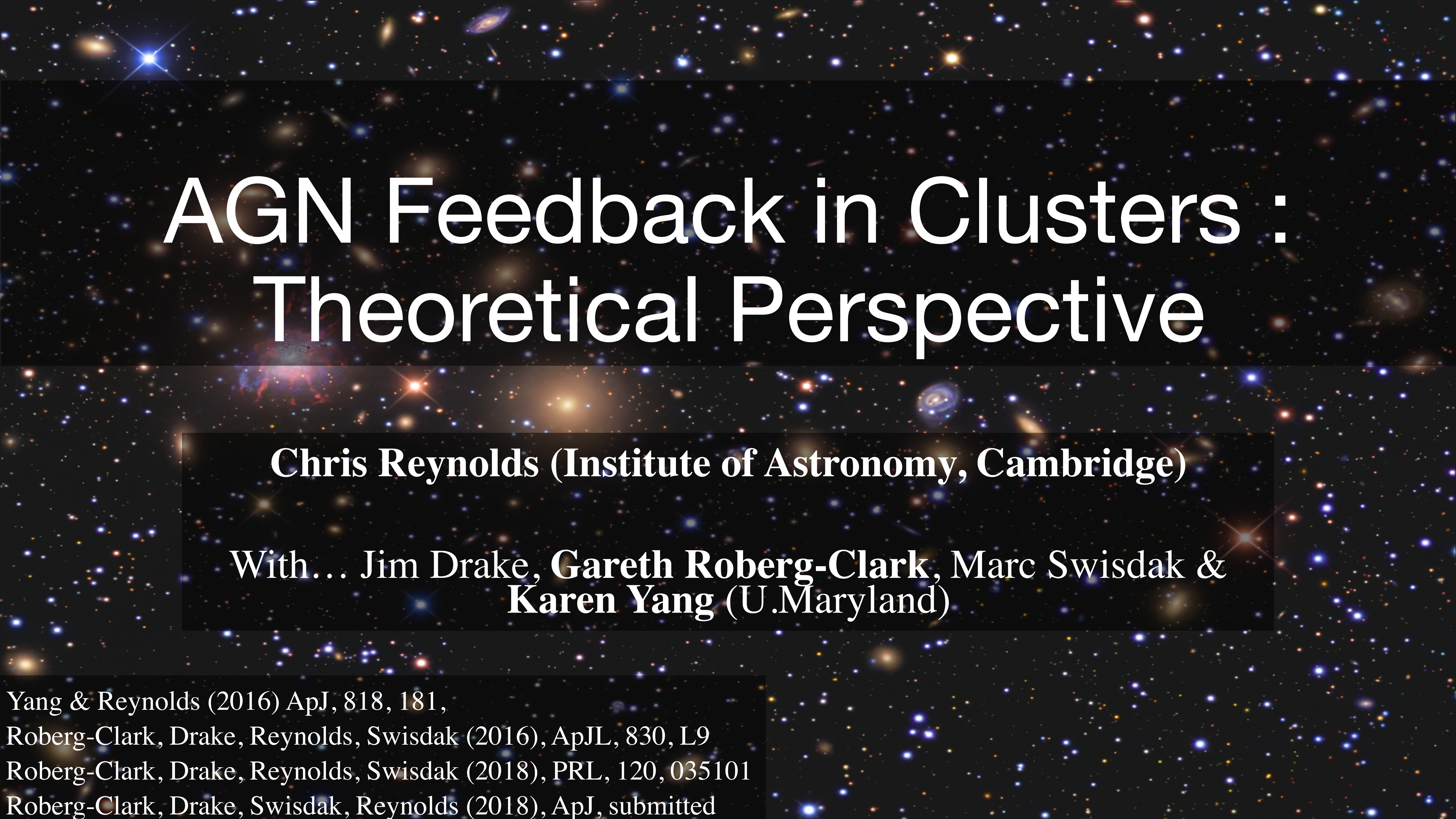


# AGN Feedback in Clusters : Theoretical Perspective

**Chris Reynolds (Institute of Astronomy, Cambridge)**

With… Jim Drake, **Gareth Roberg-Clark**, Marc Swisdak &
**Karen Yang** (U.Maryland)

Yang & Reynolds (2016) ApJ, 818, 181,
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, submitted

# Outline

- Part I : Brief Review of Open Issues in AGN Cluster Feedback
  - Success of “simple” hydrodynamic models
  - Digging into the physics of heating, cooling, and AGN fueling
  - Why do we care about details?

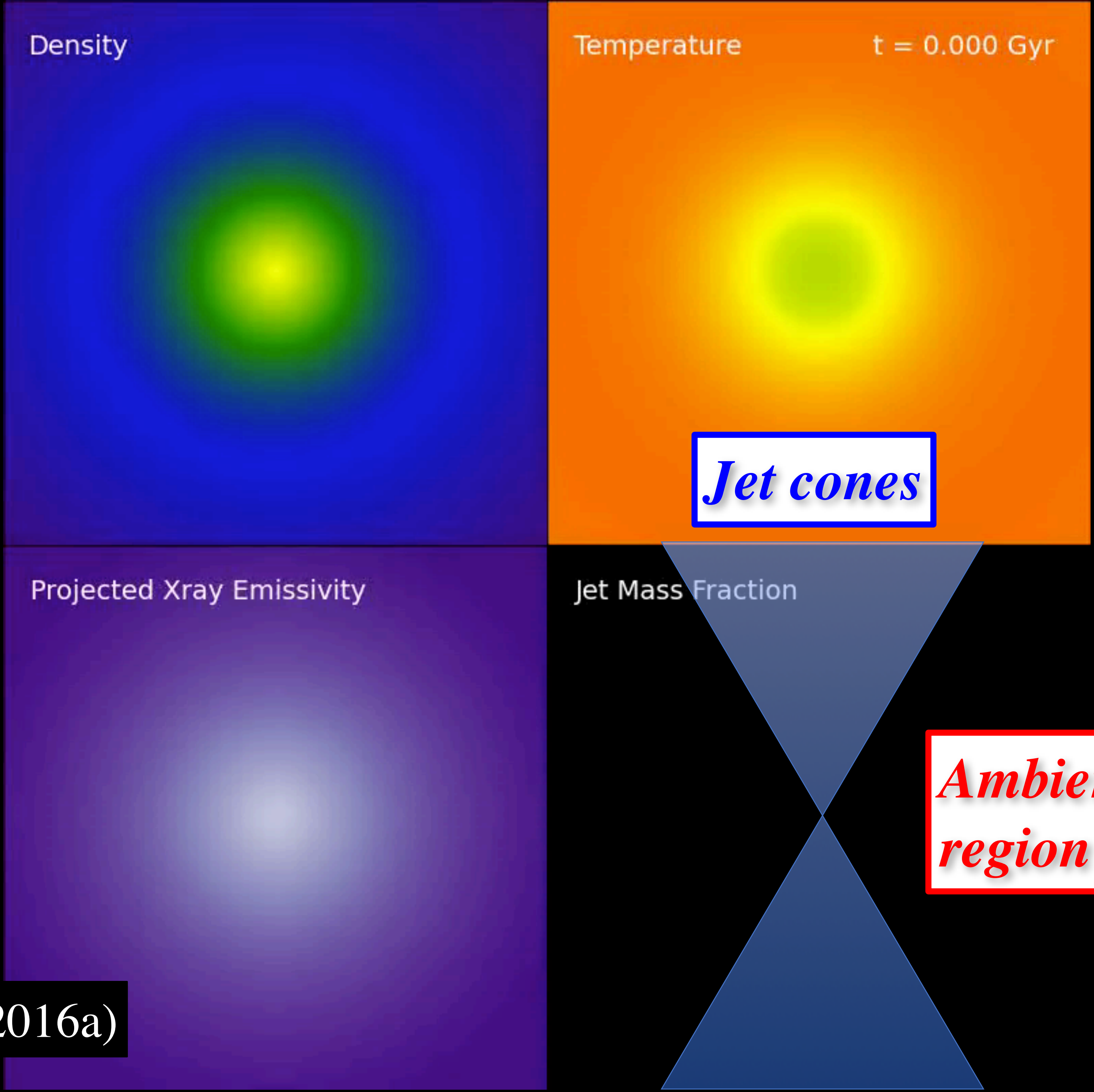
- Part II : The Microphysics of Thermal Conduction
  - Possible multiple roles of conduction
  - The ICM as a weakly-collisional, magnetized, high-beta plasma
  - Fully kinetic models... emergence of highly non-Spitzer-like transport terms (weaker temperature dependence; explicit dependence on B-field strength)

