Whistlers and Suppressed Heat Fluxes in the Intracluster Medium

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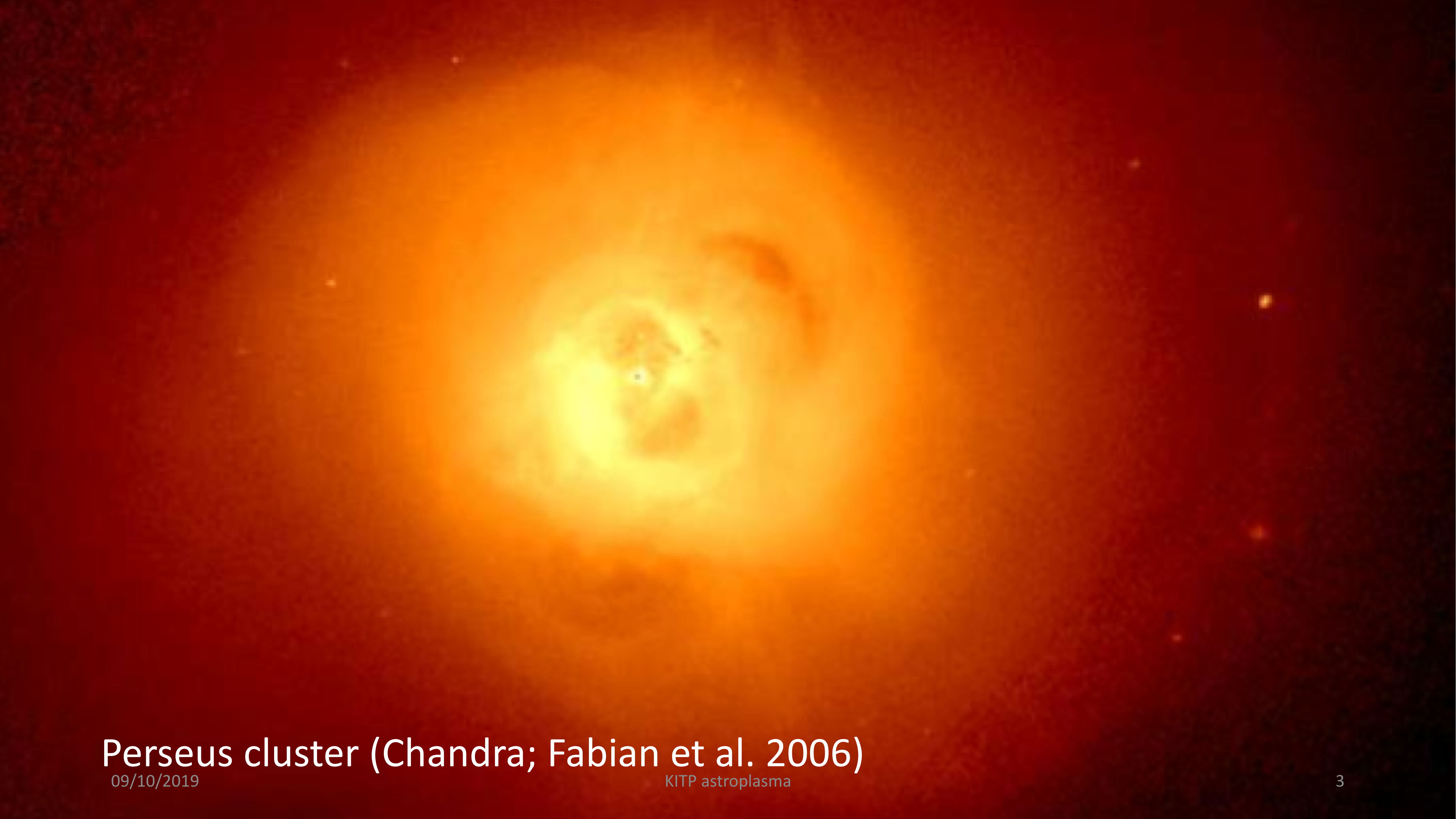
With… **Gareth Roberg-Clark**, Marc Swisdak (U.Maryland)

Roberg-Clark, Drake, Reynolds, Swisdak (2016), ApJL, 830, L9
Roberg-Clark, Drake, Reynolds, Swisdak (2018), PRL, 120, 035101
Roberg-Clark, Drake, Swisdak, Reynolds (2018), ApJ, 867, 154

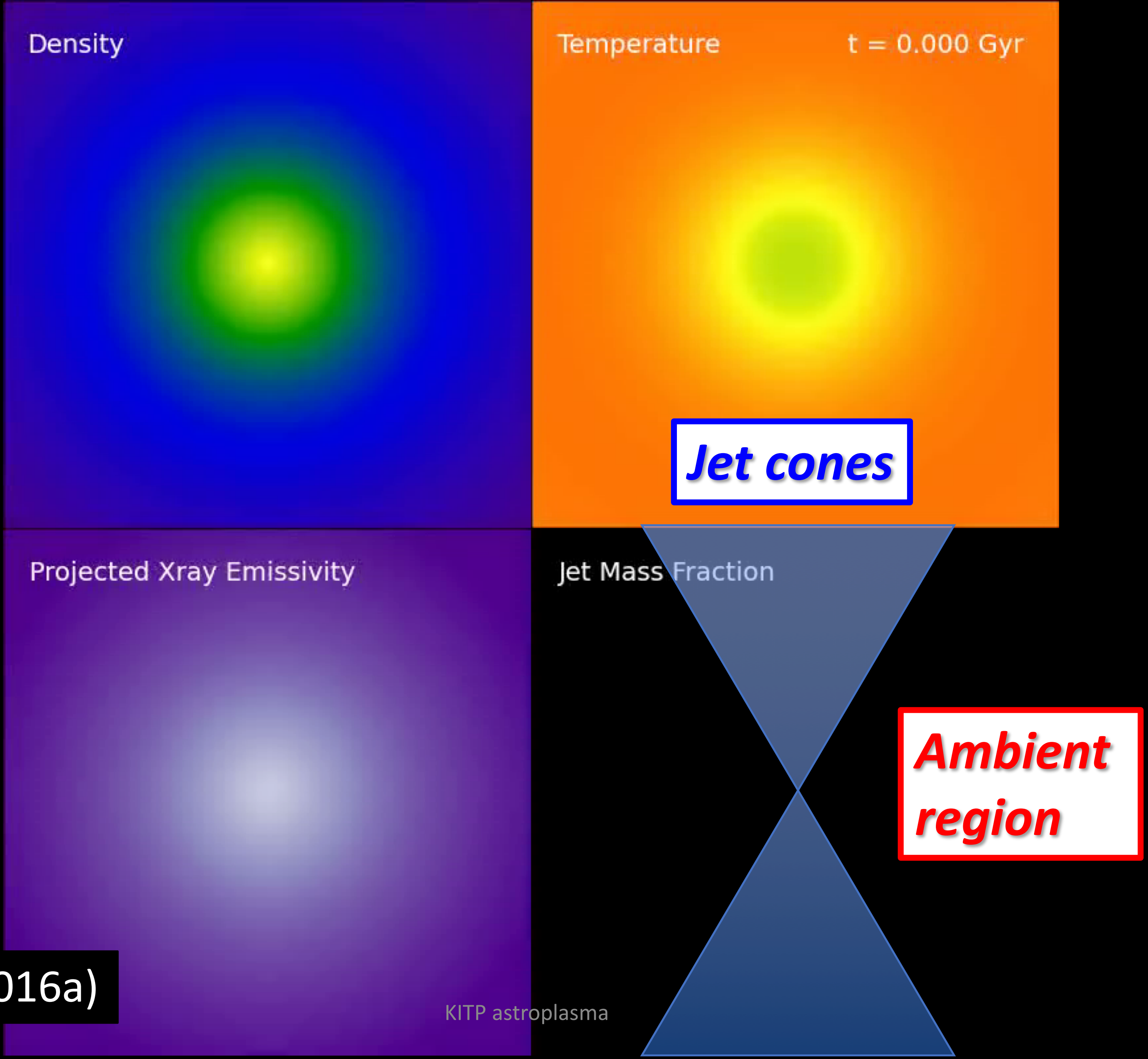
Outline

- Motivation : Cooling cores of clusters role of thermal conduction
- ICM as a high-β, weakly collisional, magnetized plasma
- Punchlines :
  - Electron heat flux carried at whistler phase speed
  - Suppression below (saturated) Spitzer by factor β

- Drivers of the whistler instability; Importance of obliquity (and >1D)
- Comparison with solar wind
- Scattering of energetic electrons
- Analogies with CR transport problem



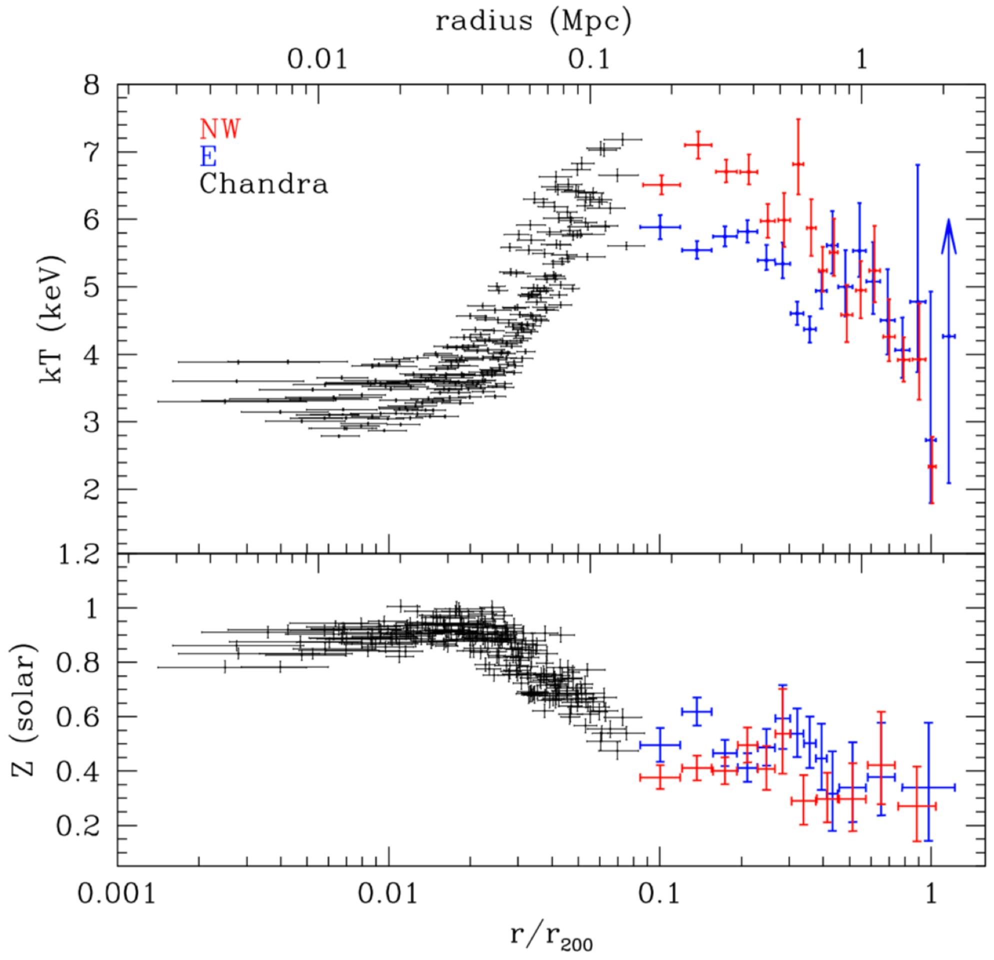
Perseus cluster (Chandra; Fabian et al. 2006)



