Suppression of electron thermal conduction in high-beta plasma

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Outline

- Background on the Cooling Flow Problem, AGN feedback and conduction in the Intracluster Medium (ICM).
- Analytic theory and simulations of kinetic heat flux instability in 1D and 2D.
- Implications for high heat flux in the ICM.

Cooling Flow Problem

- Intracluster Medium (ICM) of galaxy clusters are in a gravitational well of dark matter halo.

- ICM "cool cores" constantly radiate and have short cooling times ($t_{cool} < 10^9 yr$) and depressed temperatures (*Fabian* 1994).

- Expected star formation rates of $100 - 1000\ M_{solar}\ yr^{-1}$ (*Croton*+ 2006).

- Observations say this rate is actually an order of magnitude smaller, cooling must be offset by something.

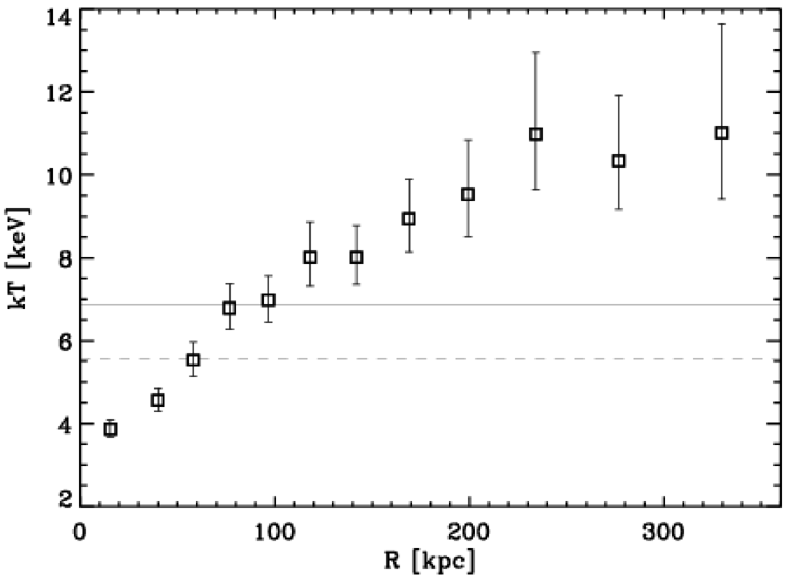
AGN Feedback

- A central galaxy (AGN or Active Galactic Nucleus) hosts a supermassive black hole.
- Accretion disk can release jets, radiation, or winds back into the ICM.
- Could lead to heating or ejection of plasma.
- Heat conduction could also help offset cooling but can’t be the only solution.

Nasa X-Ray Observation of the Perseus Cluster (Chandra Telescope).

Roles of Conduction in feedback and the ICM

- Transport of heat into the cluster core.
- Thermalization of energy in sound waves and shocks (e.g. from jets).
- Inhibition of local cooling of cluster gas → less star formation.
- Driving of large-scale fluid instabilities such as:
  - (i) Heat Flux Driven Buoyancy Instability (HBI) [$\nabla T > 0$ at inner radii]
  - (ii) Magnetothermal Instability (MTI) [$\nabla T < 0$ at outer radii]



Hicks+ (2002)

Characteristics of the ICM Plasma

- $\beta = \frac{4\pi nT}{B^2/2} \sim 100$, $B \sim 10^{-6} G$ or $10^{-10} T$
- $\mathrm{T} \sim 1 - 10\ keV$, $\mathrm{n} \sim 10^{-2} cm^{-3}$
- Electron gyro radius of $\sim 10^{8}$m, gyro period around 1 second
- (Nominal) Mean free path: $10^{18-19} m$ (100 pc). Weakly collisional (collisionless on small scales). Fluid equilibria are actually unstable – kinetic description needed.
- $\frac{T}{\nabla T} \sim 10^{21}\mathrm{m}$ $\rightarrow$ plasma will try to conduct heat. Process anisotropic because of B.
- q implies free energy source – turbulence from instabilities suppresses q even along B. Spitzer prescription not always valid.