Perseus cluster (Chandra; Fabian et al. 2006)

# ICM : The Basics

- 80% of baryons in the intracluster medium (ICM)
  - Approx. hydrostatic equilibrium
  - ~Half of clusters have short central cooling times (<1Gyr)
  - Small fraction of gas actually cools compared with naïve expectations

- Must have heat source… current view is that only AGN heating is
  - Sufficiently efficient and long lived
  - Deposits energy in right location
  - Self-regulating (small unbalanced cooling fuels AGN)
  - Is motivated the X-ray data



***Jet cones***

***Ambient region***

Yang & Reynolds (2016a)

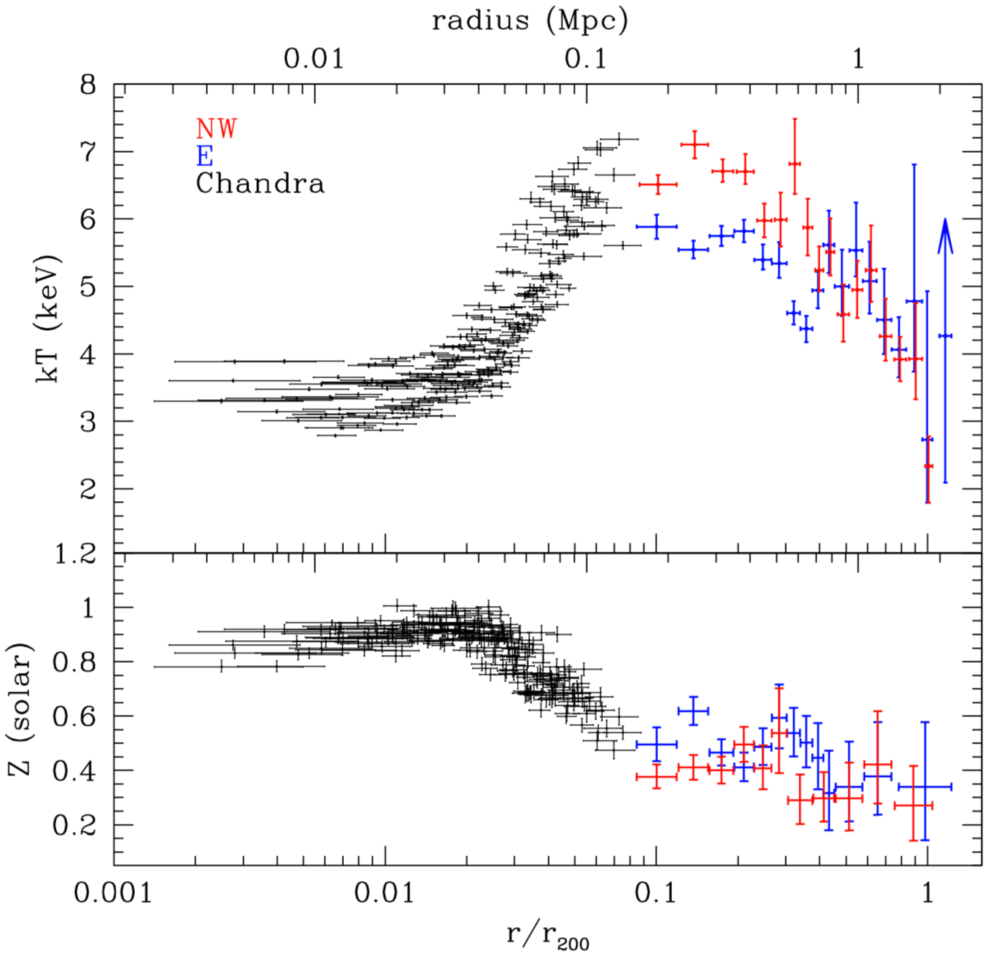
# Questions

- How does the AGN actually heat?
  - Strong shock heating? **NO – ruled out by X-ray data**
  - Turbulence? **PROBABLY NOT – hard to drive (Reynolds+2015; Weinberger+2017)**
  - Acoustic modes? **MAYBE… need to understand dissipation (Zwiebel+2018)**
  - Bubble mixing? **MAYBE… need to understand CR transport (Ruszkowski+2018)**
- How is the AGN fueled/regulated?
  - Hot-mode or cold-mode accretion? **STILL OPEN**
  - Hydrodynamic simulations find local cooling instabilities; cold gas then fuels AGN. precipitation [Voit+2015]; chaotic cold accretion [Gaspari & Sadowski 2017]
  - Debate about cooling criteria; $t_{cool}$, $t_{cool}/t_{ff}$, $t_{cool}/t_{eddy}$, $\partial(\ln K)/\partial r$, $\partial T/\partial r$
  - **Cannot understand cooling instabilities without understanding heating physics!**
- Why do we care?
  - Scaling to lower-masses (CGM) or high-z needs understanding of physics.
  - … and the physics is just neat!

# Thermal conduction

# Potential roles of thermal conduction

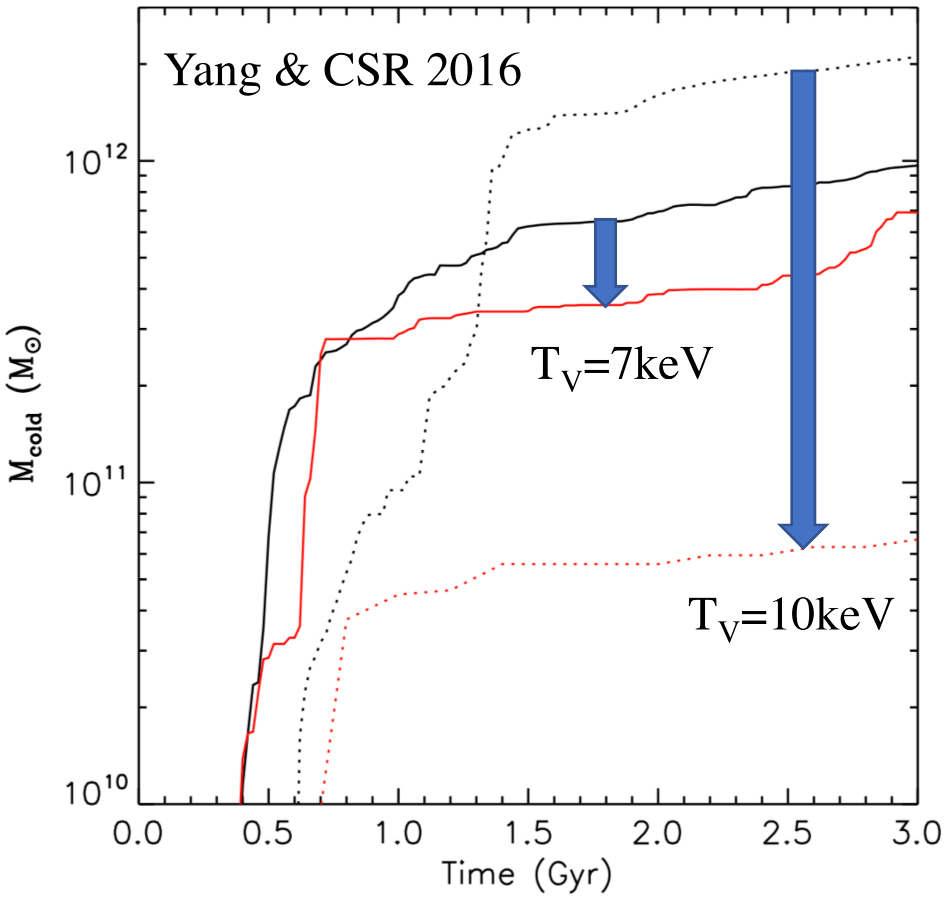
- Direct heating of cool cores… reducing the need for AGN heating (e.g. Binney & Cowie 1981; Zakamska & Narayan 2003; Bogdanovic et al. 2009; Ruszkowski & Oh 2010; Yang & CSR 2016; Fang et al. 2018)
- Suppression of cooling instabilities… regulation of AGN fueling (e.g. Field 1965; Voit et al. 2008;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

