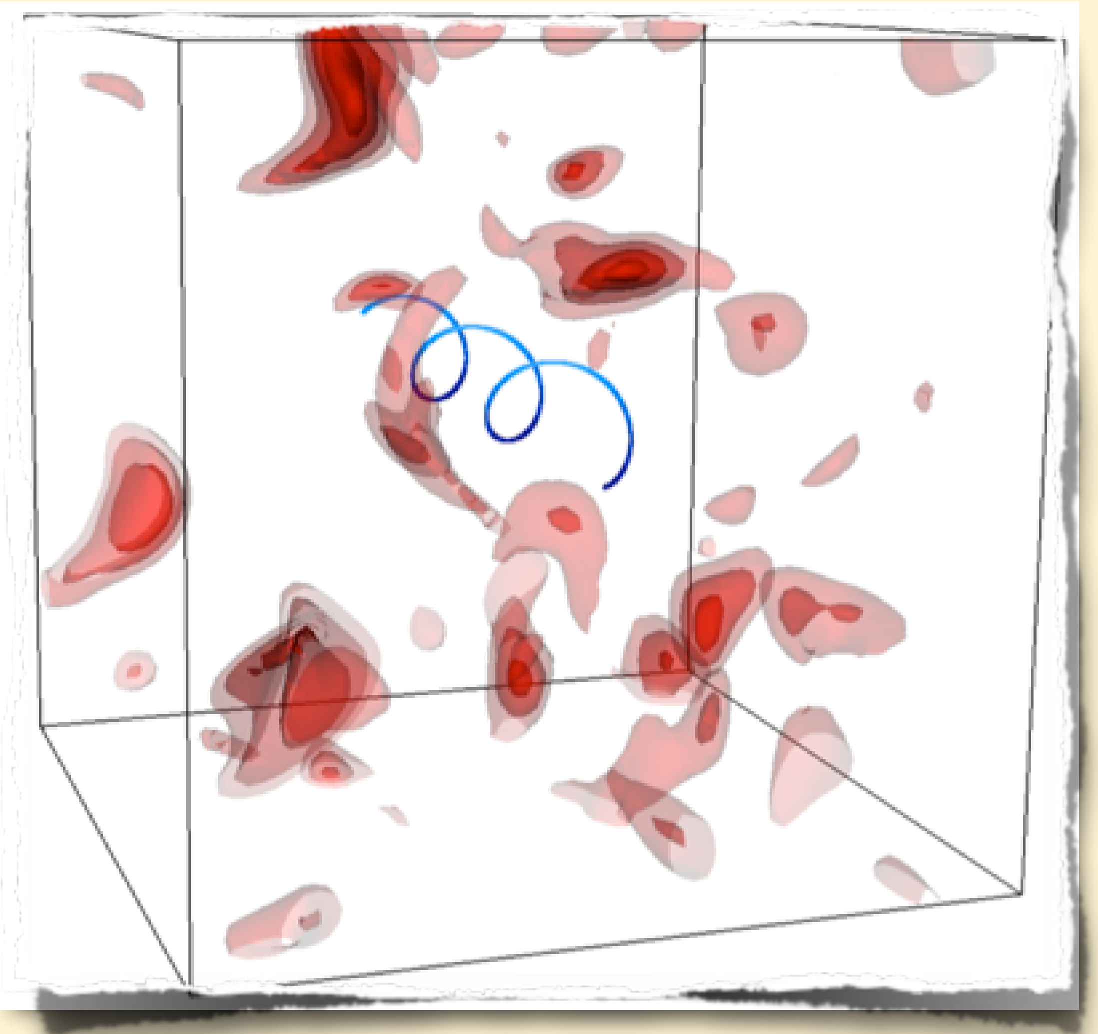
Heating of Test Particles in Numerical Simulations