テアリング不安定性のジャイロ運動論シミュレーション

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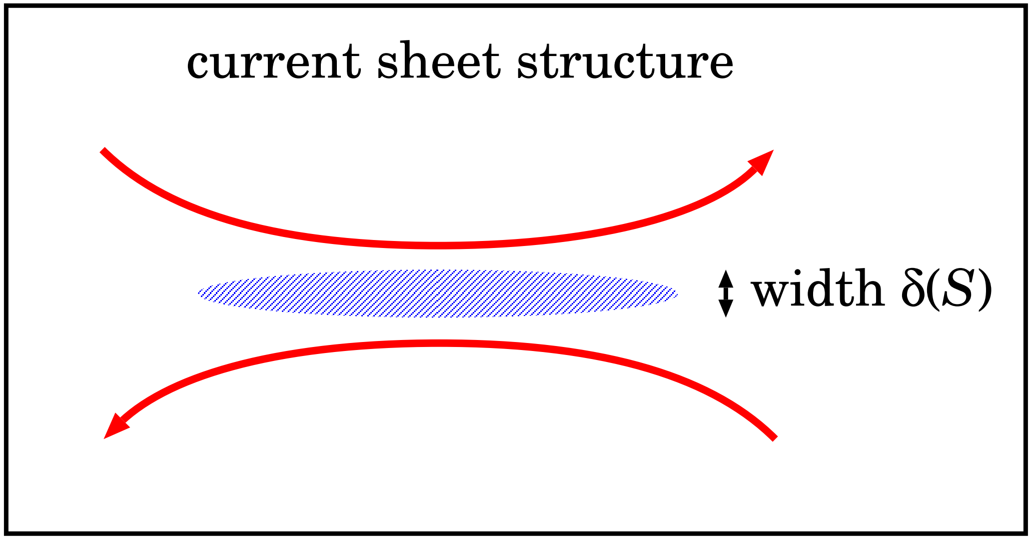
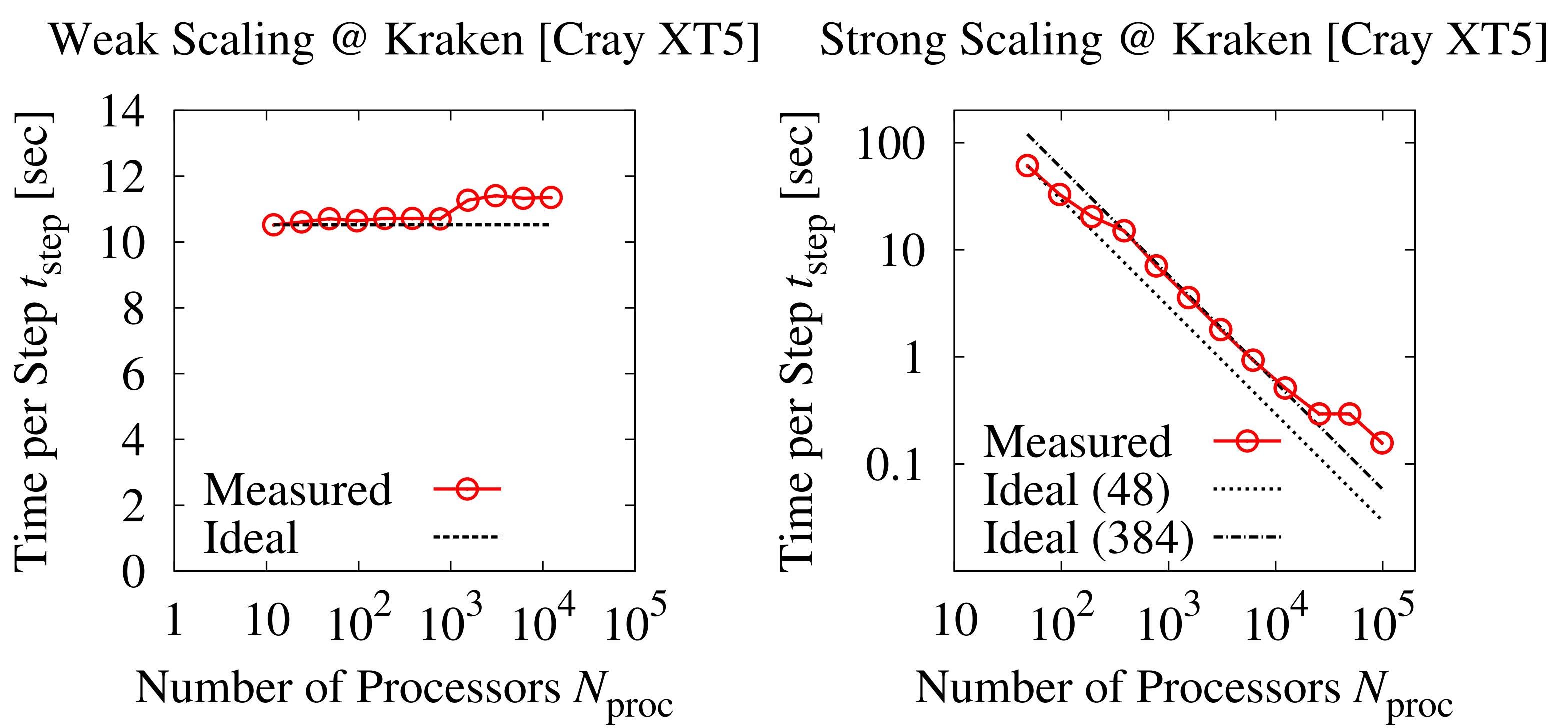
Magnetic reconnection is multiscale problem