Previous work on high β microinstabilities

- Ion instabilities:

- *Kunz+* (2014) [mirror/firehose, sheared hybrid kinetics]
- *Riquelme+* (2015) [mirror/ion cyclotron, sheared PIC]
- *Rincon+* (2015) [nonlinear mirror saturation]

- Electron + ion pressure anisotropy e.g. *Riquelme+* (2016): sheared full PIC.

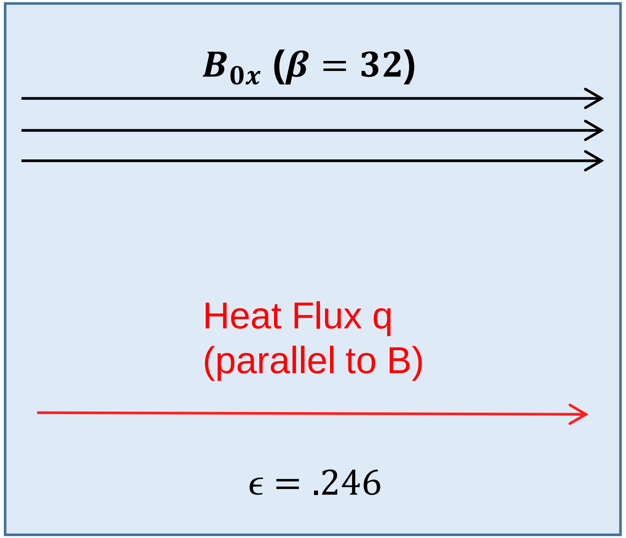
- We find a solely electron heat flux-driven instability, complementary to above work -> Pitch angle scattering mechanism for isotropizing distribution of electrons.

Heat Flux Distribution (Chapman Enskog Solution)

- Assume collisions (ν_{ei}) are balanced by a temperature gradient along B at large scales, giving an electron distribution function with a heat flux [*Levinson & Eichler* (1992)]:

$$f_0(\mathbf{r}, \mathbf{v}) = f_m\left[1 + \frac{\epsilon}{2}\left(\frac{v^2}{v_T^2} - 5\right)\frac{v_n}{v_T}\right]. \qquad (2)$$

Here $\epsilon = (|\nabla T|/\nu T)v_T$, $v_T = (kT/m)^{1/2}$, and $v_n = -\mathbf{v}\nabla T/|\nabla T|$ is the component of the velocity along the direction of the thermal flux.



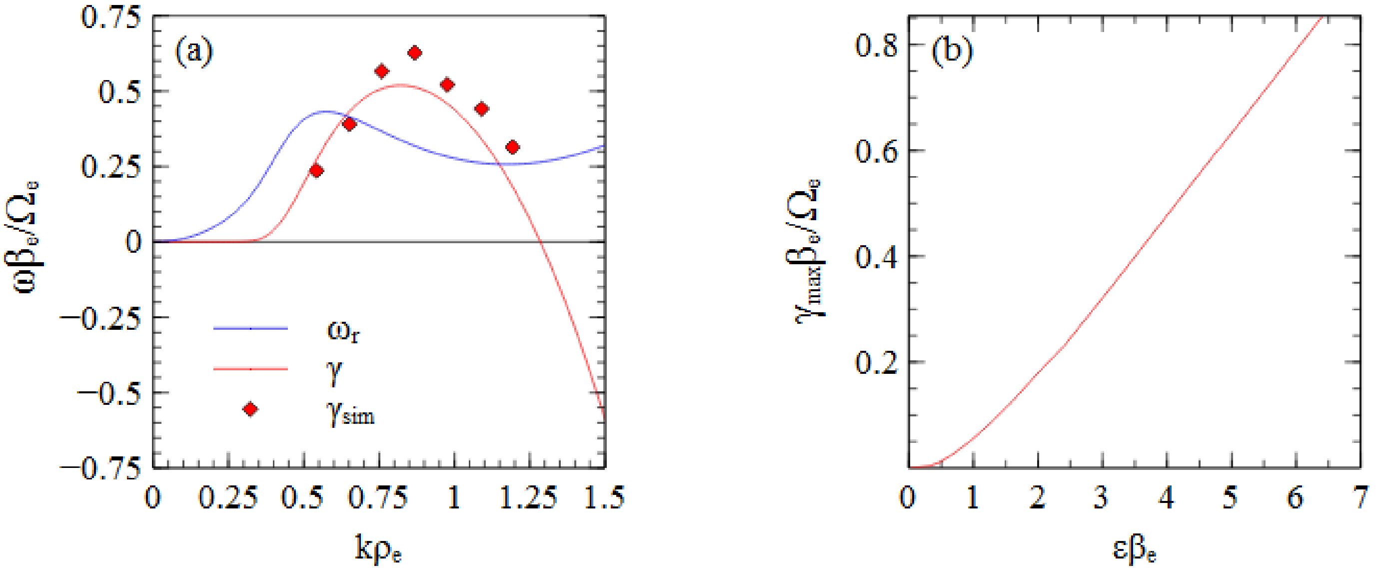
- No pressure anisotropy, no drift. Just $q \propto \int v_x v^2 f_0$
- For analytic theory and PIC simulations, use local setup with $\nabla T = 0$, collisionless.