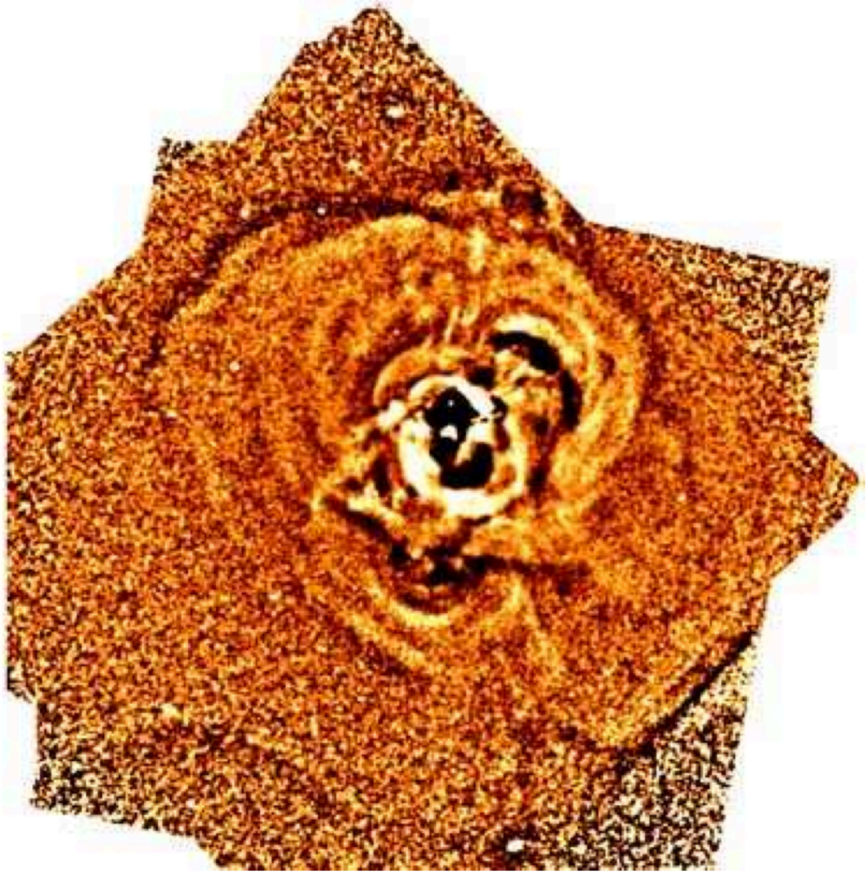
# Potential roles of thermal conduction

- 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)



# 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)



Perseus unsharp mask (Sanders et al. 2006)

# The Physics of Conduction : Classical Theory

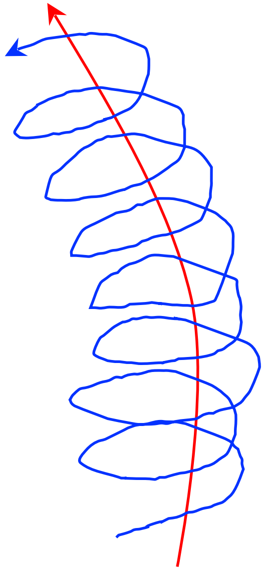
- ”Classical” result (Spitzer)
  - Assuming strong collisionality

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

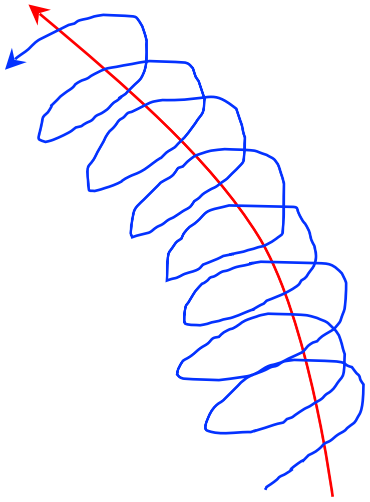
$$\begin{aligned} \mathbf{q} &= -\chi \nabla T \\ \chi &= 4.6 \times 10^{-7} T^{5/2}\,\mathrm{erg\,cm^{-1}\,s^{-1}\,K^{-1}} \end{aligned}$$

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

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



# Microphysics of the ICM



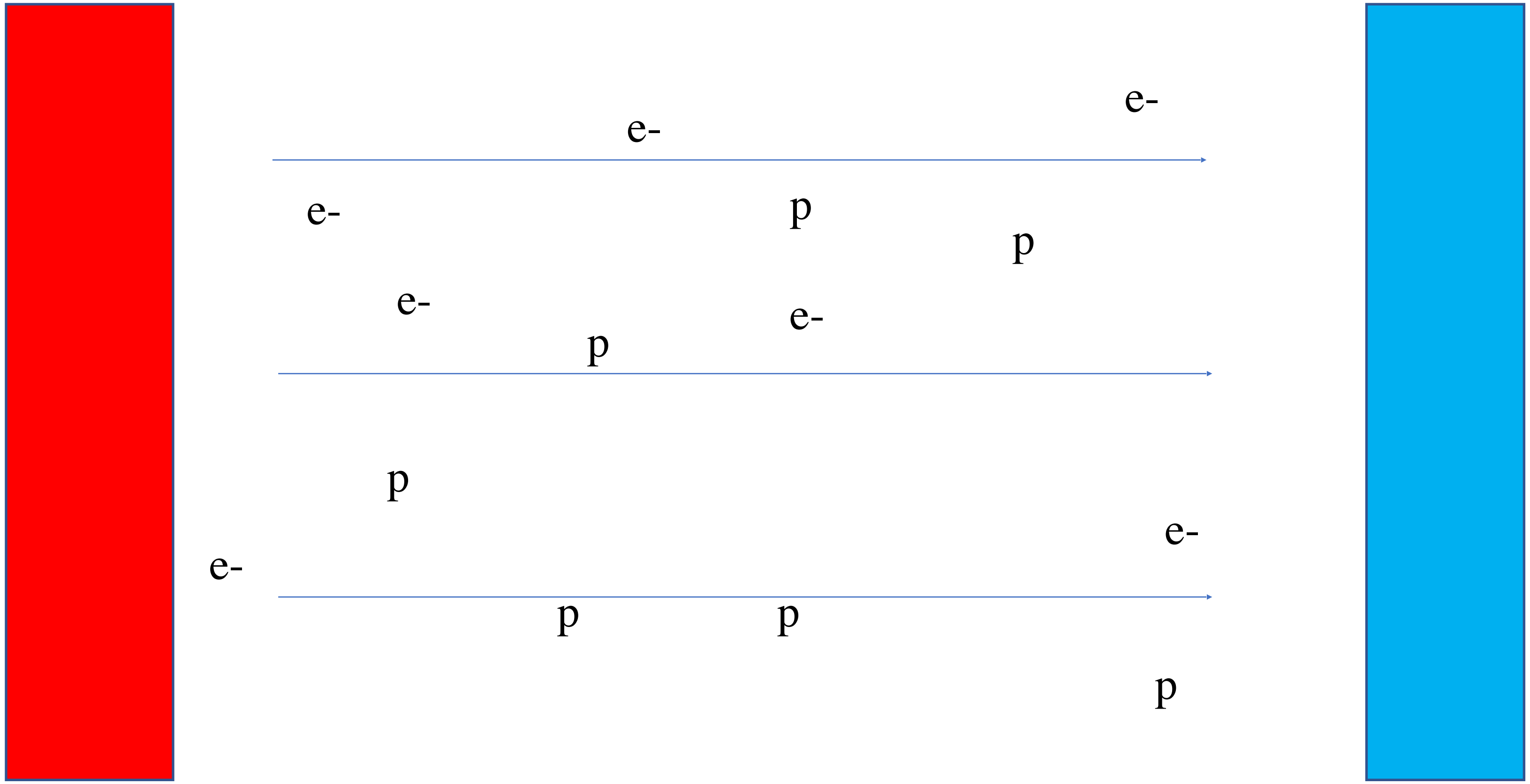
- Interesting scales and dimensionless numbers
  - Mean free path $\lambda_e = 2\left(\frac{T}{8\,\mathrm{keV}}\right)^2 \left(\frac{n}{0.01\mathrm{cm}^{-3}}\right)^{-1}$ kpc
  - Electron gyroradius $r_e \approx 2\times 10^8 \left(\frac{T}{8\,\mathrm{keV}}\right)^{1/2} \left(\frac{B}{1\mu\mathrm{G}}\right)^{-1}$ 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.