Yang & Reynolds (2016a)

Potential roles of thermal conduction

- Direct heating of cool cores… reducing the need for AGN heating (e.g. Binney & Cowie 1981; Zakamska & Narayan 2003; Bogdanovic et al. 2009; Ruszkowski & Oh 2010; Yang & CSR 2016; Fang et al. 2018)
- Suppression of cooling instabilities… regulation of AGN fueling (e.g. Field 1965; Voit et al. 2008; Yang & CSR 2016)
- Dissipation of AGN-driven waves… mechanism for AGN heating (e.g. Fabian et al. 2005; Tang & Churavov 2018; Zweibel et al. 2018)



Simionescu et al. (2011)

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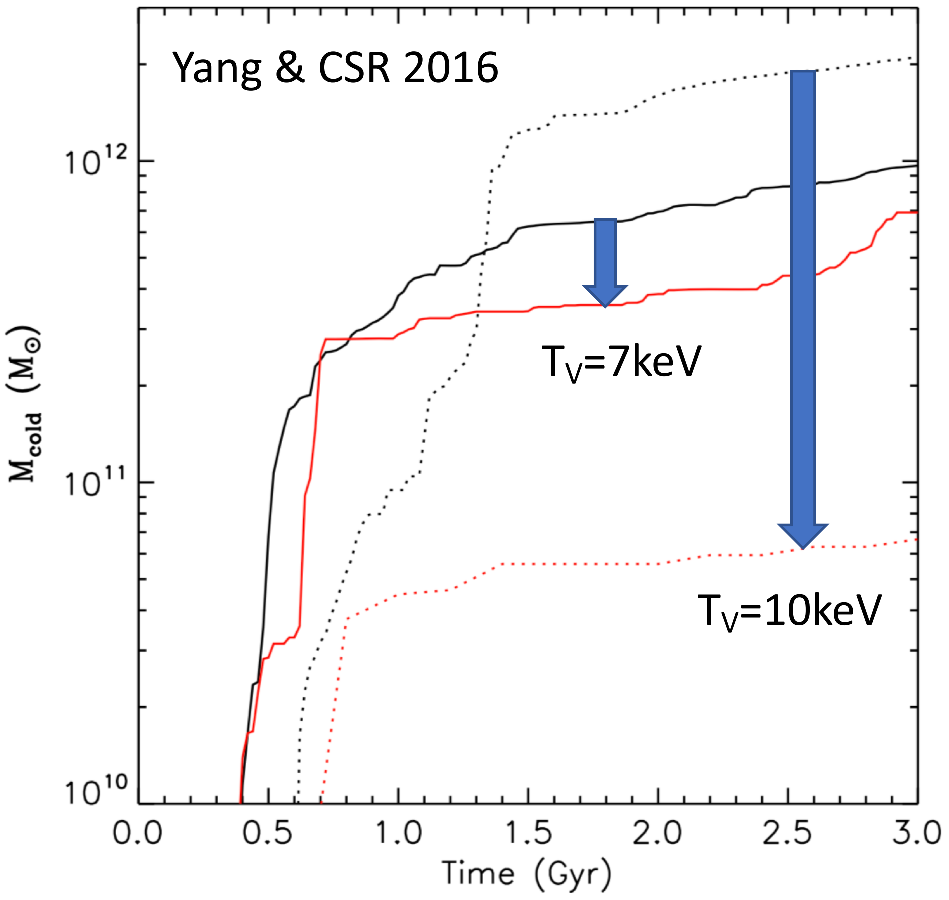

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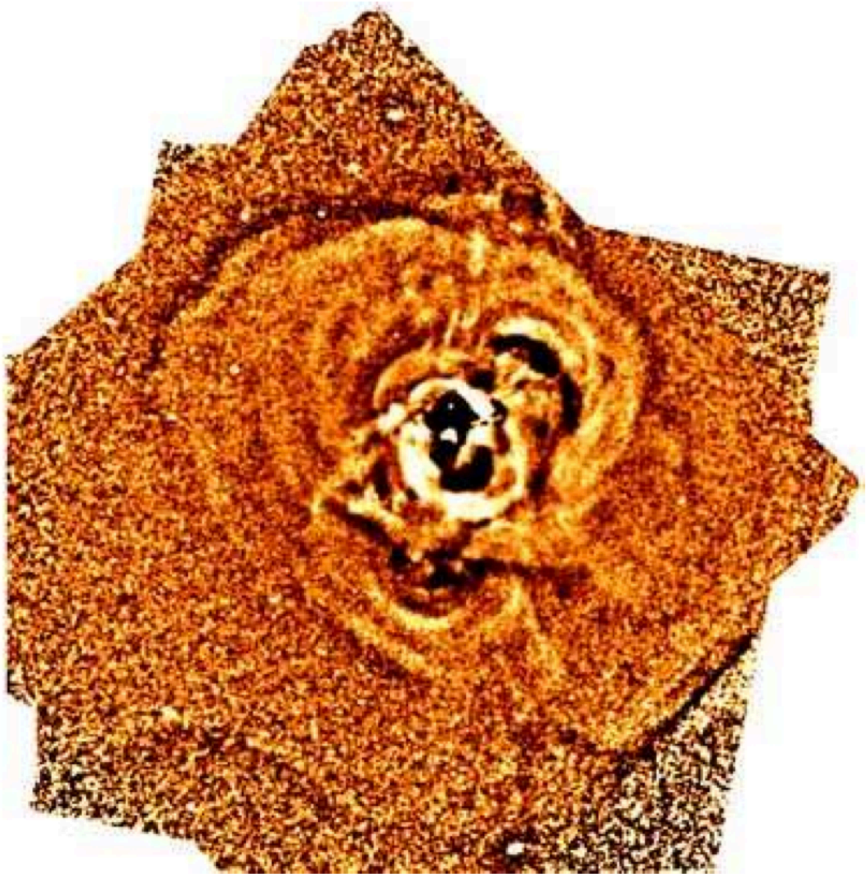


Perseus unsharp mask (Sanders et al. 2006)

The Physics of Conduction : Classical Theory

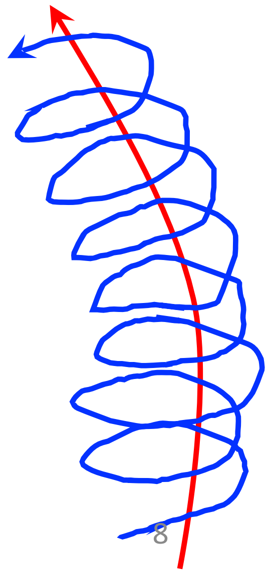
- ”Classical” result (Spitzer)
    - Assuming strong collisionality

$$\begin{aligned} \mathbf{q} &= -\chi \nabla T \\ \chi &= 4.6 \times 10^{-7} T^{5/2}\,\mathrm{erg\,cm^{-1}\,s^{-1}\,K^{-1}} \end{aligned}$$

$$\left(\kappa \equiv \frac{\chi T}{P} \sim \lambda_e^2 \nu_{\rm ce} \right)$$

- Modification for magnetic fields (Braginskii) – heat flux strongly suppressed across field lines, but proceeds like above along field lines

$$\mathbf{q} = -\chi \mathbf{b} (\mathbf{b} \cdot \nabla) T$$

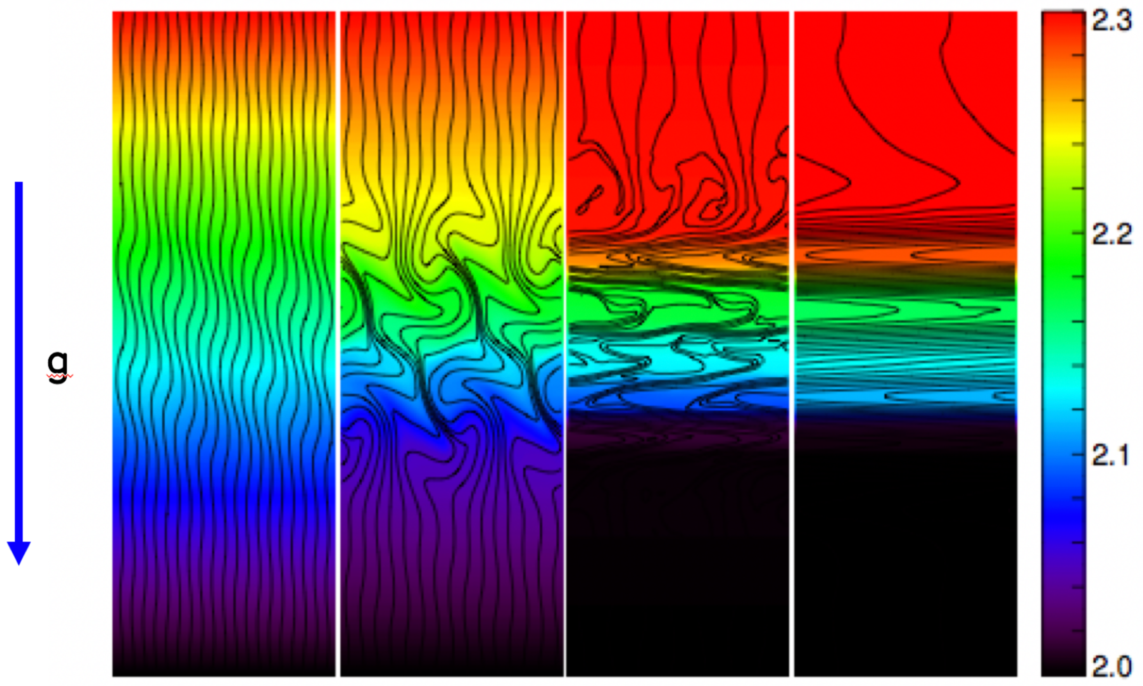


With anisotropic conduction, temperature (not entropy) gradients drive buoyancy instabilities…

b_z \ $\frac{dT}{dz}$	<0 (Outskirts)	>0 (Core)
≈0	MTI	g-mode driven overstable by radiative cooling
≈1	g-mode driven overstable by conductive heat flux	HBI