Linear Theory

- 1D solution ($k = k_{\parallel}$) of linearized Vlasov-Maxwell system. Cartesian geometry.
- Neglect ion contributions (very weak damping $\propto \left(\frac{m_e}{m_i}\right)^{\frac{1}{2}}$)
- Assume circular polarization (whistler-like).
- Obtain:

$$\frac{(kd_e)^2}{\omega} = \frac{1}{n_o} \frac{\int d^3v \frac{v_\perp}{2} \left[\left(1 - \frac{kv_x}{\omega}\right) \frac{\partial f_o}{\partial v_\perp} + \frac{kv_\perp}{\omega} \frac{\partial f_o}{\partial v_x} \right]}{\omega - kv_x - \Omega_e}$$

- For standard whistler ordering $\omega \sim (kd_e)^2 \Omega_e,\ kd_e \sim 1$, bulk resonance at $v_\parallel \sim v_{Te}/\sqrt{\beta_e} \to 0$ (heavily damped at high beta β_e)
- Instead let $k\rho_e \sim 1,\ \omega \ll \Omega_e$: instability can now occur, resonance at $v_x = -\Omega_e/k$



- Good agreement between growth rate for linear theory (red) and PIC simulations (red diamonds).
- $\omega \sim \frac{\Omega_e}{\beta}, \frac{\omega}{k} \sim \frac{v_{Te}}{\beta} \ll v_{Te},$
- No threshold for instability.

$$\omega = \frac{\Omega_e}{\beta_e}\left(k^2\rho_e^2 + \epsilon\beta_e k\rho_e h_2\right)\frac{1}{h_1},$$

$$h_1(k\rho_e, \epsilon) = \frac{\Omega_e}{k n_0}\int d^3\mathbf{v}\,\frac{f_0}{v_x + \Omega_e/k}$$

$$h_2(k\rho_e) = \frac{1}{k\rho_e}\frac{1}{\epsilon}\int d^3\mathbf{v}\,\frac{v_x f_0 + (v_\perp^2/2)\partial f_0/\partial v_x}{v_x + \Omega_e/k}$$