# Physics of Conduction : New Theory

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)

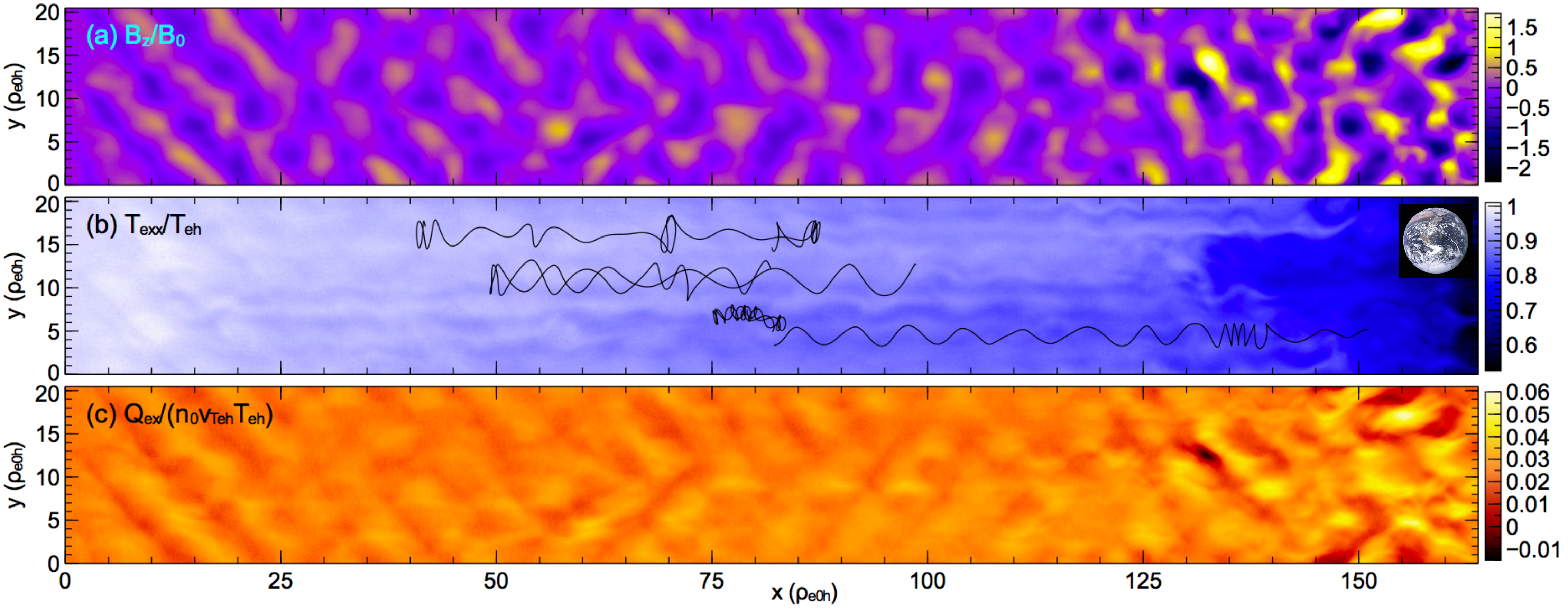
Scan $\beta$=0.25-128



Particle in cell (PIC) simulations (“charged n-body problem”)
Heat flux between hot and cold plates (Roberg-Clark et al. 2018)

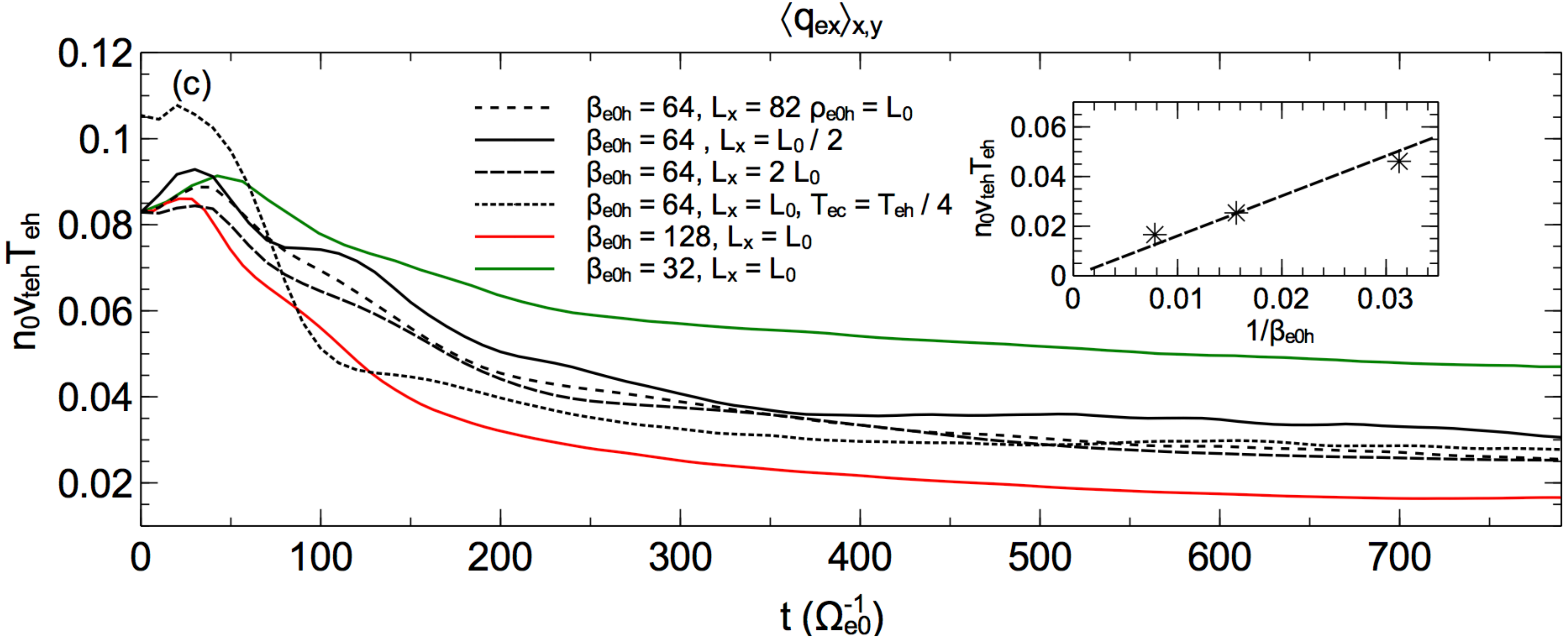
# Example high-$\beta$ case; $\beta=64$

- Heat flux drives whistlers (modified circ pol e/m waves) Levinson & Eichler (1992)
- 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