- Physics to break flux-freezing is necessary for field lines to change its topology: primarily by collisions (resistivity).
  $\Rightarrow$ Only collisions set a spatial scale in MHD model.
- Resistive spatial scale for weakly collisional plasmas falls below kinetic scales (MHD theory is not valid).
- Relevant kinetic scales: $d_{\mathrm{i,e}}$ [inertia], $\rho_{\mathrm{i,e}}$ [FLR], ρ_{S} [Sound].



AstroGK: Astrophysical Gyrokinetics Code

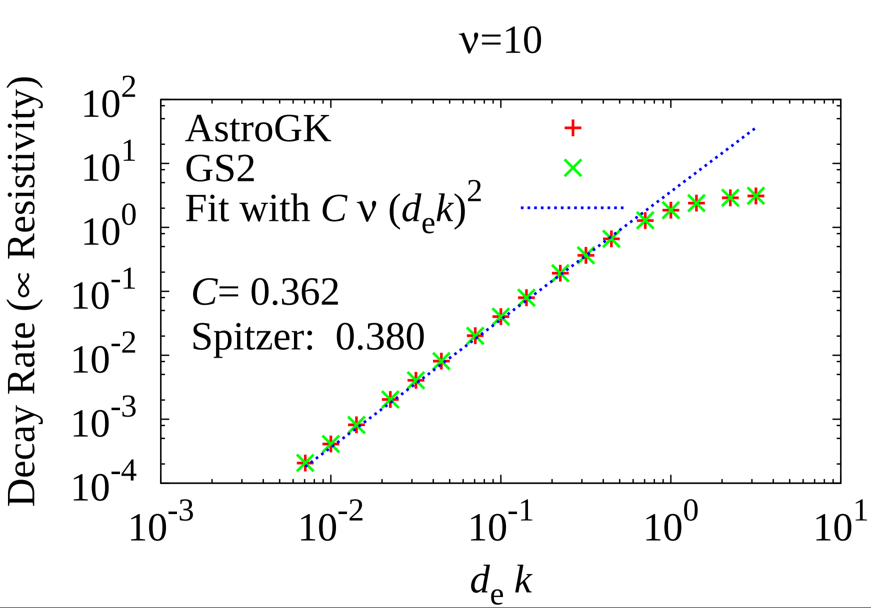
- Eulerian continuum, local flux tube, δf, electromagnetic code.
- Publicly available at https://sourceforge.net/projects/gyrokinetics/.
- Numata *et al.*, J. Comput. Phys. **229**, 9347 (2010).