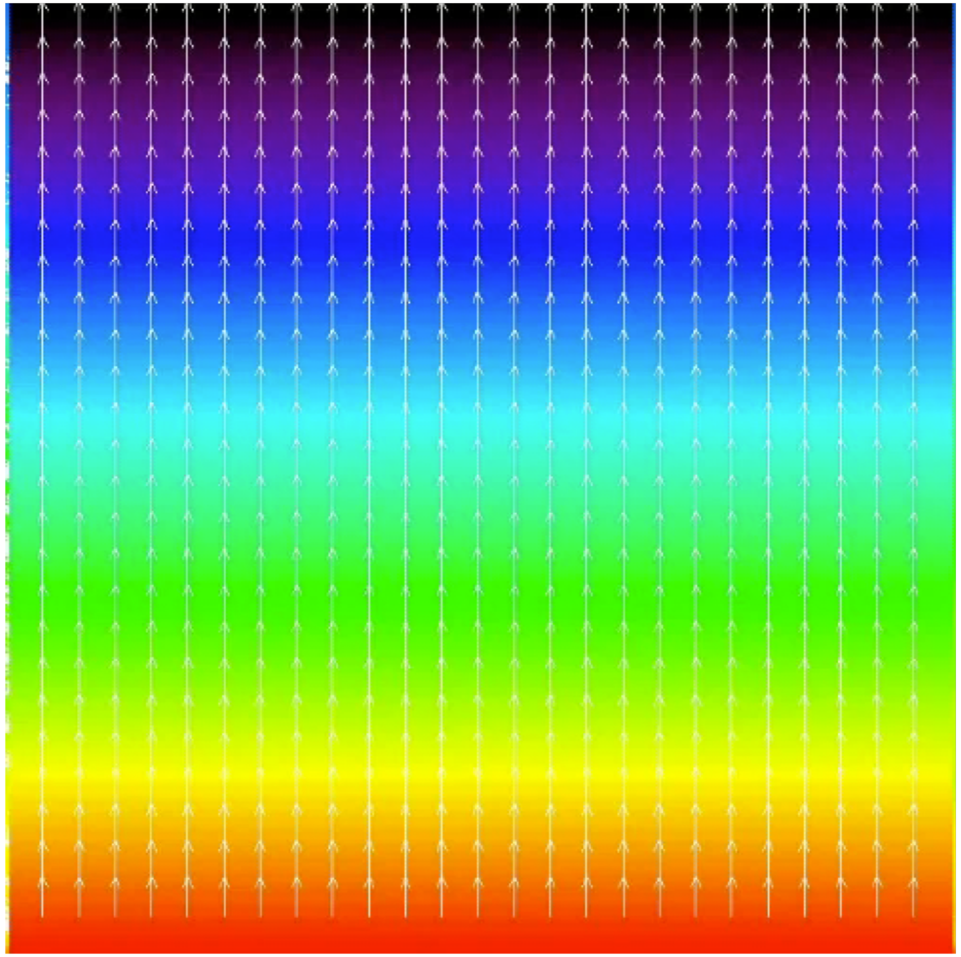
Balbus & Reynolds (2010)

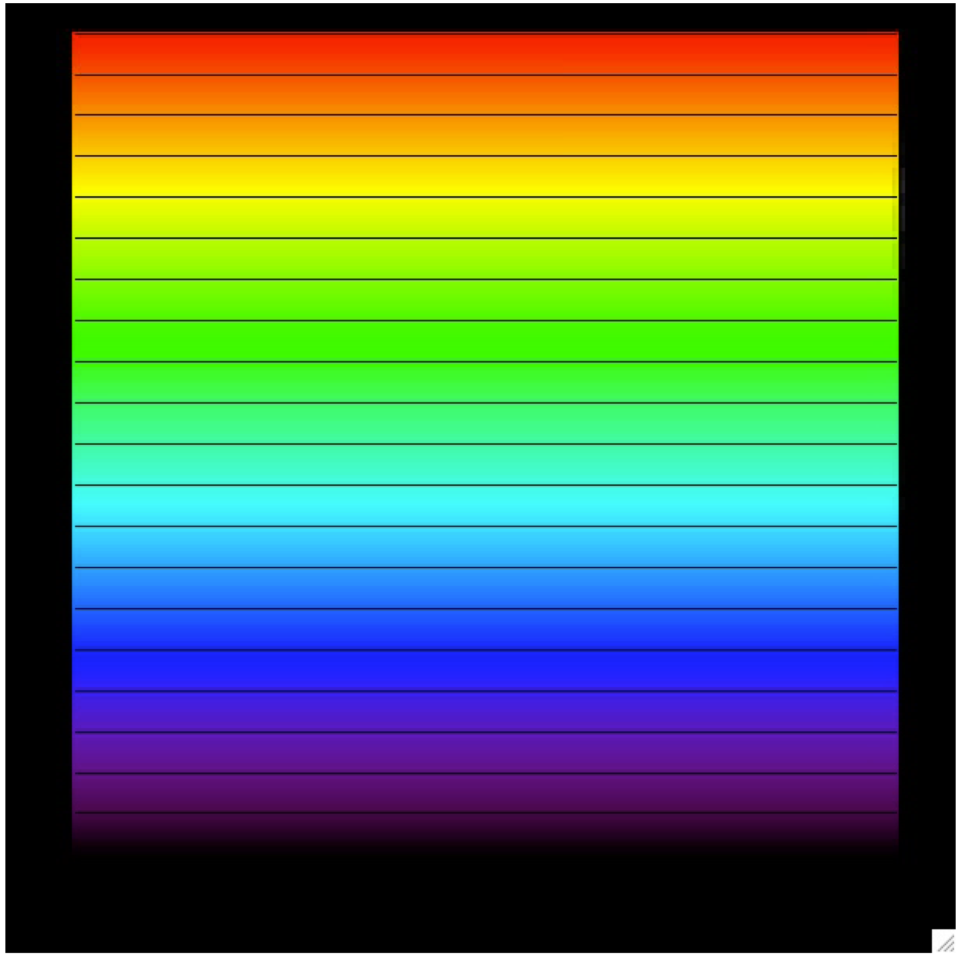
Temperature (color) and magnetic field (lines)



(b)

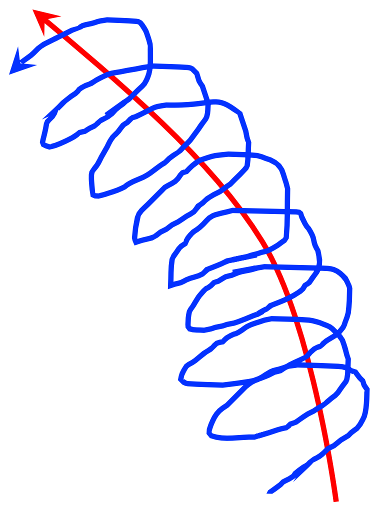
Avara et al. (2012)
also… Parrish & Quataert (2008)McCourt et al. (2011)





Heat-flux driven and radiative-cooling overstabilities (T.Bogdanovic 2013, unpublished)

Microphysics of the ICM



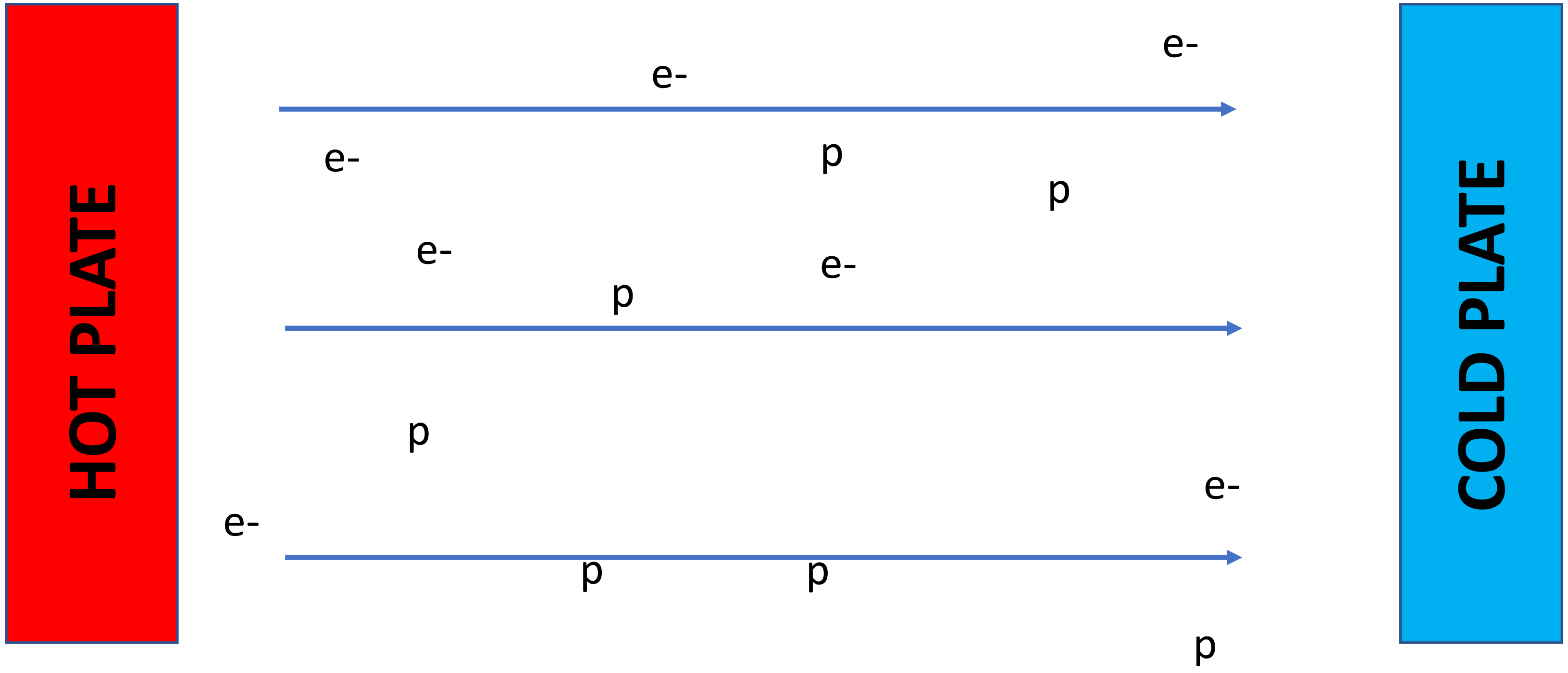
- Interesting scales and dimensionless numbers
  - Mean free path $\lambda_e = 2 \left(\frac{T}{8\,\mathrm{keV}}\right)^2 \left(\frac{n}{0.01\mathrm{cm}^{-3}}\right)^{-1}$ kpc
  - Electron gyroradius $r_e \approx 2 \times 10^8 \left(\frac{T}{8\,\mathrm{keV}}\right)^{1/2} \left(\frac{B}{1\mu\mathrm{G}}\right)^{-1}$ cm
  - Ratio of thermal-to-magnetic pressure $\beta \equiv \frac{p_{\mathrm{th}}}{p_{\mathrm{mag}}} \sim 100$
- So ICM is weakly collisional, strongly-magnetized, high-β plasma.
- Very susceptible to instabilities driven by deviations of velocity distribution from isotropic Maxwellian.