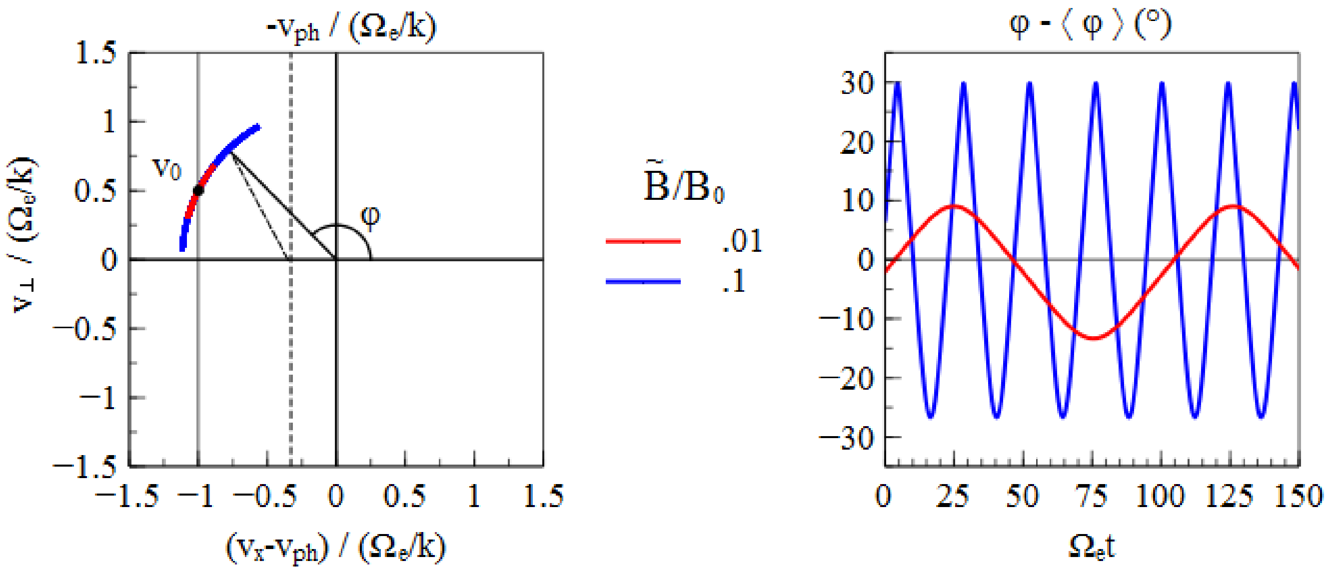
1D Nonlinear Theory

- Particles can be trapped in a single linear mode if they are near resonance, $v_x = -v_r = -\Omega_e/k$.

- In frame of wave, $v_x = v_{ph} = \frac{\omega}{k}$, no electric field. Particles must move along circular arcs in phase space.

- This implies energy conservation in wave frame and non-conservation (instability drive) in lab frame.

- Particles execute trapping motion because of conservation of energy and an energy-like quantity (not μ) as they experience oscillating B.



$(\theta = kx)$ $\quad\quad$ $\ddot{\theta} + \omega_b^2 \sin\theta = 0,$ $\quad\quad$ $\tilde{\Omega}_e = e\tilde{B}/m_e c$

