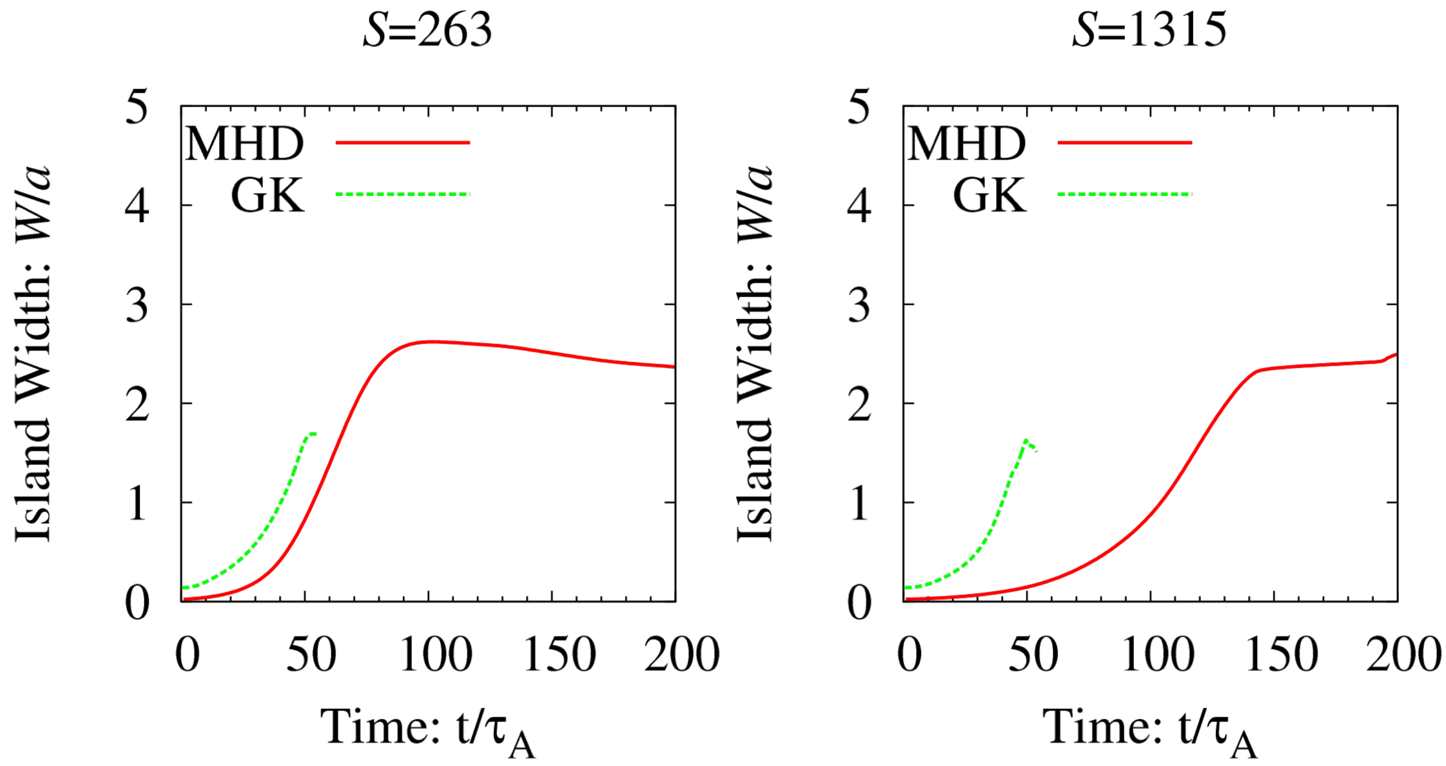


Diamagnetic stabilization seems weaker in GK model



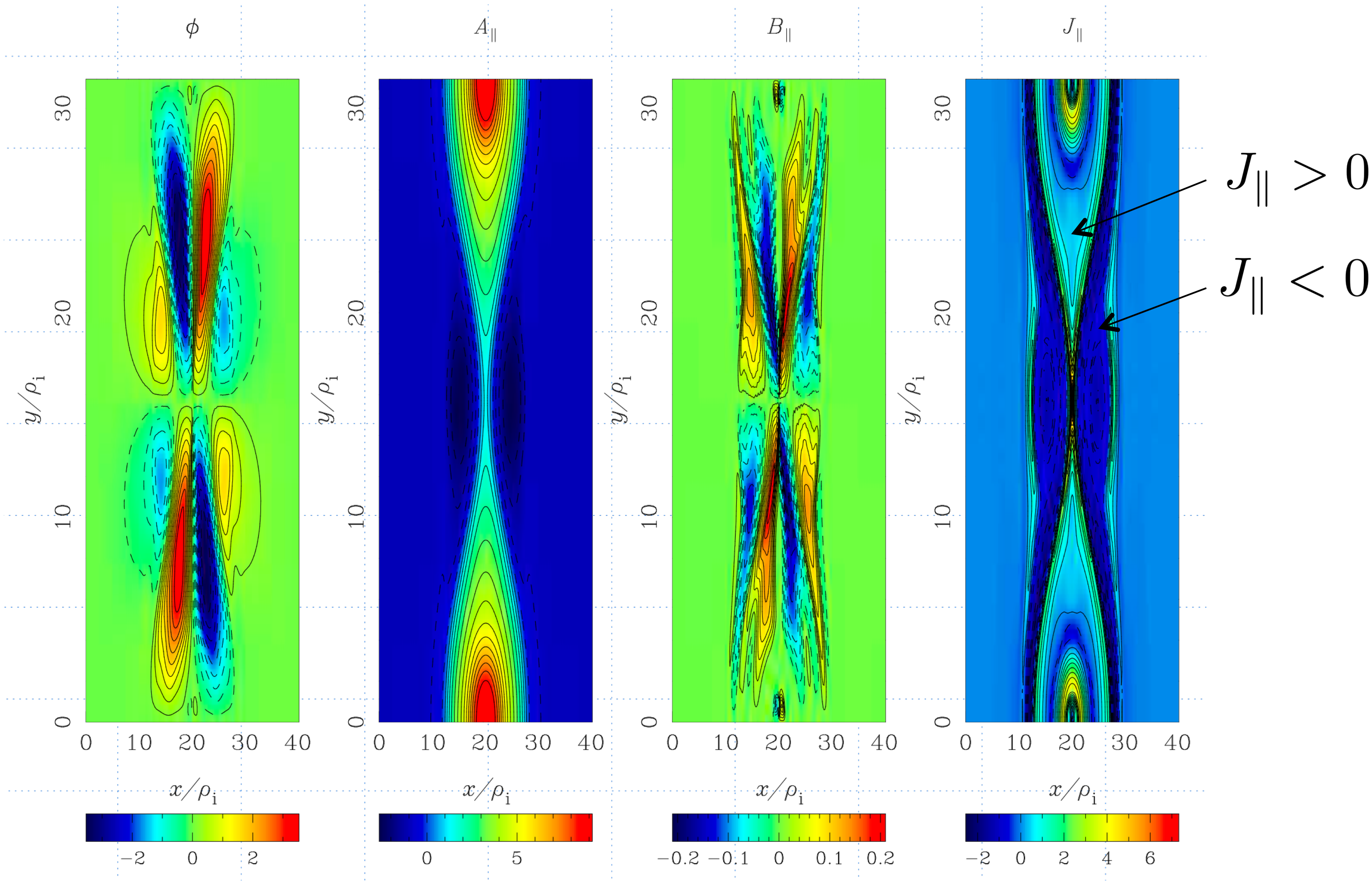


Nonlinear Resistive Case: island width vs t



Smaller island saturation width in AGK

(R. Numata et al 2010)



(AGK, R. Numata et al 2010)

Summary

- GK codes have potential to explore kinetic reconnection physics in the strong guide field limit
  given some parameter restrictions
- But linear benchmarks still have some unresolved issues (Ti dependence, GENE vs AGK…)
- Nonlinear studies in progress
- Small Δ' regime may be very numerically challenging