PIC (p3d) models of heat flux

P3D code
(Zeiler et al. 2002)

Fully kinetic mode
m_p/m_e=1600
$\partial/\partial z$=0
T_h/T_c=2-10
32k x 4k cells
560 particles/cell
(~10^{11} particles)

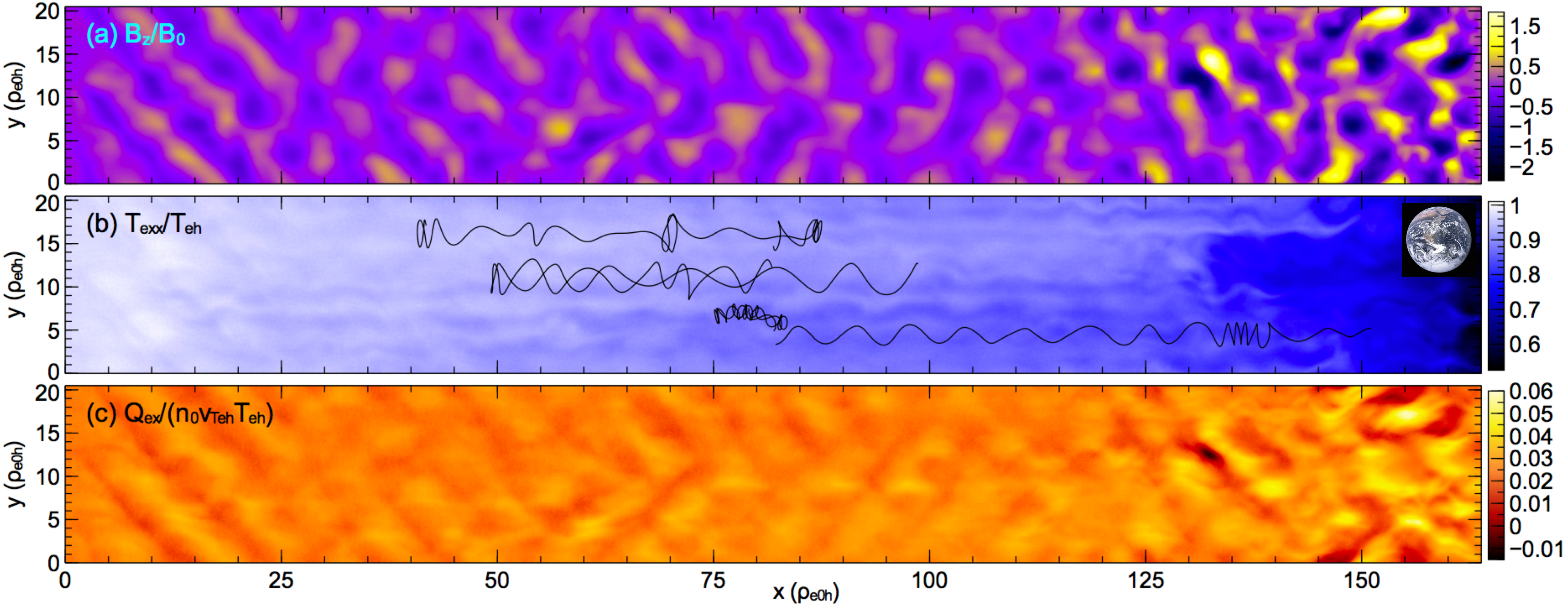
Scan β=0.25-128



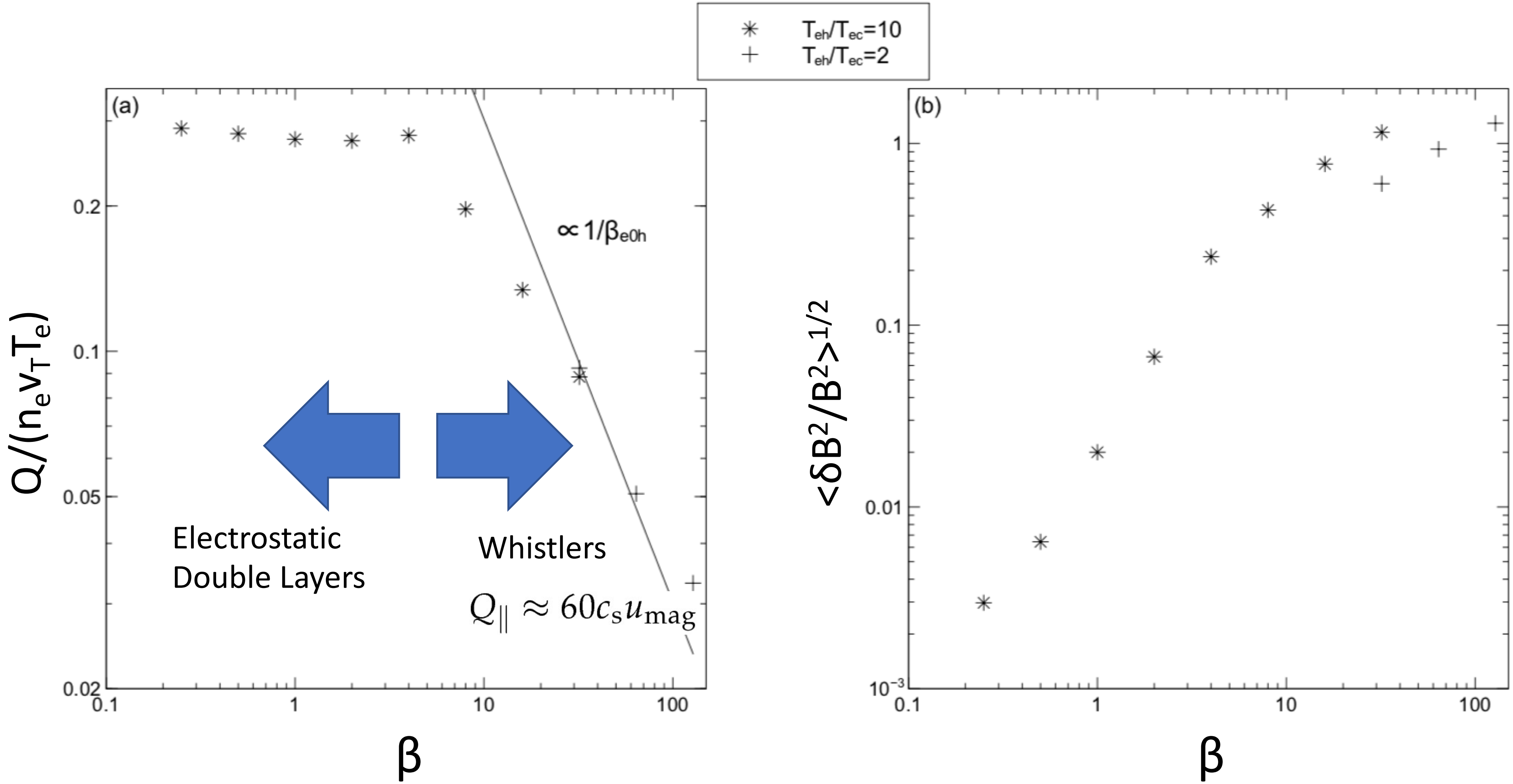
Sustain electron temperature via hot and cold plate boundary conditions
Re-inject particles from hot and cold thermal reservoirs when they hot boundary
B allowed to evolve freely
2D domain; either freeze ions or assume close-to-physical mass ratio

Example high-β case; β=64

- Heat flux drives whistlers
- Driven by particles resonating with whistlers $\omega = kv_x + n\Omega_e \qquad (n = -1, 0, +1)$
- When $\delta B/B>0.3$, overlapping resonances scatter e^- ; suppresses heat flux



Roberg-Clark et al. (2016); Roberg-Clark et al. (2018); also Komarov et al. (2018)



Roberg-Clark et al. (2018b)

Heat flux in terms of whistler phase speed…

- Dispersion relation…

$$\omega = \frac{k^2 \rho_e^2 \Omega_e}{\beta_e} \qquad k\rho_e \sim 1$$

$$\Rightarrow \frac{\omega}{k} \sim \frac{v_{Te}}{\beta_e}$$

- Whistlers as scattering centers – imagine whistler as a bucket that traps particles and convects their energy along the B-field:

$$q_{\|} = \alpha n_0 \frac{\omega}{k} T_{eh} \sim n_0 m_e \frac{v_{Teh}^3}{\beta_{e0h}} = v_{Teh} \frac{B_0^2}{8\pi}$$

Consistent with hypothesis of Levinson & Eichler [1992]
See also Gary et al. [1994], Pistinner & Eichler [1998].