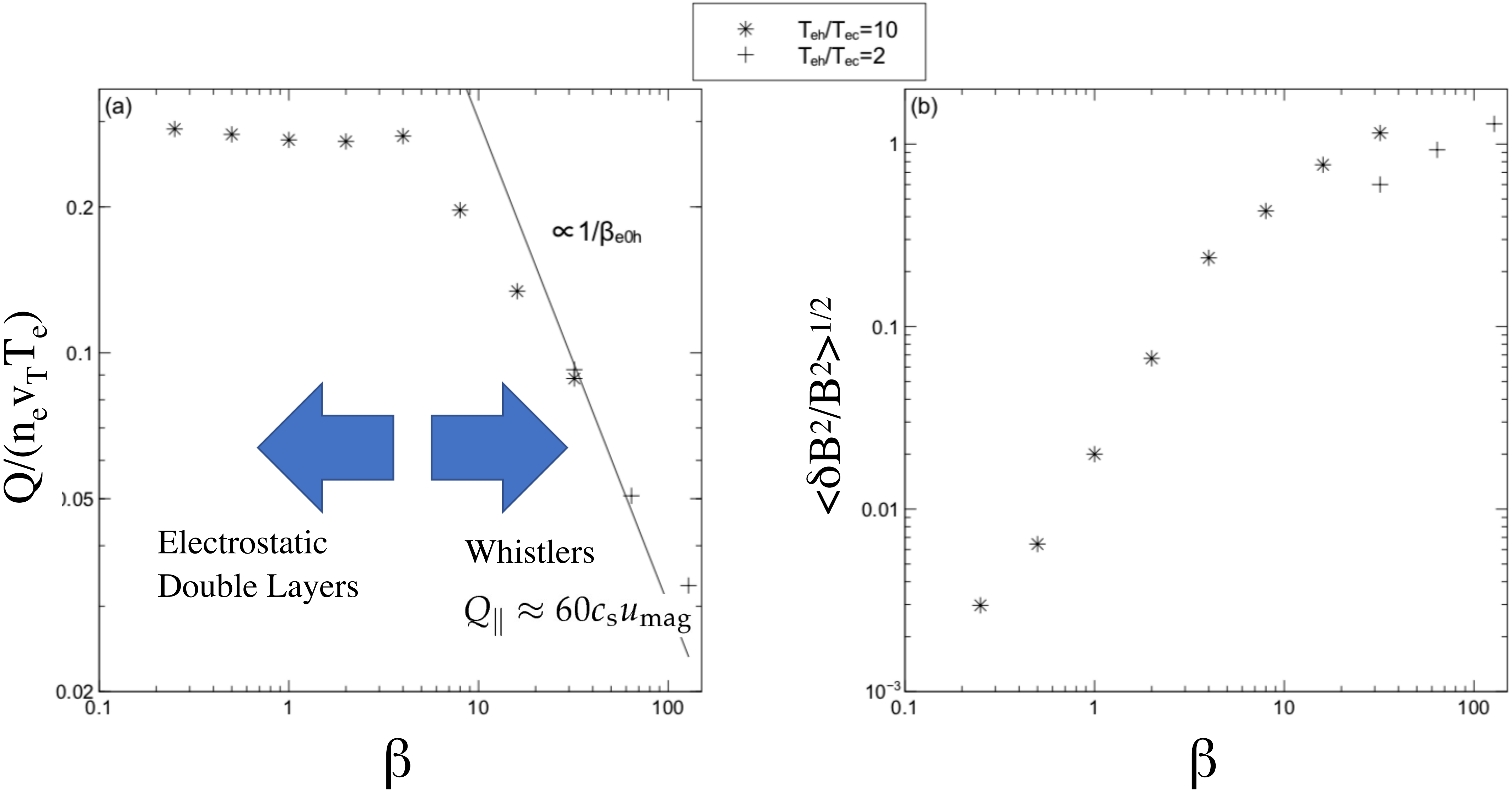


Roberg-Clark et al. (2016); Roberg-Clark et al. (2018); also Komarov et al. (2018)

# Heat flux independent of ∇T… characteristic of a “saturated” heat flux



Roberg-Clark et al. (2018b)



Electrostatic
Double Layers

Whistlers

$Q_{\|} \approx 60 c_{\mathrm{s}} u_{\mathrm{mag}}$

Roberg-Clark et al. (2018b)

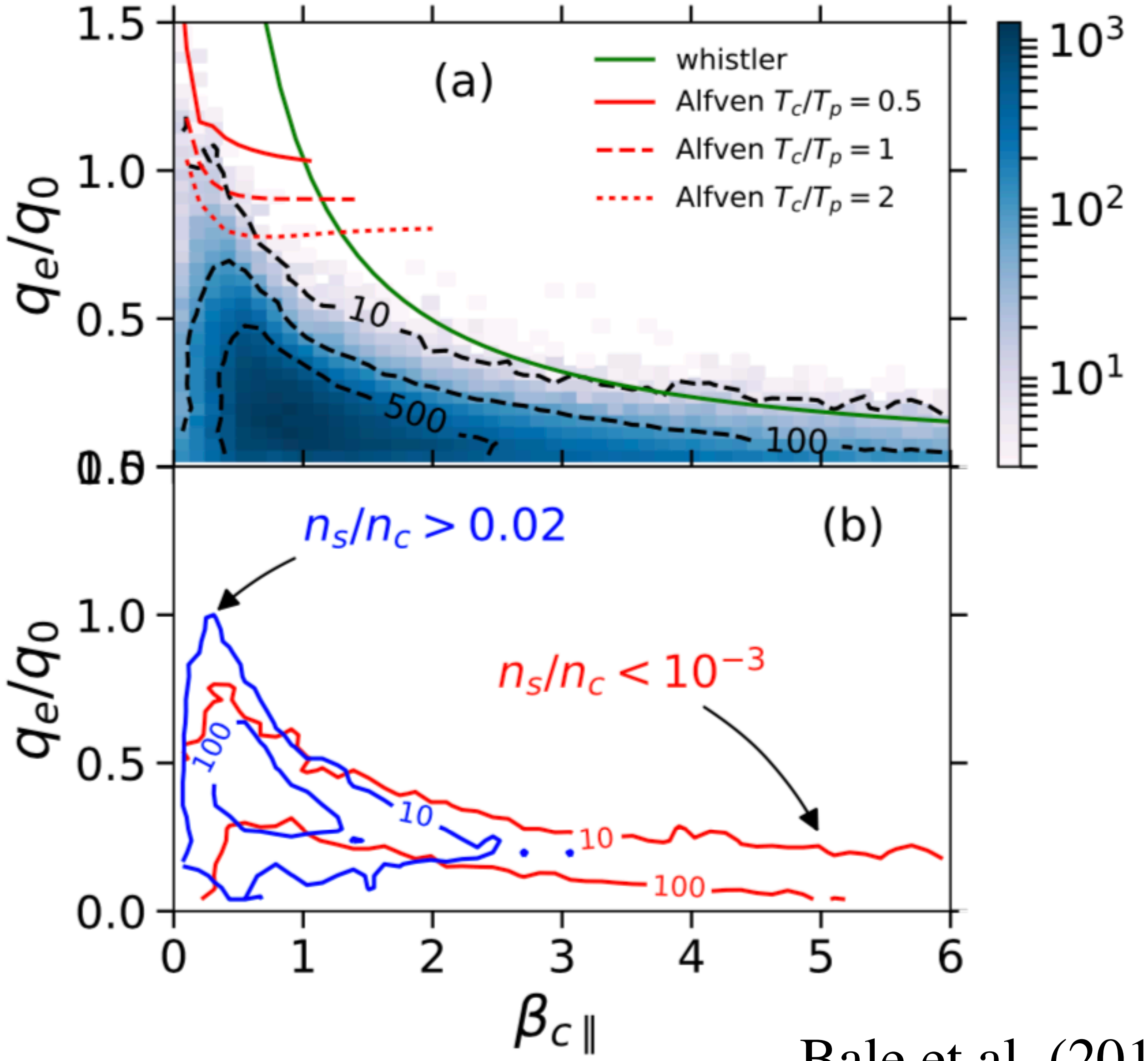
# SOLAR WIND @ 1AU

In-situ measurements e- distribution function from WIND spacecraft

Low-β… agrees well with Spitzer

High-β… $q_{||} \sim 1/\beta$. Good agreement with whistler suppression theory.