Collisions in AstroGK

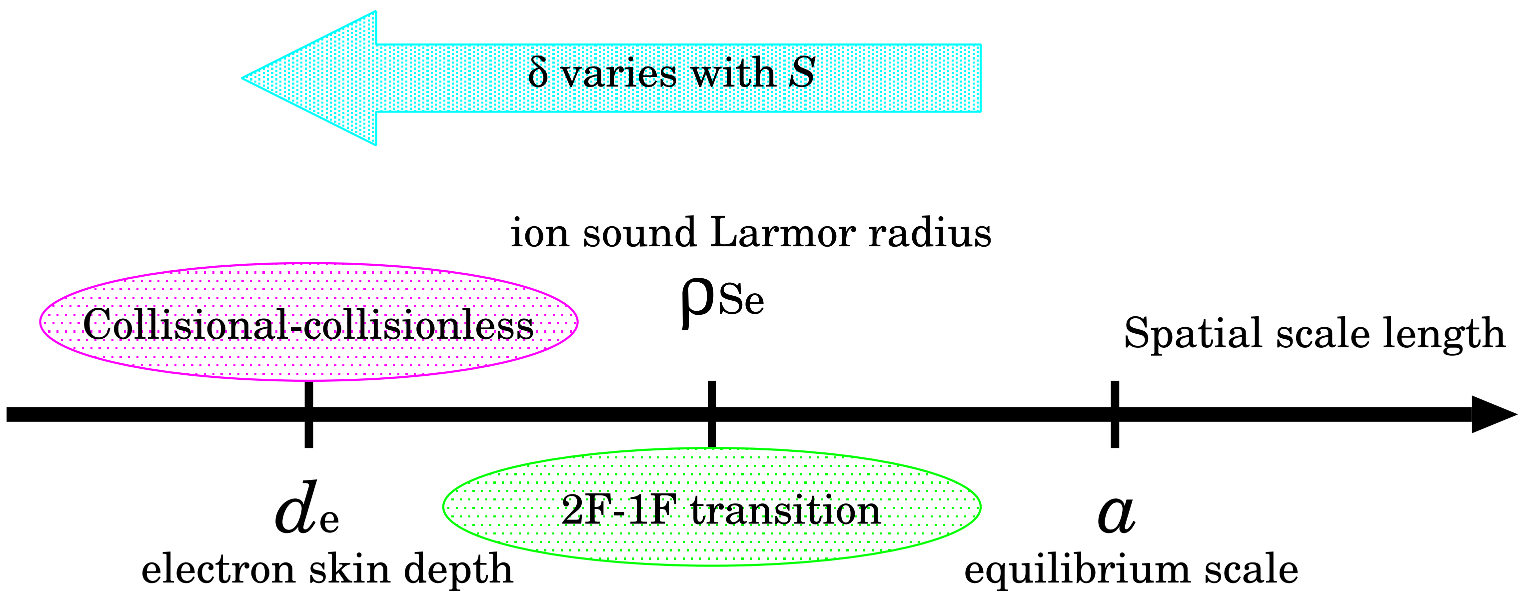
Recently, linearized collision operators for gyrokinetic simulations, which satisfies physical requirements are established and implemented in AstroGK [Abel *et al*, 2008; Barnes *et al*, 2009]

The operators are the pitch-angle scattering (Lorentz), the energy diffusion, and moments conserving corrections to those operators for like-particle collisions. Electron-ion collisions consists of pitch angle scattering by background ions and ion drag are also included.



Problem setup

Collisionality ν_e is scanned to vary current layer width δ. As ν_e is decreased, the current layer width becomes narrower, and the ion and electron kinetic scales become important.