If L_T is temperature scale length then we replace Spitzer

$$Q_{\rm Spitzer} = \frac{0.5 n_e m_e v_T^3}{L_T/\lambda_e + 4}$$

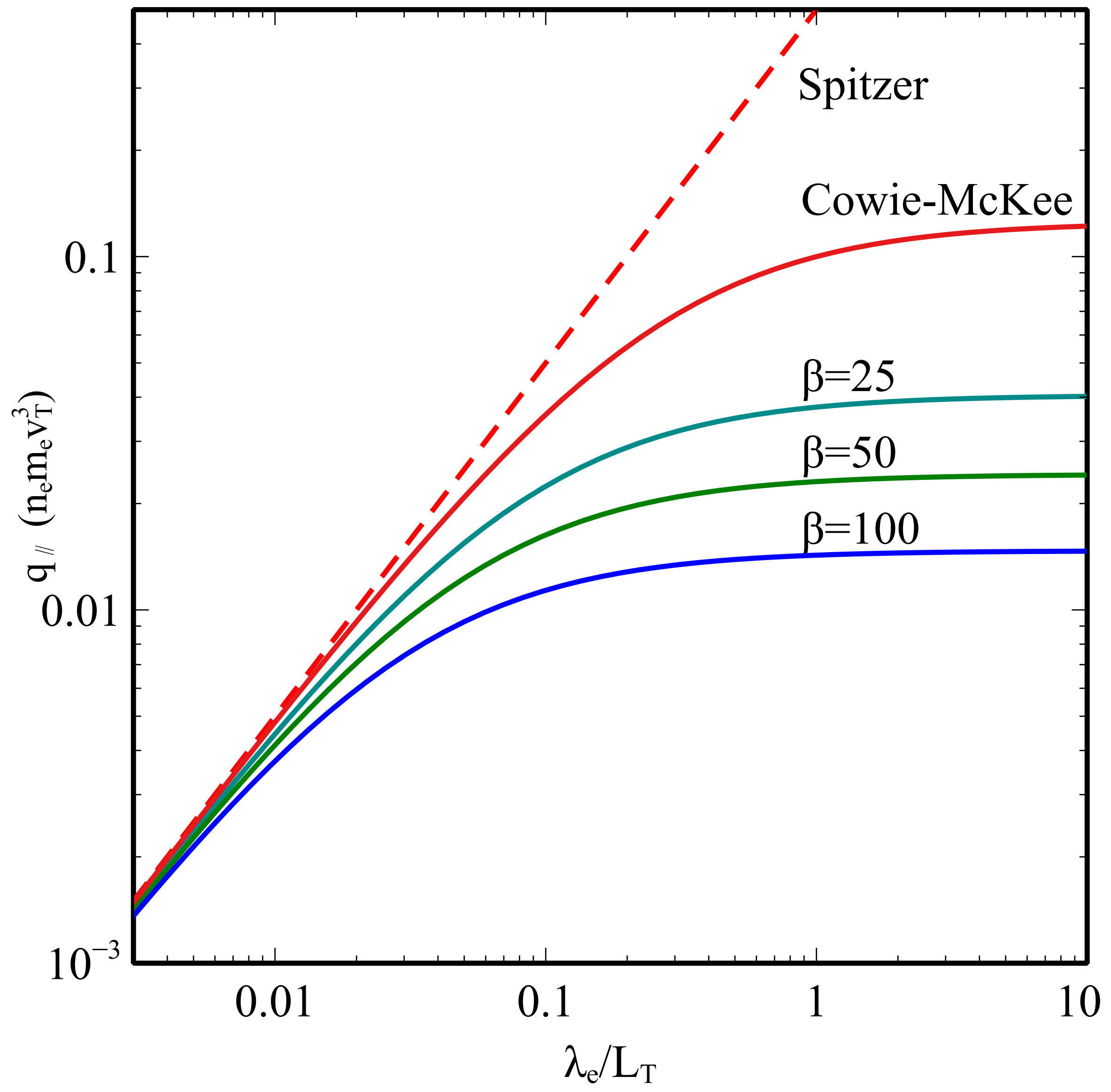
with

$$Q_{\rm icm} = \frac{0.5 n_e m_e v_T^3}{L_T/\lambda_e + 4 + \beta/3}$$

Whistler physics becomes important when

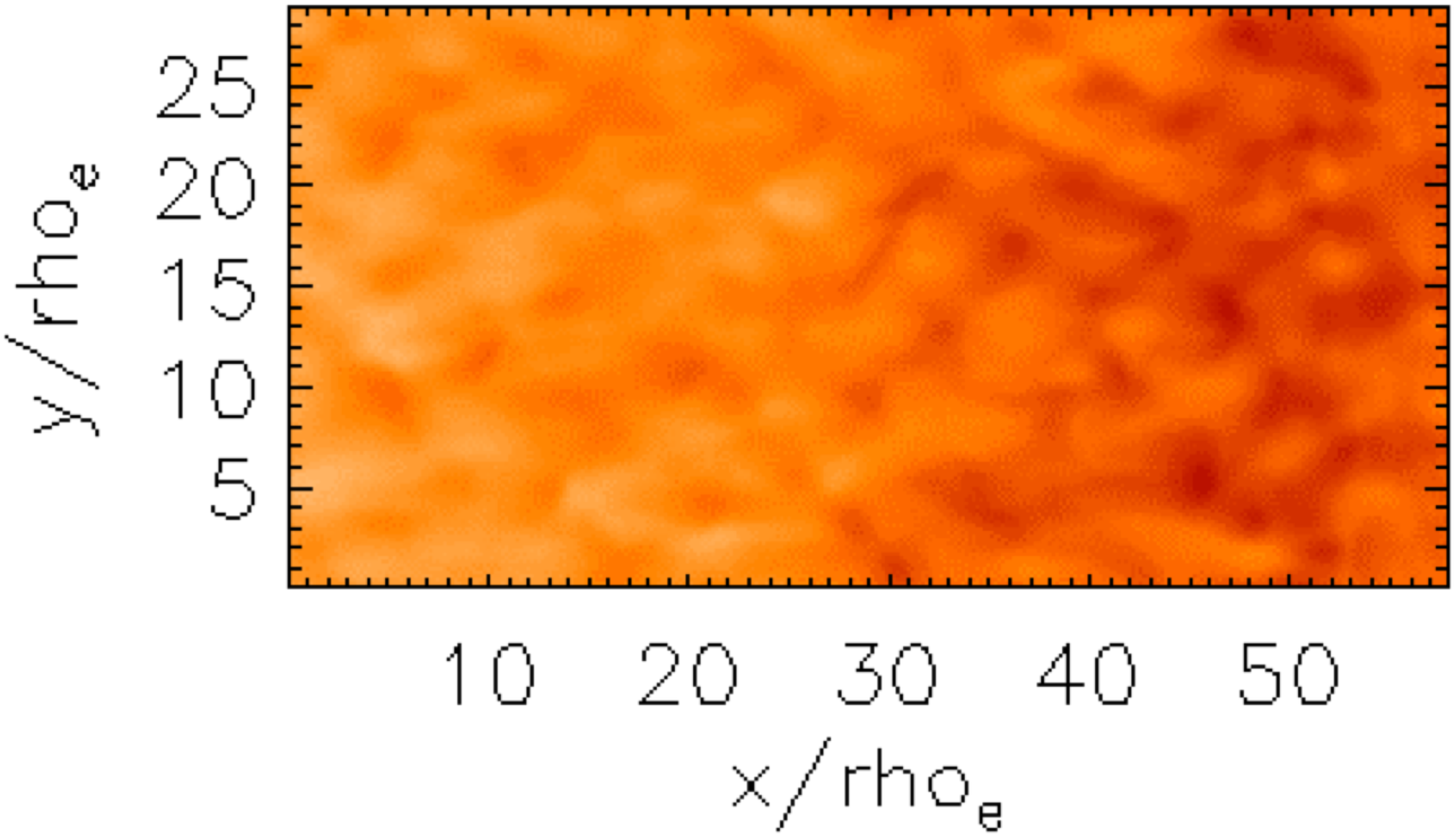
$$L_T < \frac{\beta}{3}\lambda_e \sim 30\lambda_e$$

As well as suppression, heat flux has different scaling with T and depends on B. Important for stability calculations