All scales much larger than electron gyroradius (500km) which also sets whistler scale.



Bale et al. (2013)
Tong et al. (2018)

If $L_T$ is temperature scale length then we replace Spitzer

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

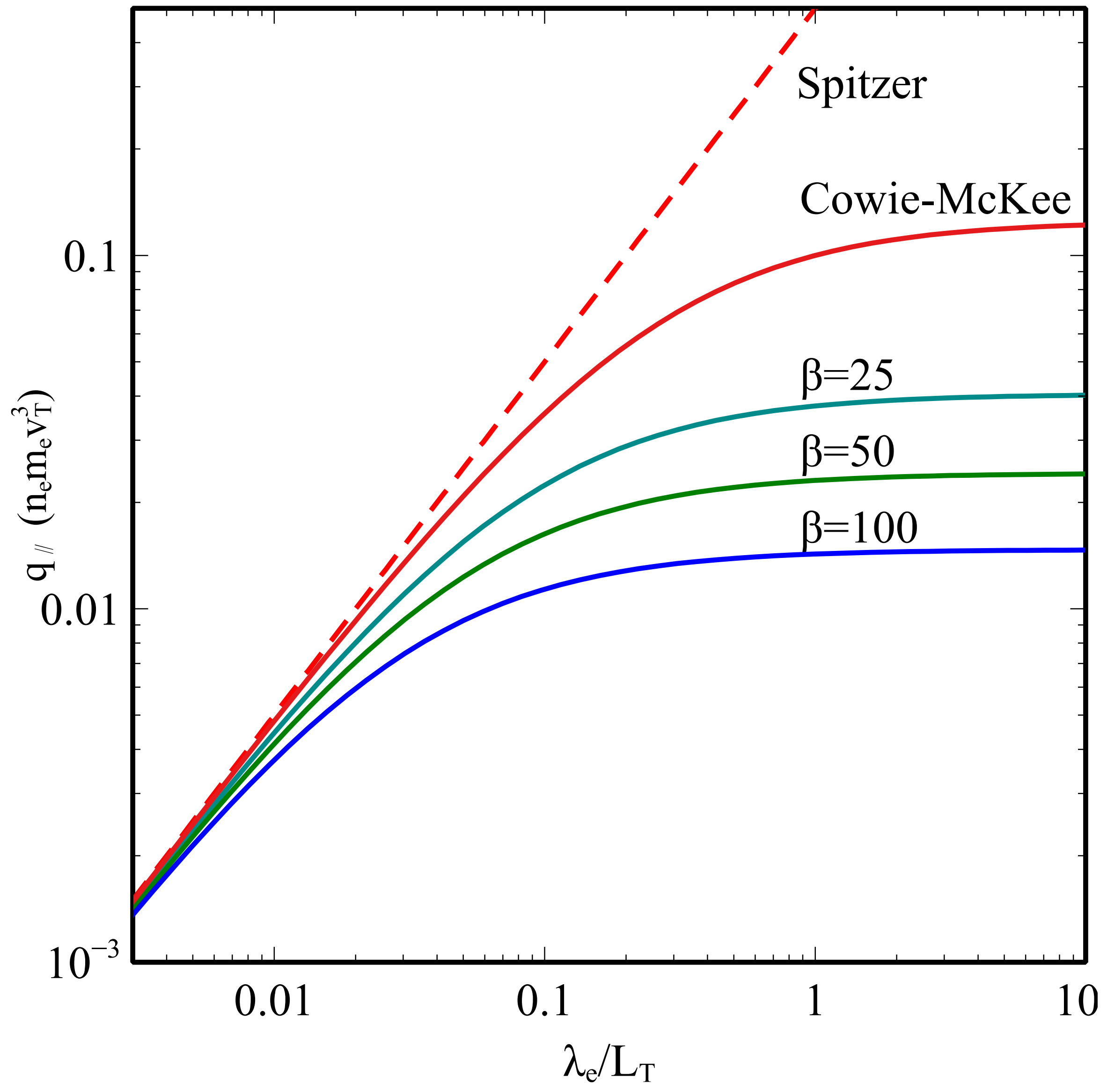
with

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

Whistler physics becomes important when

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

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



# Summary

- Galaxy clusters are an excellent laboratory for studying feedback physics, i.e., ICM heating and cooling processes and AGN fueling

- Thermal conduction in intracluster medium (ICM) may play important roll in cool core clusters and cluster-scale AGN feedback
- ICM is weakly-collisional, high-$\beta$ plasma – extremely rich microphysics!
- New understanding of thermal conduction beyond Spitzer theory… for temperature moderately strong $\nabla$T find saturated heat flux at

$$Q_{||} \approx 60 c_{\rm s} u_{\rm mag}$$

- More work needed to understand role of collisions and full implications of large scale-separation between whistler- and astrophysical-scales

# Properties of the whistlers

- Heat flux in high-β systems throttled by scattering off whistler waves

$$\left.\begin{aligned} &\omega \sim \frac{\Omega_e}{\beta} \\[2em] &k r_e \sim 1 \end{aligned}\right\} \quad \boxed{v_{\mathrm{w}} = \frac{\omega}{k} \sim \frac{v_T}{\beta}}$$

Note: standard "cold plasma" whistlers with

$$\omega \sim \Omega_e \qquad k d_e = \frac{k r_e}{\sqrt{\beta}} \sim 1$$

are strongly damped here.

- PIC simulations find heat fluxes in collisionless regime

$$\begin{aligned} Q_{\|} &= \alpha n_e T_e v_w \qquad (\alpha{\sim}3) \\ &= \frac{\alpha n_e m_e v_T^3}{2\beta} \\ &= \frac{1}{2}\alpha v_T U_{\mathrm{mag}} \end{aligned}$$