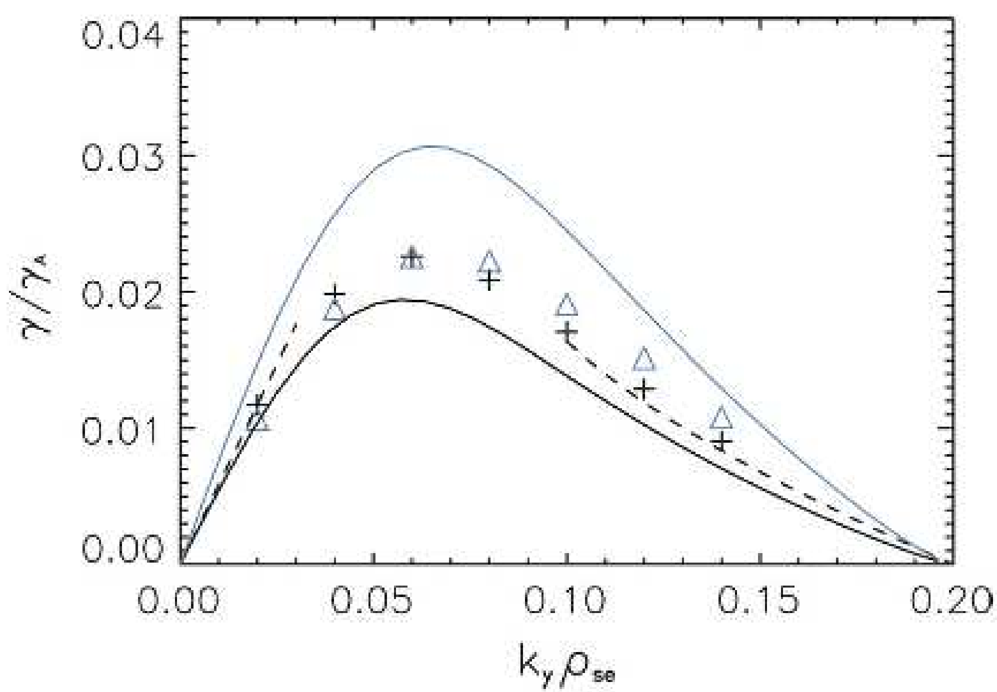


Case 1 electron scale $\ll$ ion scale $\sim \delta \ll$ equili. scale

Case 2 electron scale $\sim \delta \ll$ ion scale $\lesssim$ equili. scale

Dispersion relation

Typical form of dispersion relation of tearing instability.

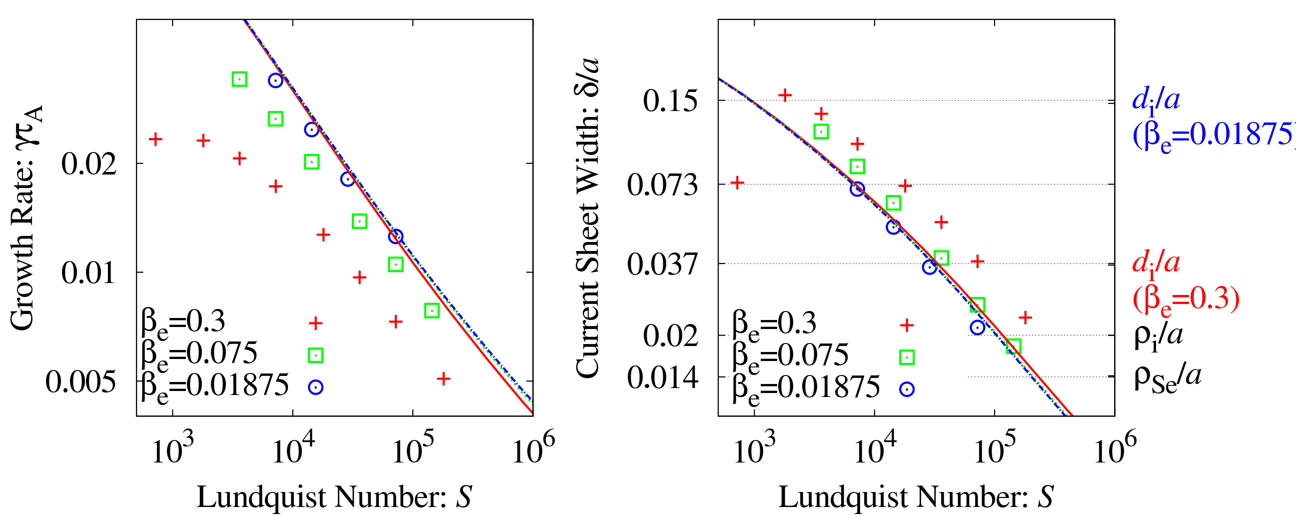


[Fig. taken from Rogers *et al.*, 2011]