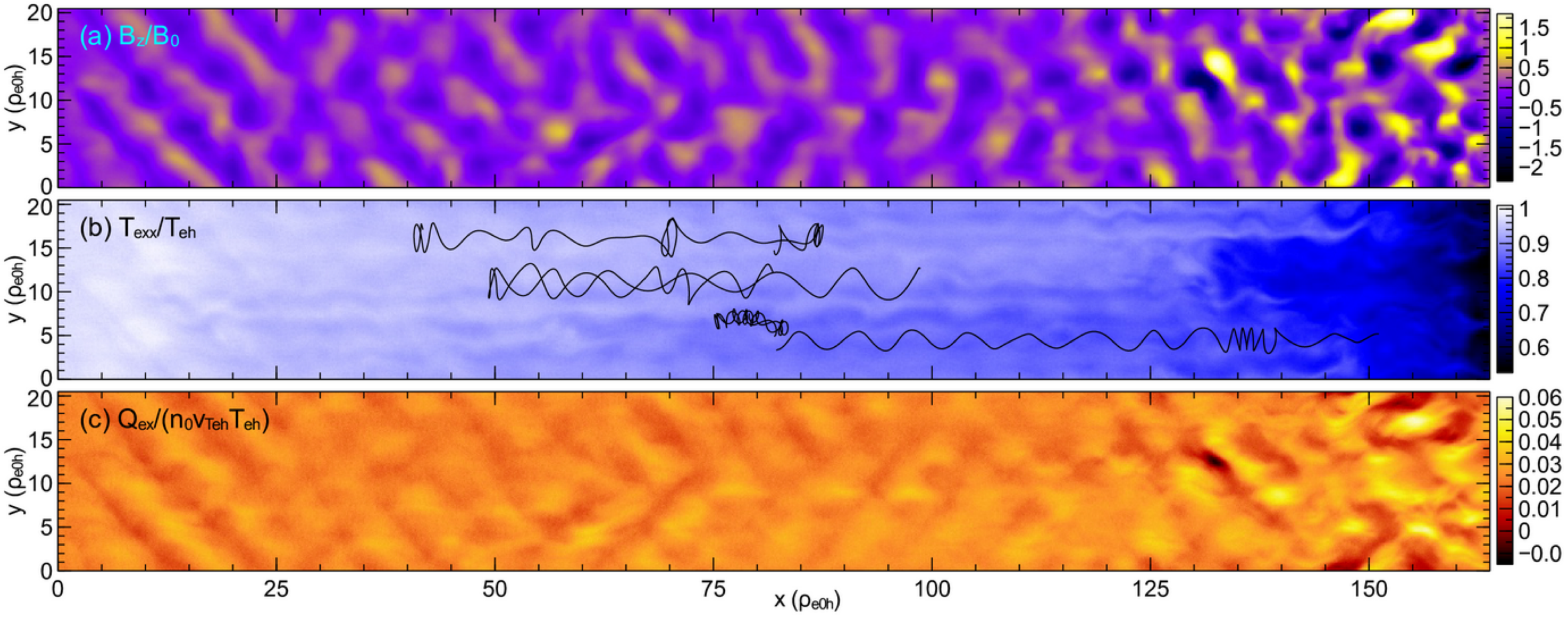


Physics of whistler suppression

Electron temperature evolution

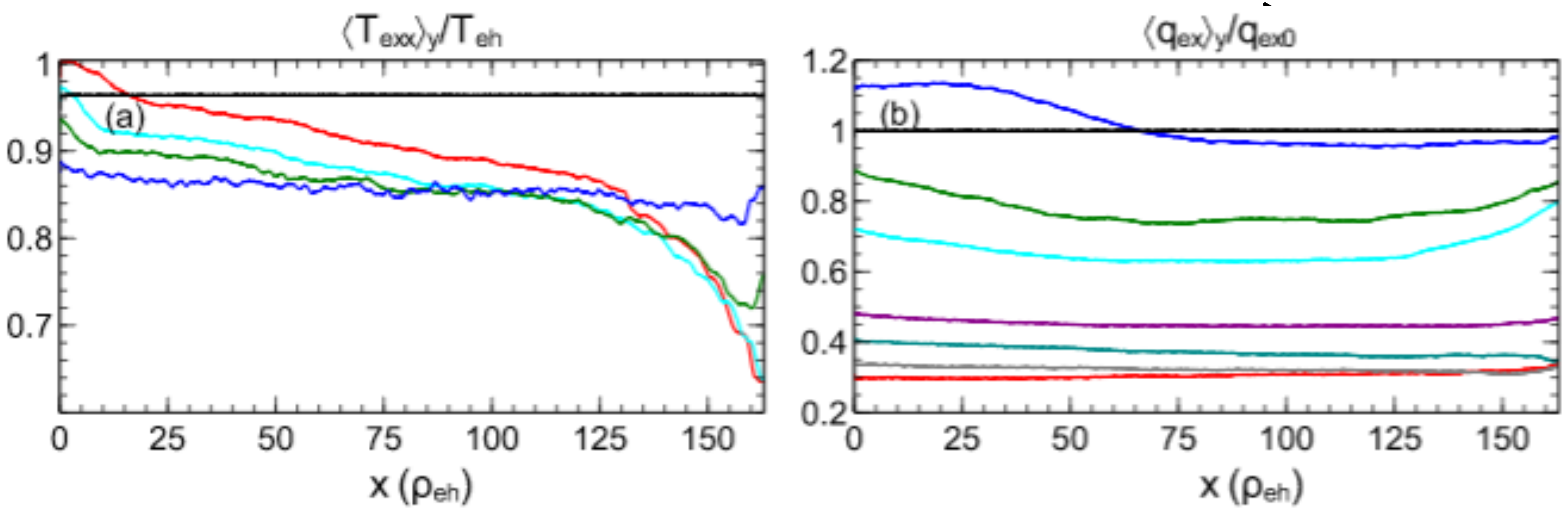


Steady state

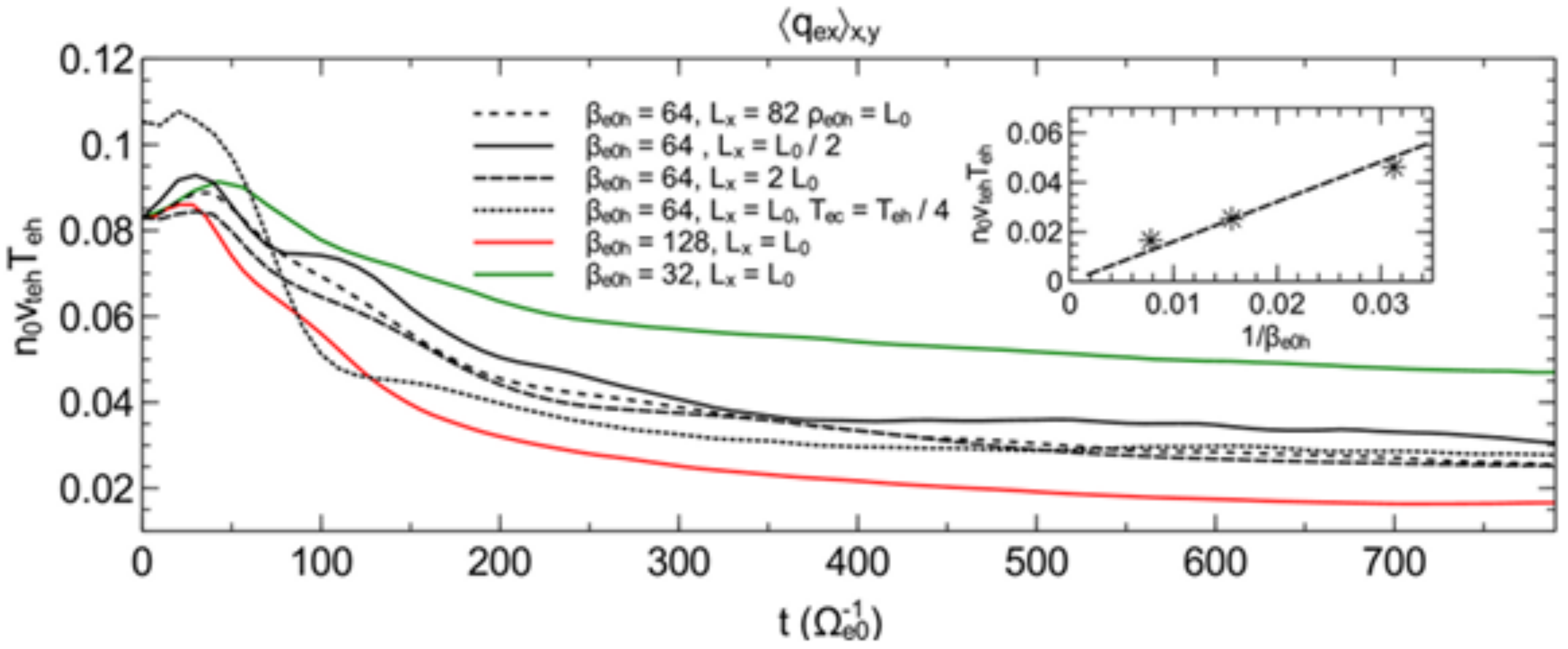


- Whistler waves driven unstable by the electron heat flux
  - Right-hand rotating electromagnetic waves
  - Oblique waves with $k\rho_{eh} \sim 1$
  - Resonantly scatters electrons (Karimabadi et al 1992, GRC et al 2016, Dalena et al 2012)

Time evolution of temperature and heat flux profiles

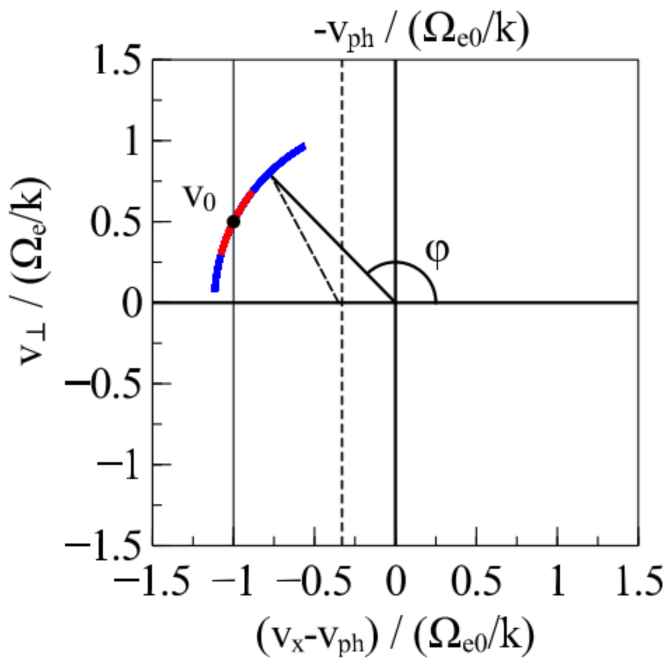


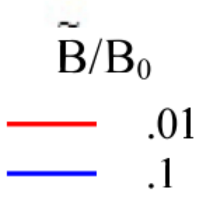
Variation in steady state with parameters



- Heat flux largely insensitive to imposed temperature gradient
- Follows linear scaling with $1/\beta_{e0h}$ (inset)

Scattering by whistlers (heat flux instability)





$$\omega - k_x v_x - \Omega = 0 \Rightarrow v_x = \frac{\omega - \Omega}{k_x} < 0$$

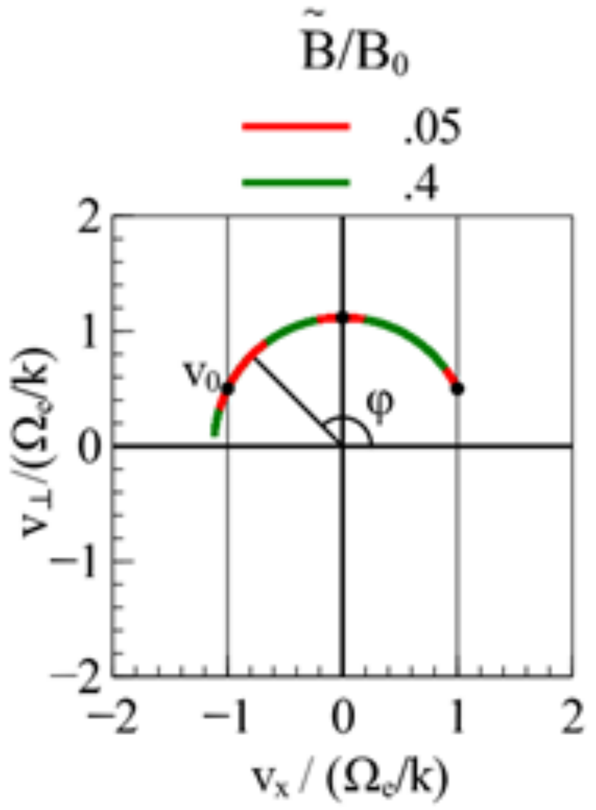
- Anisotropic distribution functions from the heat flux are robustly unstable to a whistler instability at high β
  - Instability is resonant, with energy conservation in the frame of a parallel whistler.
  - Pitch angle scattering (μ-non-conservation) and trapping for resonant particles particles.
- For parallel whistlers, resonance happens with backward-moving electrons (primary cyclotron resonance).
  - Only weak scattering of backward electrons for parallel whistlers
  - Only single resonance

Off-angle whistlers

- Oblique propagation introduces resonances at multiple harmonics of the electron cyclotron frequency:

$$\omega - k_x v_x - n\Omega = 0$$

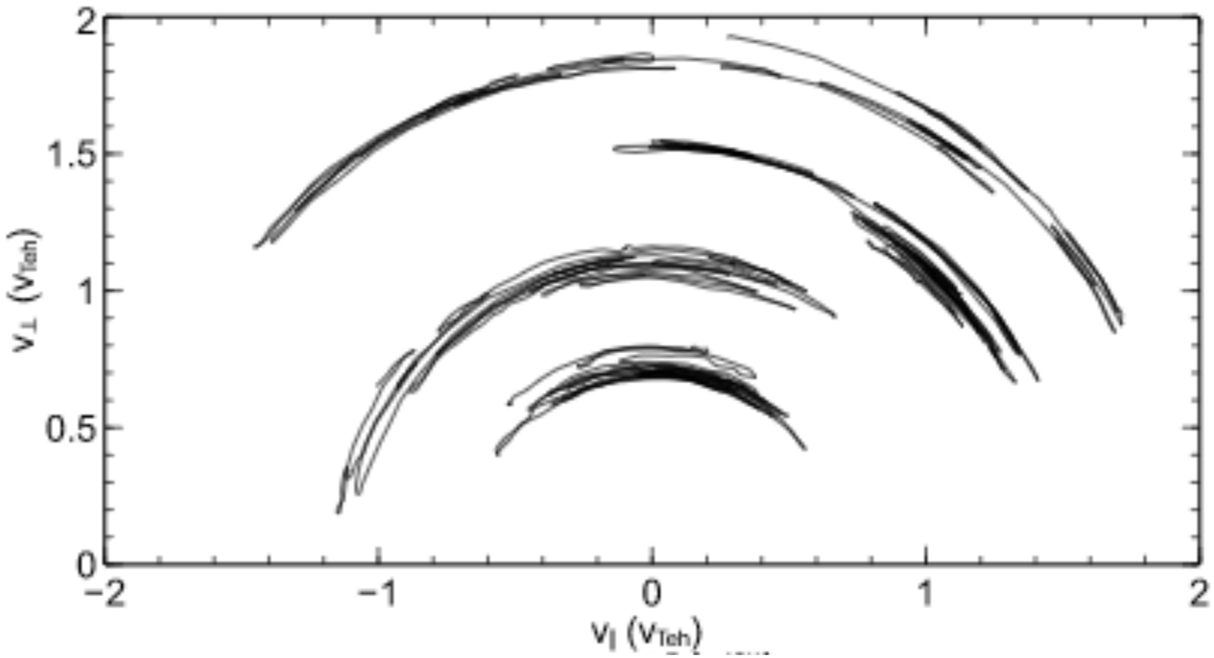
with n an integer



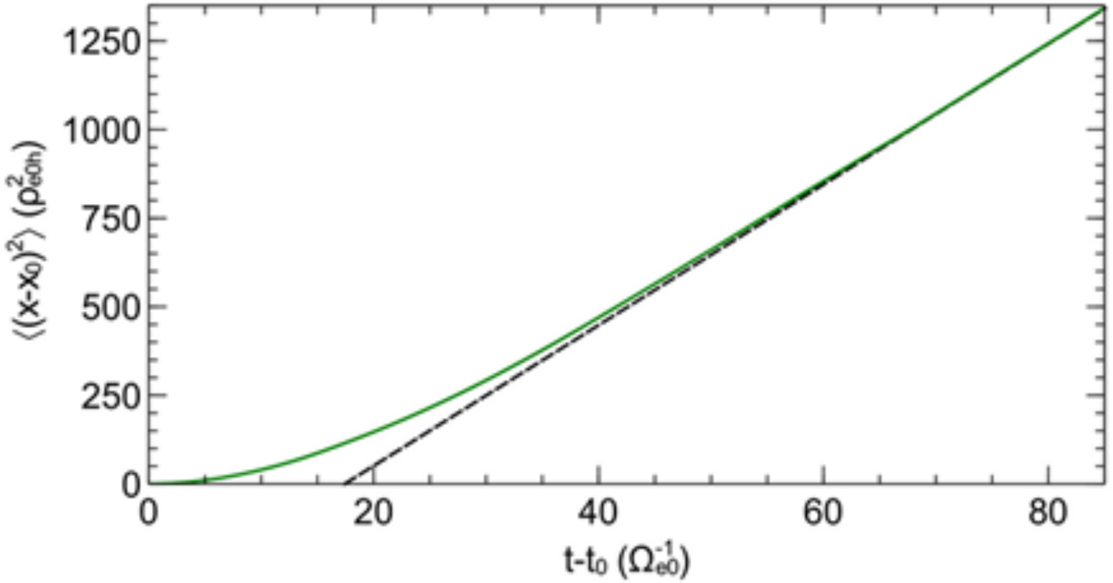
- For a large amplitude wave the resonances overlap, causing irreversible diffusive behavior – <u>effective at reducing heat flux</u>