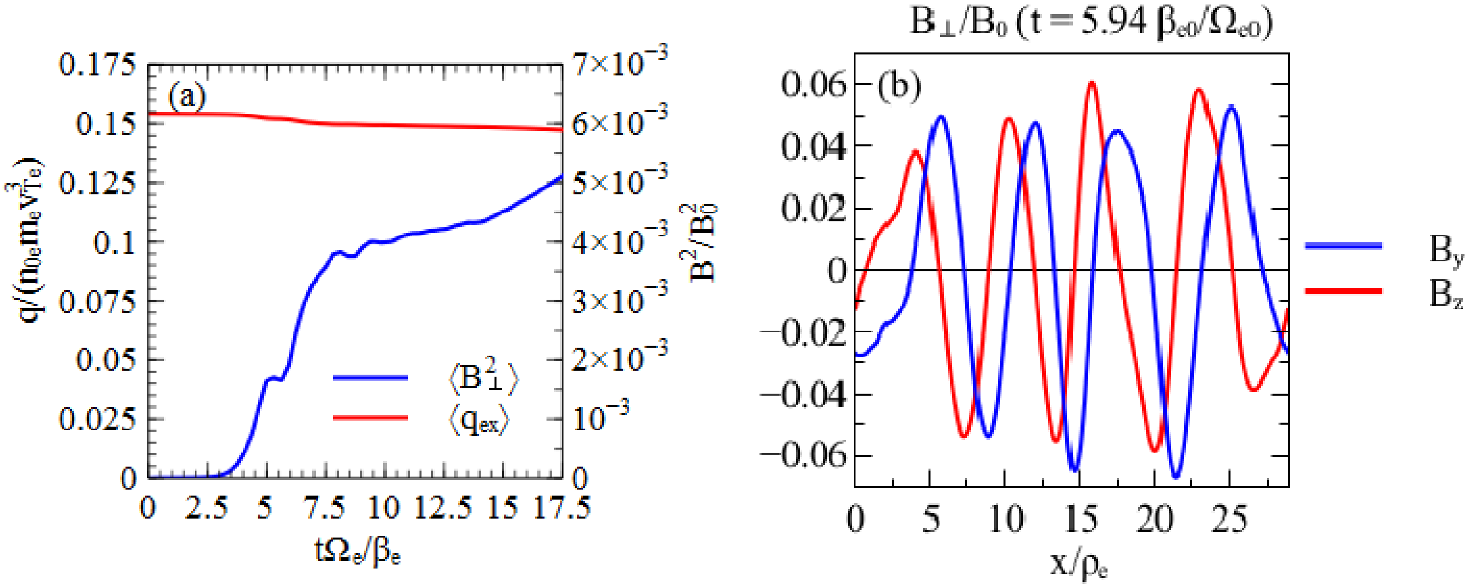
where $\omega_b = \sqrt{kv_{\perp 0}\tilde{\Omega}_e}$ is the bounce frequency associated with deeply trapped particles. Integrating once yields

$$\frac{1}{2}\dot{\theta}^2 - \omega_b^2(1 - \cos\theta) = \frac{1}{2}\dot{\theta}_0^2$$

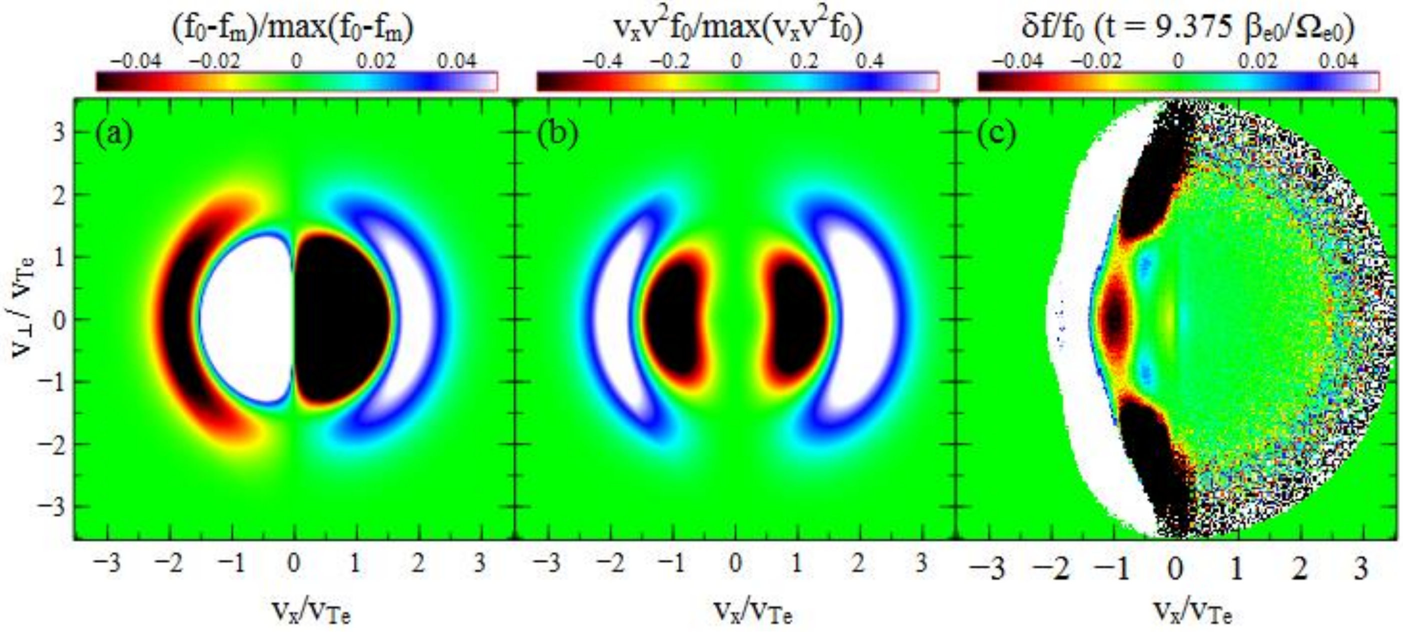
(Dalena+ 2012,
Mace+ 2012)