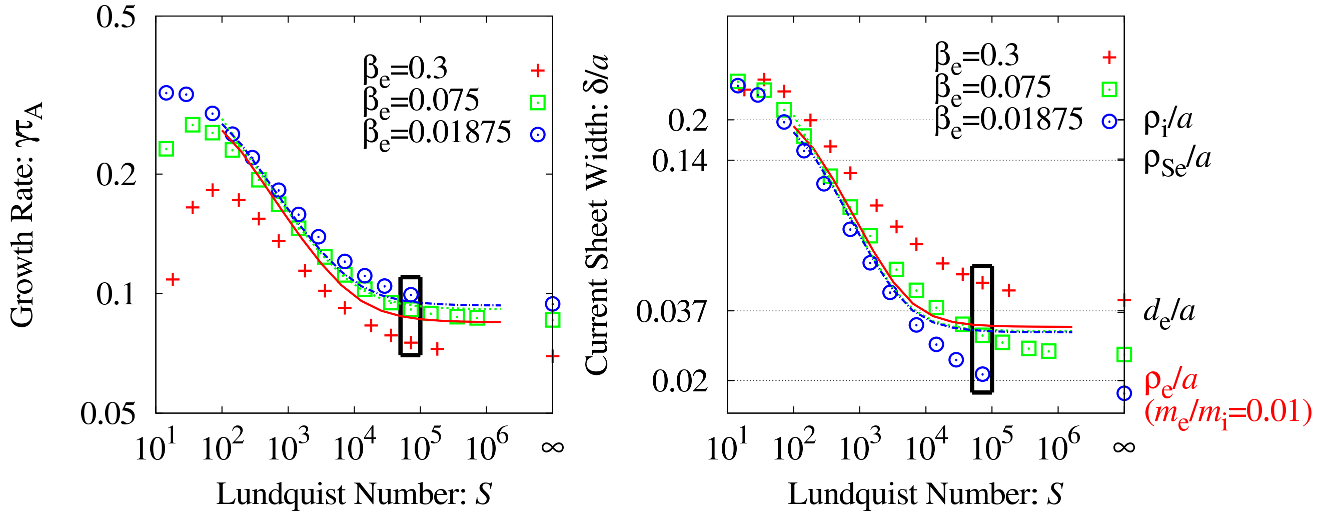
Large Δ' $\gamma\tau_{\rm A} \sim S^{-1/3}$
Small Δ' $\gamma\tau_{\rm A} \sim S^{-3/5}$

MHD to two-fluid MHD

- Growth rate and current layer width scaling against Lundquist number S are obtained from GK simulation. [dots]
- Scalings are compared with reduced two-fluid model by Fitzpatrick (Fitzpatrick, 2010). [lines]
- GK and 2F results agree well only for low-β_e.
- 2F model assumes $\beta_e \ll \sqrt{m_e/m_i}$, which is marginally satisfied for $\beta_e = 0.01875$ case.
- Eqn. of state used in 2F model may not be valid.

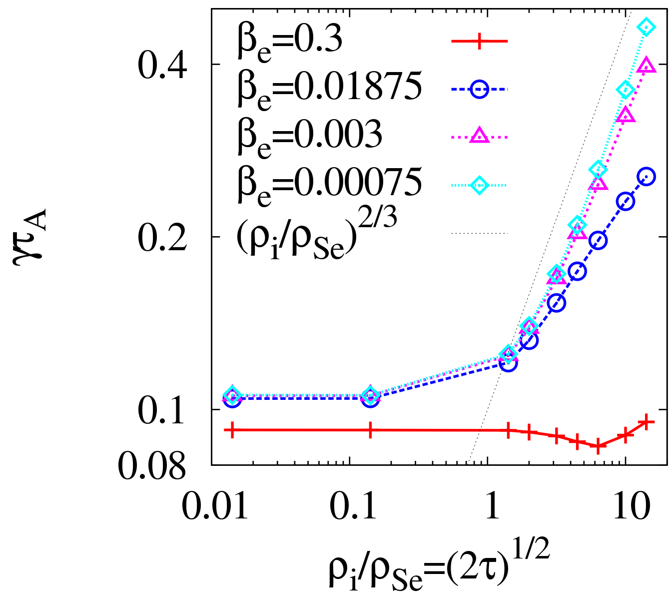


- Collisional-collisionless transitional regime is reproduced: For large S, electron inertia mediates reconnection instead of collisions.



Ion temp. dependence: kinetic Alfvén wave

- Ion temperature ($\tau \equiv T_{0\mathrm{i}}/T_{0\mathrm{e}}$) dependence.
- Theoretical prediction, $\gamma\tau_{\mathrm{A}} \sim \tau^{1/3}$, because of the transition of Alfvén wave to kinetic Alfvén wave.
- For higher β_{e}, sound wave couples to Alfvén wave. A compressible effect play a role, and $\tau^{1/3}$ dependence is no longer seen.



Summary

- We have performed linear GK simulations of tearing instability. It is shown that growth rate scaling with collisionality agrees well with prediction by 2F model only for low beta case.
- For large beta, coupling of Alfvén wave with ion sound wave becomes significant. General non-polytropic equation of state should be considered for pressure perturbations.
- See Numata *et al.*, Phys. Plasmas **18**, 112106 (2011) for more detail.
- Related future works planned: Nonlinear simulations to study kinetic effects on magnetic reconnection, diamagnetic stabilization of tearing instability [@Dartmouth], microtearing turbulence [with Loureiro *et al.*]
- Gyrokinetics is a suitable approach to multiscale kinetic plasmas. `AstroGK` is a well-established gyrokinetics code. It is free!