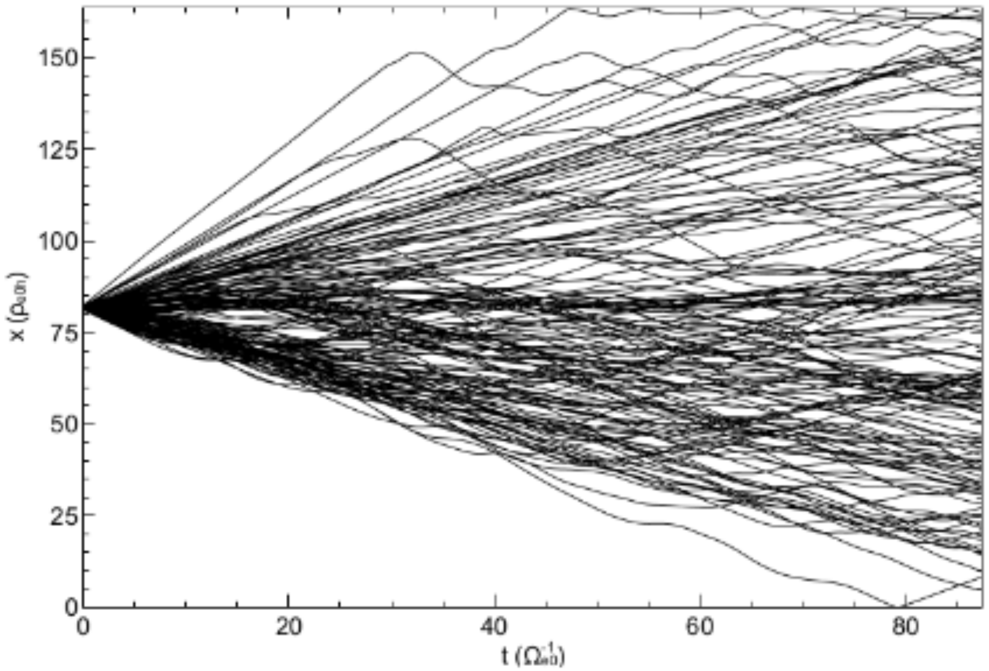
Particle trajectories from simulation

- Diffusion in pitch angle occurs rapidly (time scale order of cyclotron period)
  - On a constant energy contour in the whistler frame – slow compared with the thermal speed



Diffusion in space

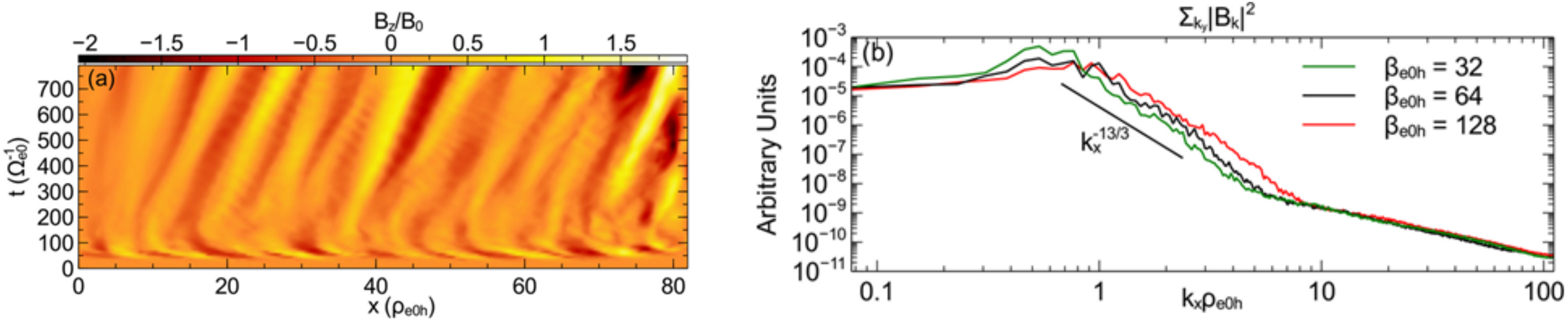




- Scattering in real space (left) is also very fast (order cyclotron period).
- Spacetime plot (right) shows diffusive nature of trajectories

$$D_{\|} \sim 7\rho_{e0h}^2\Omega_{e0}$$

Whistlers as moving scattering centers



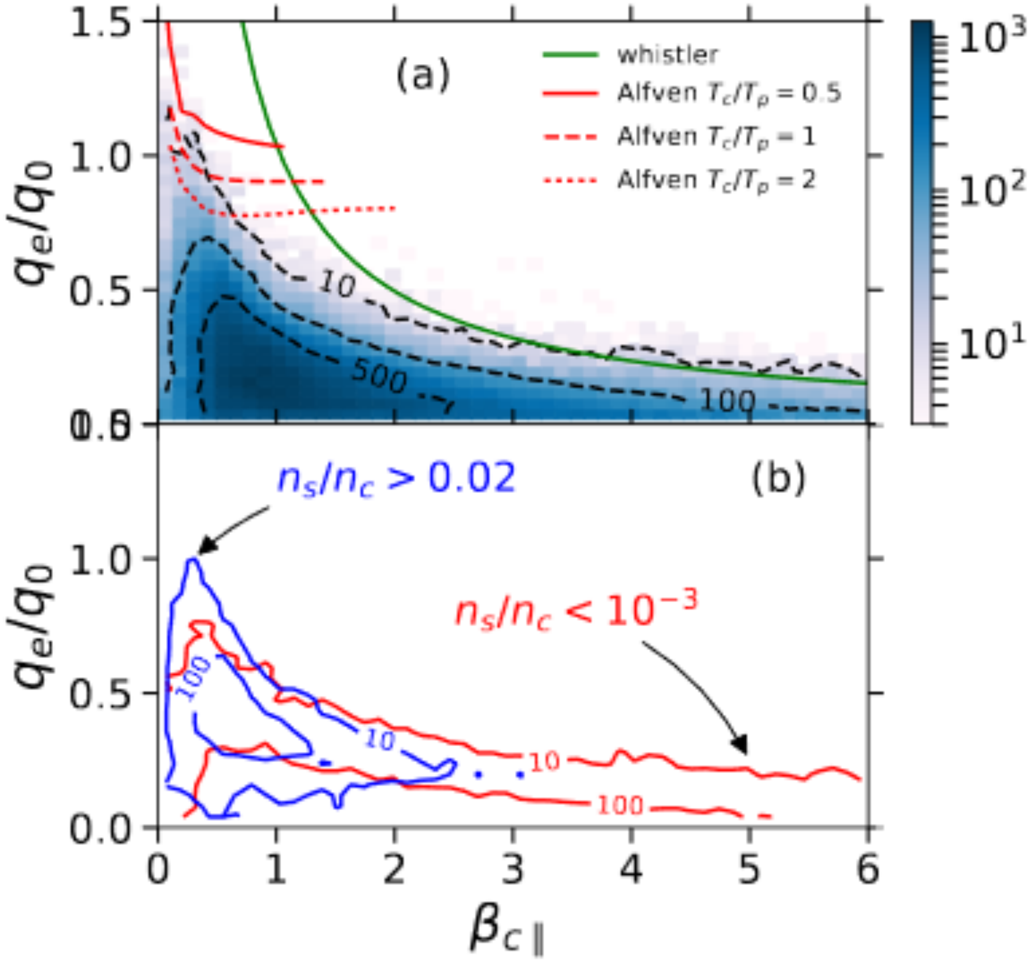
- Spacetime plot (left) of fluctuations reveals mostly uniform translation of waves to towards cold plate.
- Power spectra have a peak near $k\rho_e \sim 1$ even when β changes.

Confirmation in solar wind observations

- Heat flux is suppressed at below the free-streaming value

$$q_0 = \frac{3}{2} n_0 T_0 v_{te}$$

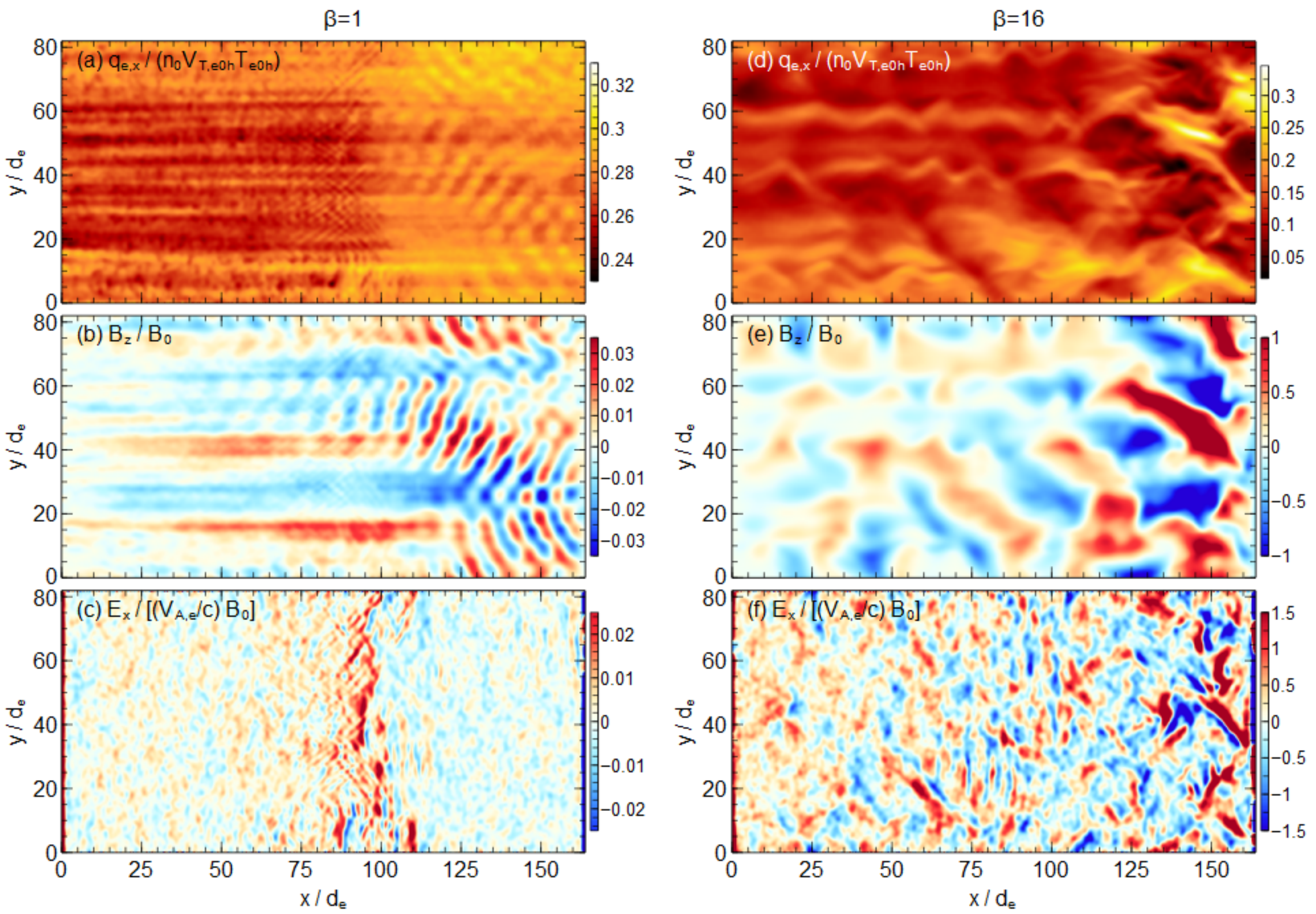
- Tong et al. [arXiv 2018] confirm that maximum heat flux scales as β for β > 2
- What happens in our simulations at lower β?