1D PIC Simulations

- We use P3D (full PIC, Drake group at UMD).
- Run instability as initial value problem, periodic boundary conditions.
- Stationary ions.

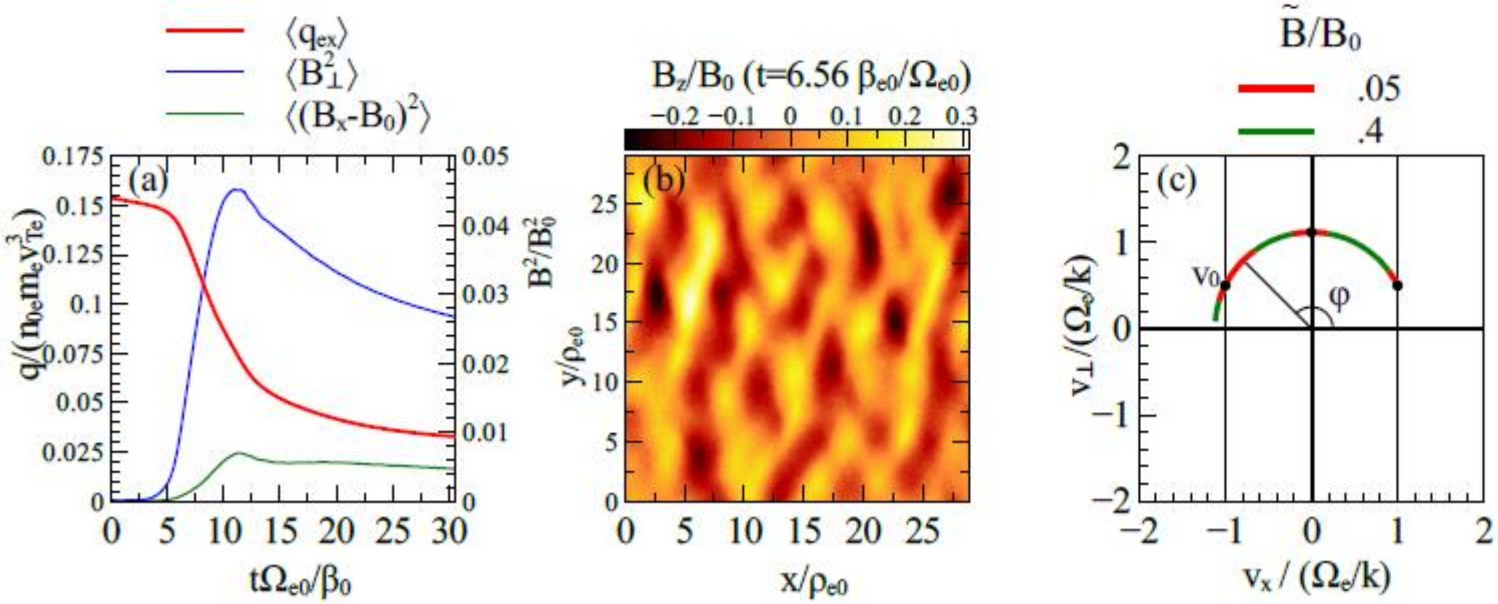


Reasons for Weak Heat Flux Suppression in 1D



- Resonance can only happen in $v_{\parallel} < 0$ half-plane in 1D. Nowhere near large heat flux and excess particles at $v_{\parallel} \cong 2v_{Te}$