$\Omega_e$ : electron gyrofrequency

$r_e$ : electron gyroradius

$v_T$ : electron thermal speed

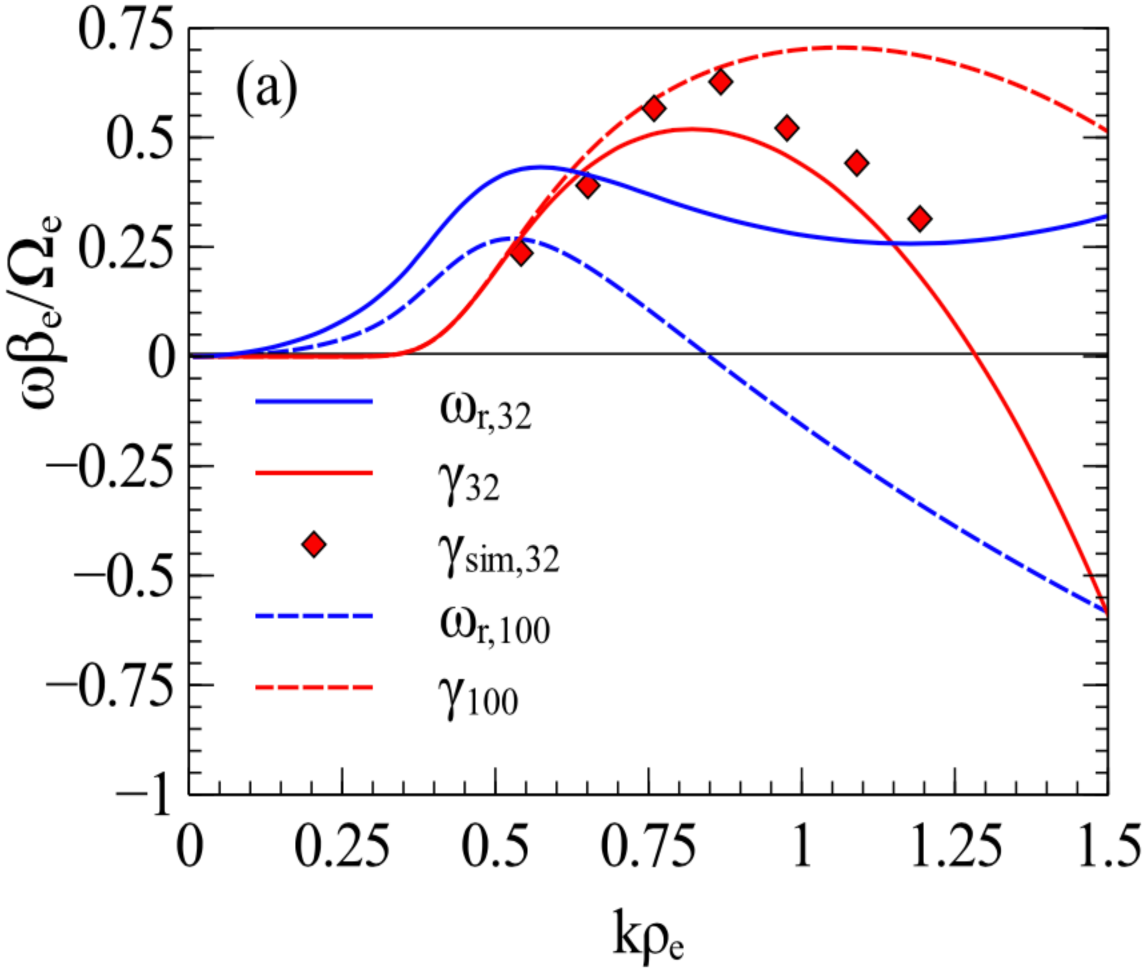
$d_e$ : electron skin depth

$v_w$ : whistler phase speed

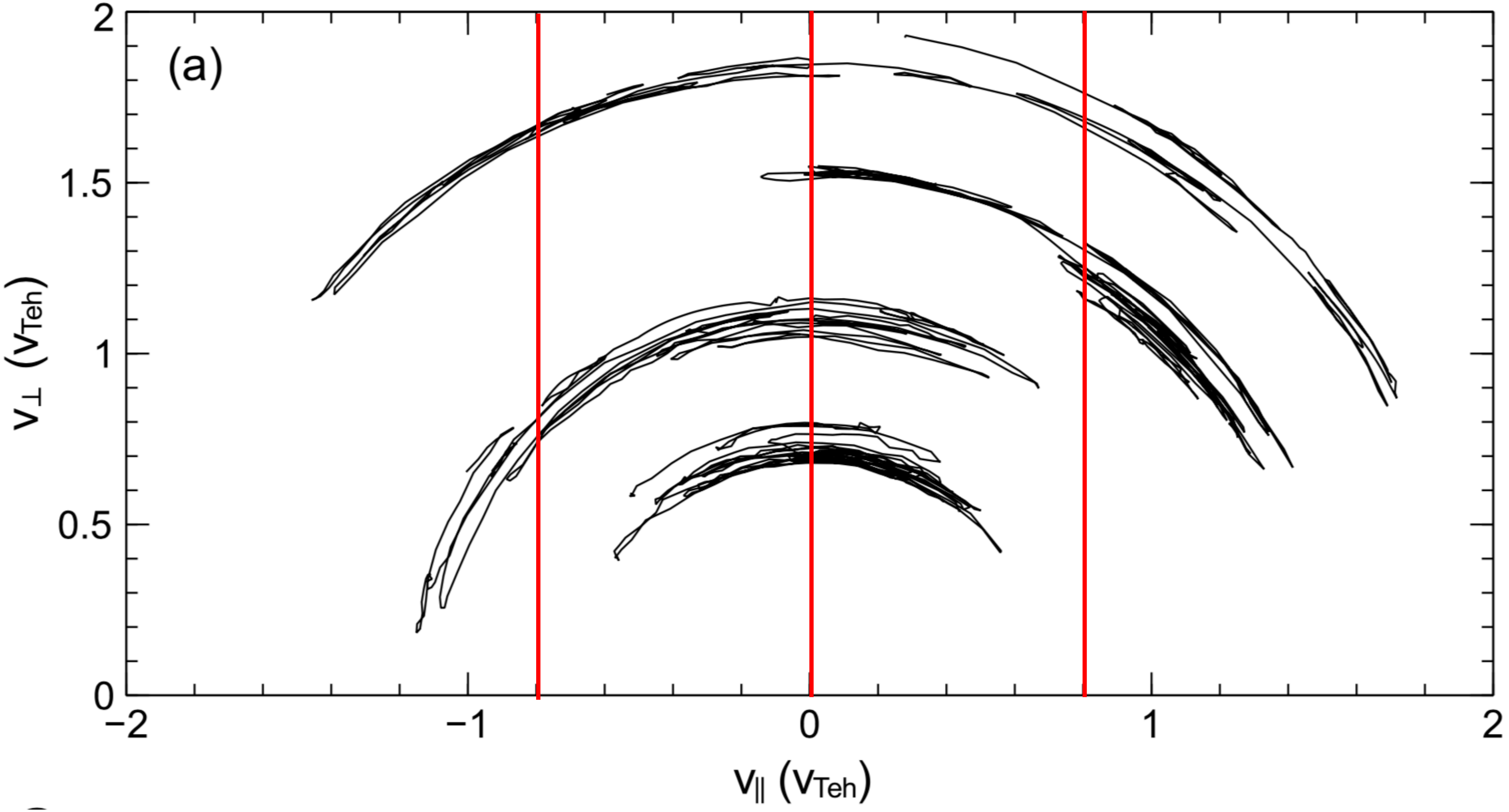
$U_{\mathrm{mag}}$ : magnetic energy density

$$\frac{k^2c^2}{\omega^2} - \frac{\omega_{pe}^2}{\omega n_0}\int d^3\mathbf{v}\,\frac{v_\perp}{2}\,\frac{\left[\left(1-\frac{kv_x}{\omega}\right)\frac{\partial f_0}{\partial v_\perp}+\frac{kv_\perp}{\omega}\frac{\partial f_0}{\partial v_x}\right]}{\omega - kv_x - \Omega_e} = 0, \qquad (1)$$