PIC simulations of low β

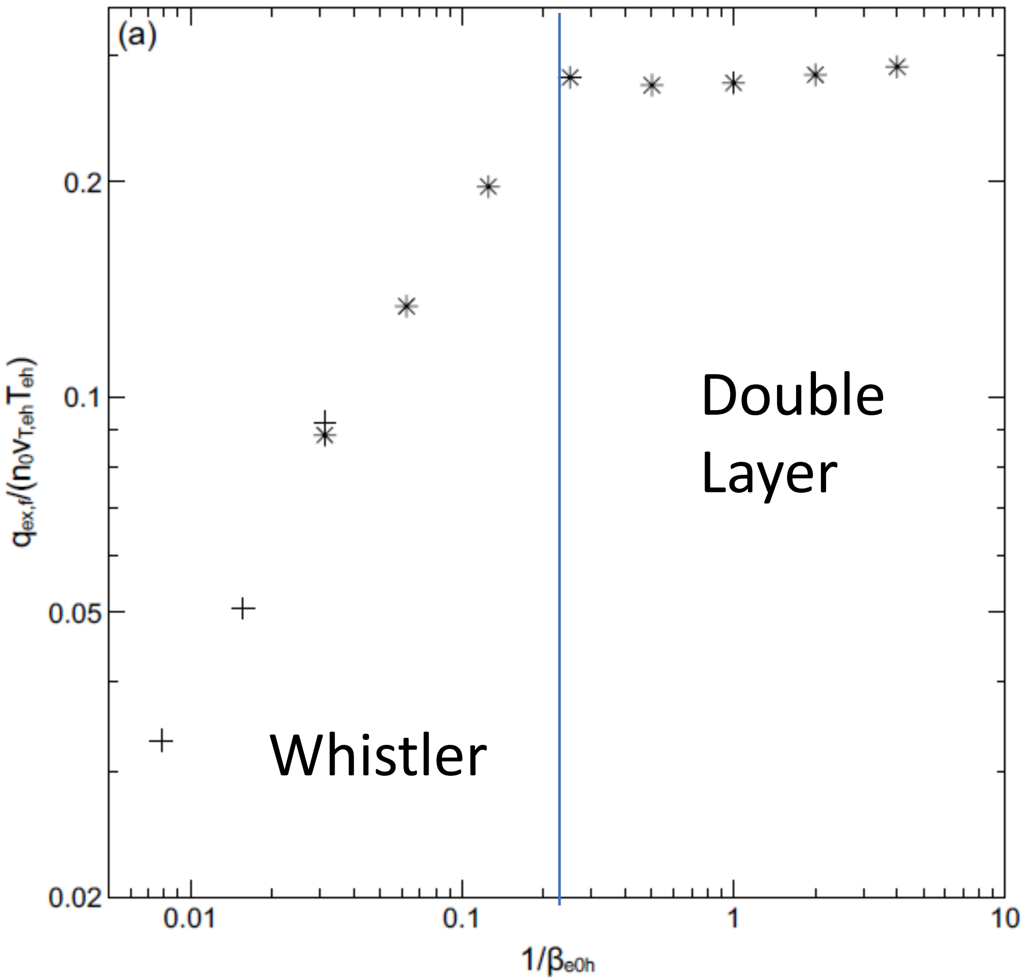
- Same setup as before, but with hot/cold temperature ratio of 10 and stronger magnetic field (lower β)
- Mobile ions
- Whistlers and double layers (DLs) act together to suppress heat flux for a range of
- DLs were not there previously because the whistler scattering reduces the return current driver.

Beta 1 vs. 16: Transition from whistler to DL



Heat flux versus β

- Heat flux rolls over to a constant value at
  β ~ 4



Scattering of energetic electrons

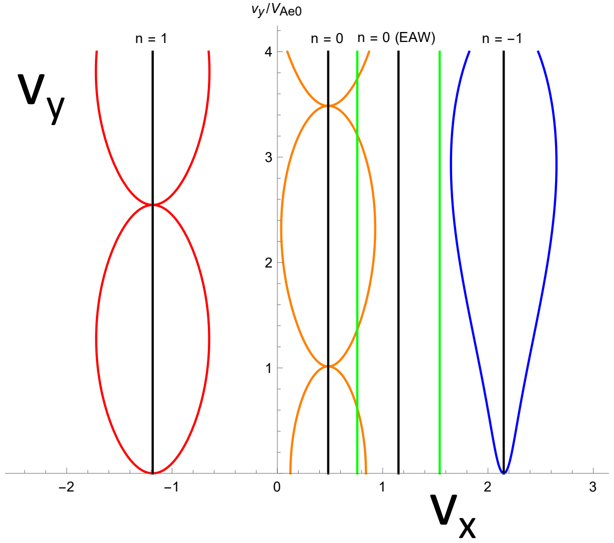
- The possible self-confinement of energetic electrons during reconnection or at shocks is critical to understanding mechanisms for acceleration and resultant spectra
  - Free streaming transit time is often short compared with energy gain times in non-relativistic reconnection
- Can whistlers scatter high energy (relativistic electrons)
- Carry out simulations with an initial κ distribution of energetic electrons with $T_{e\parallel} >> T_{e\perp}$

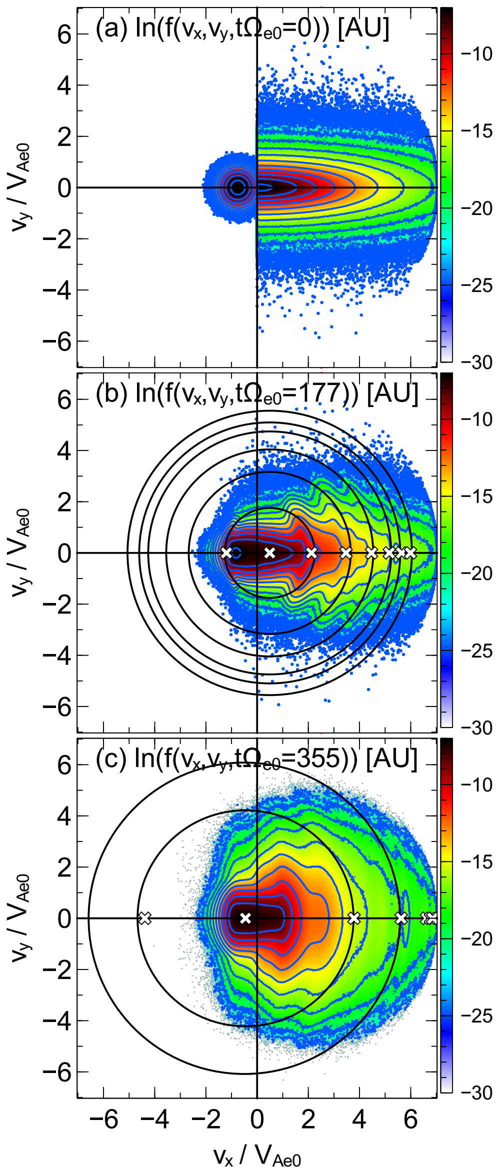
$$f_e \sim \left(1 + \frac{v_x^2}{\kappa v_{tx}^2} + \frac{v_\perp^2}{\kappa v_{t\perp}^2}\right)^{-(1+\kappa)}$$

Scattering of electrons

- The anisotropic κ distribution drives oblique whistlers
  - Drive dominated by the n=-1 resonance – the "fan instability"
  - Energetic electrons also scattered through the n=1,0,-1,-2,-3, … resonances
- Large trapping widths in phase space

Roberg –Clark et al 2019





Modeling electron thermal transport in ICM plasma

- Need a model that includes convection of thermal energy down a temperature gradient but also includes parallel diffusion limited by either whistlers or classical Coulomb collisions
- Follow the lead of the modelers of cosmic rays (e.g., Thomas and Pfrommer 2019)
- Include equations for the electron energy, electron momentum and right and leftward propagating whistler waves
  - Include the drag force of whistlers acting on the hot electrons and the back-reaction on the whistlers
  - Include both the energy drive of the whistlers and energy dissipation (phenomenological)

Electron transport equations

- Three coupled equations for the electron energy $\varepsilon_h=3p_h/2$, the electron momentum $m_e n_h V_{hd}$ and the right and left propagating whistler waves $\varepsilon_\pm$
  - Can also include the forces acting on the background ions but ignore for now
- Coupling takes place through the drag forces mediated by the whistlers $g_\pm$
- Energy $$\frac{\partial \varepsilon_h}{\partial t} \pm \nabla_{\|}\left(V_d(\varepsilon_h + P_h)\right) = -V_w g_+ + V_w g_- + Q_{w+} + Q_{w-}$$
- Momentum $$0 = -\nabla_{\|} P_h - g_+ - g_- \qquad g_\pm = \upsilon_\pm \rho_h (V_{hd} \mp V_w)$$
- Whistlers $$\frac{\partial \varepsilon_\pm}{\partial t} \pm \nabla_{\|}(V_w \varepsilon_\pm) = \pm V_w g_\pm - Q_{w\pm} \qquad \upsilon_\pm = \alpha \Omega_e \frac{\varepsilon_\pm}{\varepsilon_B}$$

Electron transport equations (cont.)

- Energy

$$\frac{\partial \varepsilon_h}{\partial t} \pm \nabla_\parallel \left(V_{st} (\varepsilon_h + P_h) \right) - \nabla_\parallel D_\parallel \nabla_\parallel P_h = V_{st} \nabla_\parallel P_h + 4\rho_h V_w^2 \frac{\upsilon_+ \upsilon_-}{\upsilon_+ + \upsilon_-} + Q_{w+} + Q_{w-}$$

- Whistlers

$$\frac{\partial \varepsilon_\pm}{\partial t} \pm \nabla_\parallel (V_w \varepsilon_\pm) = \mp \frac{\upsilon_\pm}{\upsilon_+ + \upsilon_-} V_w \nabla_\parallel P_h - 2\rho_h V_w^2 \frac{\upsilon_+ \upsilon_-}{\upsilon_+ + \upsilon_-} - Q_{w\pm}$$

$$V_{st} = \frac{\upsilon_+ - \upsilon_-}{\upsilon_+ + \upsilon_-} V_w \qquad D_\parallel = \frac{\varepsilon_h + P_h}{\rho_h (\upsilon_+ + \upsilon_-)} \sim \rho_{th}^2 \Omega_e \frac{\varepsilon_B}{\varepsilon_+ + \varepsilon_-} \qquad \upsilon_\pm = \alpha \Omega_e \frac{\varepsilon_\pm}{\varepsilon_B}$$

- Smooth transition from Bohm-like to Spitzer conductivity
- How do temperature fronts propagate? What about thermal instability?

Conclusions

- Heat flux instability strongly suppresses thermal conduction at high β via oblique whistlers
- At lower β whistlers become subdominant and heat flux levels off to constant fraction of free-streaming value
- Whistlers scatter energetic electrons through high order resonances of oblique waves – implications for cosmic ray transport?
- Transport model for electron heat flux limited by whistlers is being developed for implementation in large-scale simulation models
- Implications for the thermal stability of galaxy clusters remains to be explored