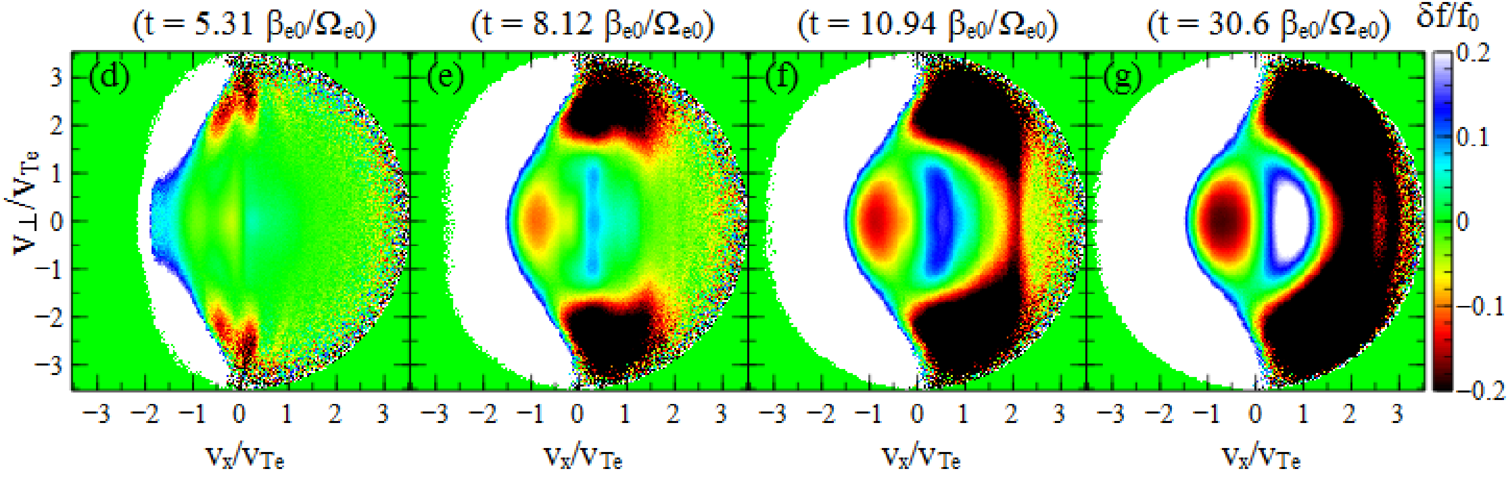
2D Results



Off-angle propagation allows $n = 0$ (Landau) and $n = \pm 1, \pm 2, \ldots$ (Cyclotron) resonances.
Resonant overlap leads stochastic diffusion of particle phase space trajectories. See: *Karimabadi*+,1992, JGR

Resonances in 2D simulations

- Snapshots in time of $\delta f = \frac{f - f_0}{f_0}$



Thermal Conductivity Estimate

- Replace collision frequency with peak growth rate

$$\nu_w = \gamma = \epsilon \Omega_e$$

$$\epsilon = \sqrt{\rho_e / L_T}$$

$$q_{\|} \propto v_{te} n T_e \sqrt{\frac{\rho_e}{L_T}}$$

$\sim 10^{-6}$ for ICM

Conclusions

- Electron thermal conduction may be strongly suppressed in galaxy clusters.
- Proposed scattering mechanism is particle trapping by unstable monochromatic whistler modes.
- Resonant overlap leads to large-angle deflections in phase space, but must have at least 2D system.
- Driven system (not IVP) will likely give more realistic results and estimates for thermal conductivity.