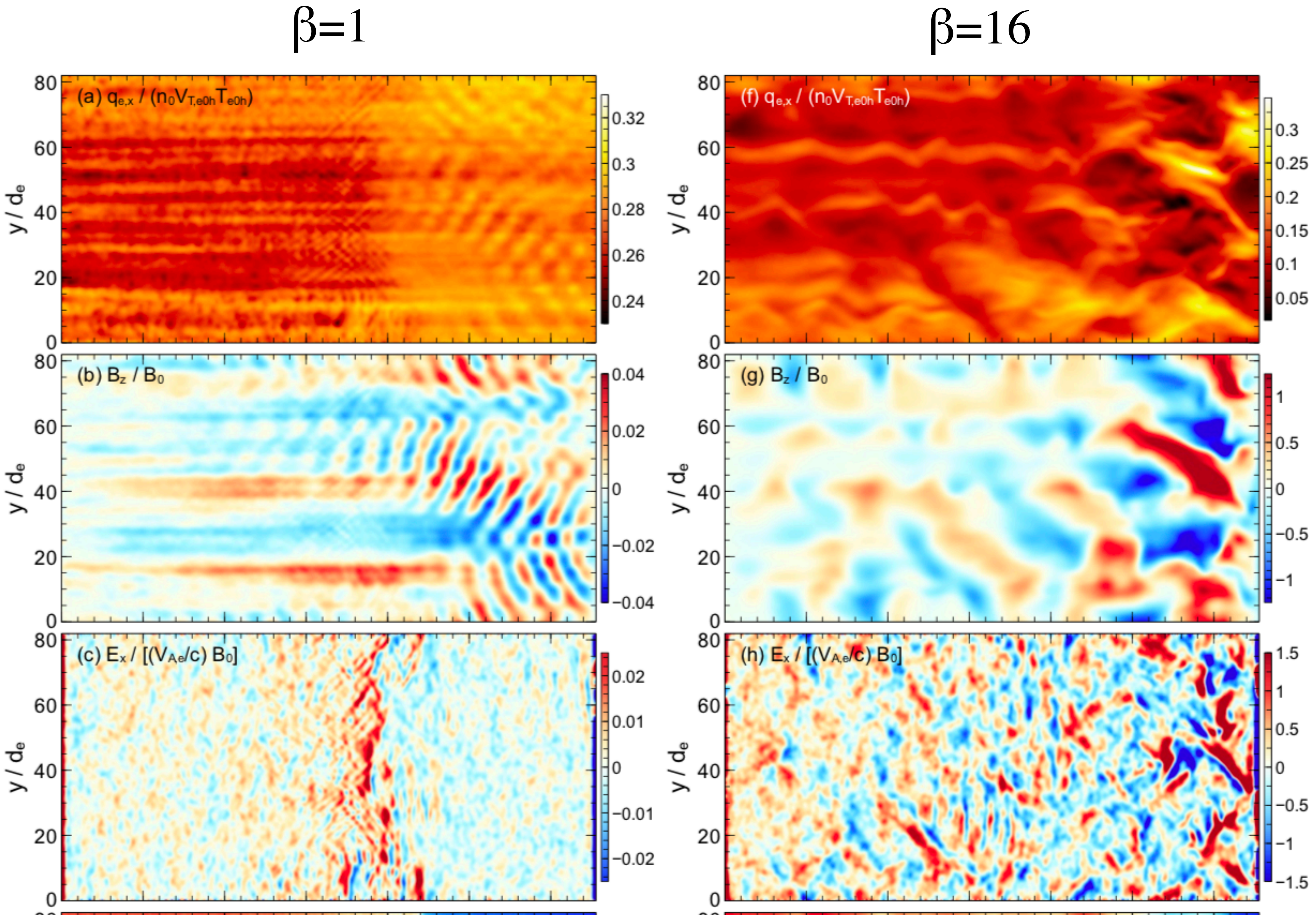
where $\omega_{pe} = (4\pi n_0 e^2/m_e)^{1/2}$ is the plasma frequency, $\Omega_e = eB_0/m_e c$ is the cyclotron frequency, $f_0(\mathbf{v})$ is the initial electron phase space distribution, $v_{Te} = (2T_e/m_e)^{1/2}$ is the thermal speed, $\rho_e = v_{Te}/\Omega_e$ is the Larmor radius, $d_e = c/\omega_{pe}$ the skin depth, and $\beta_e = 8\pi n_0 T_e/B^2$.



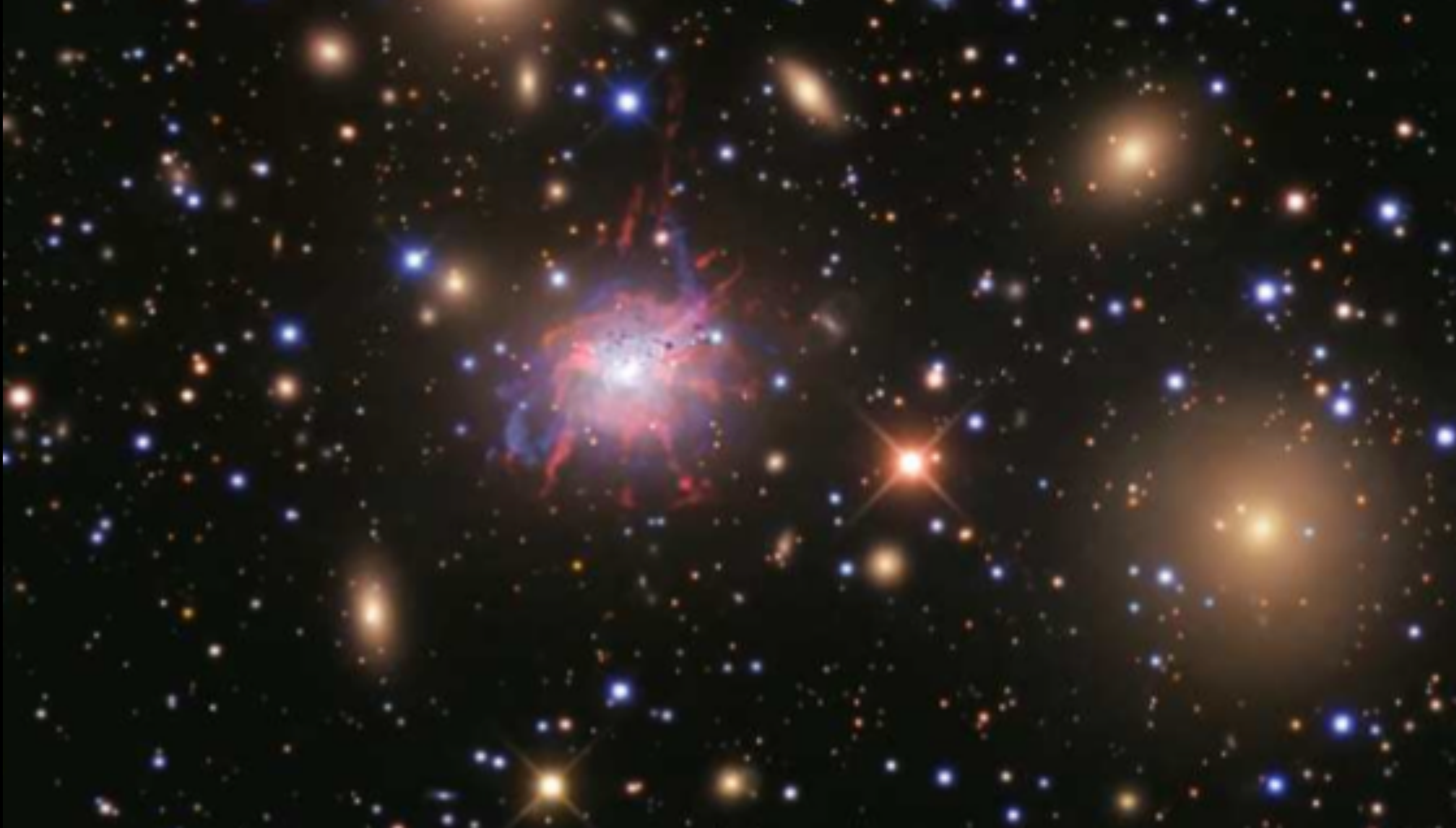
Roberg-Clark et al. (2016)



Roberg-Clark et al. (2018)



Electrostatic double layers ← Whistler dominated physics



Unsharp-mask image of Perseus (10arcsec smoothed structure subtracted out)

Sanders et al. (2006)