of MHD Turbulence and the Solar Wind

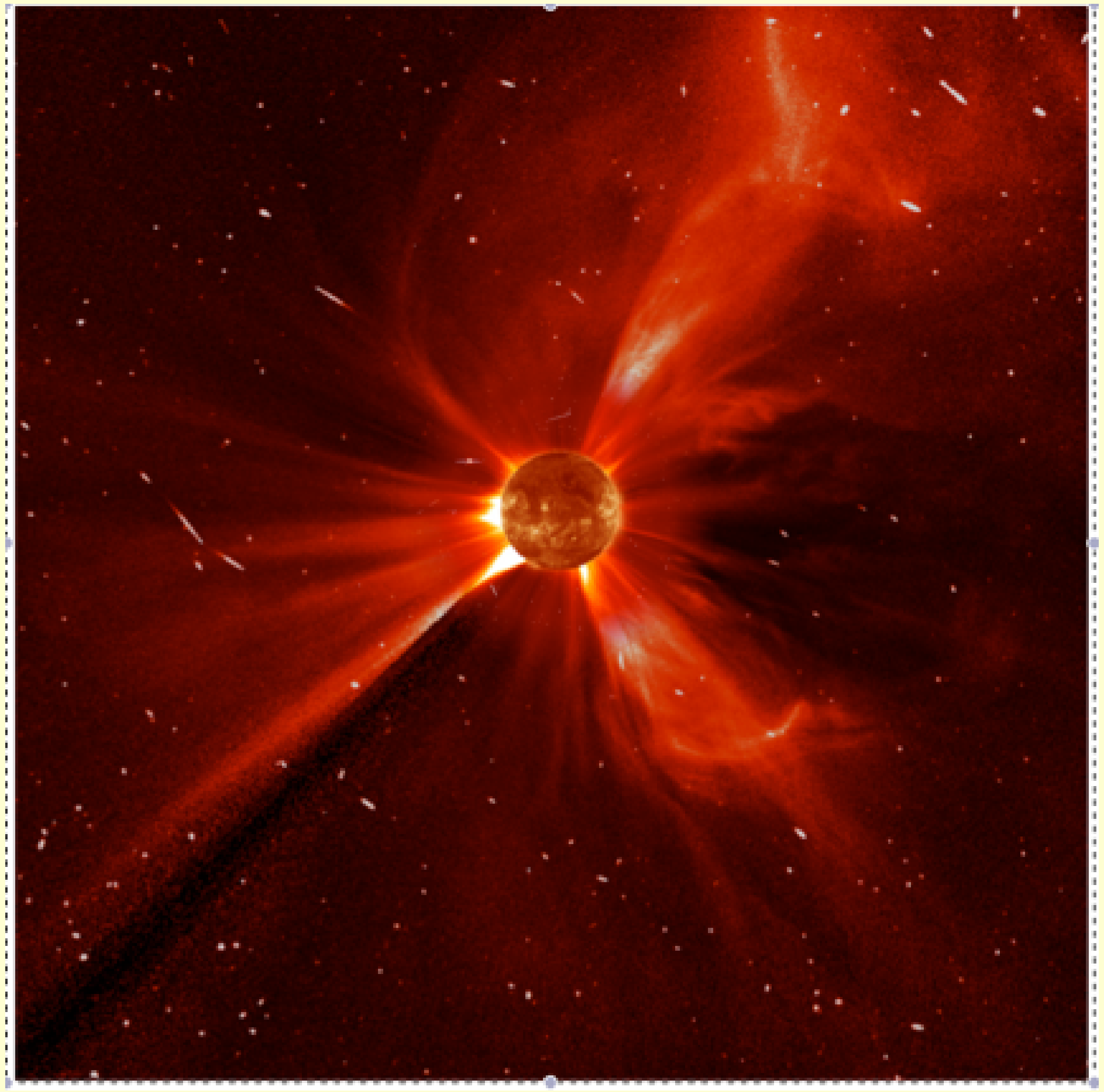


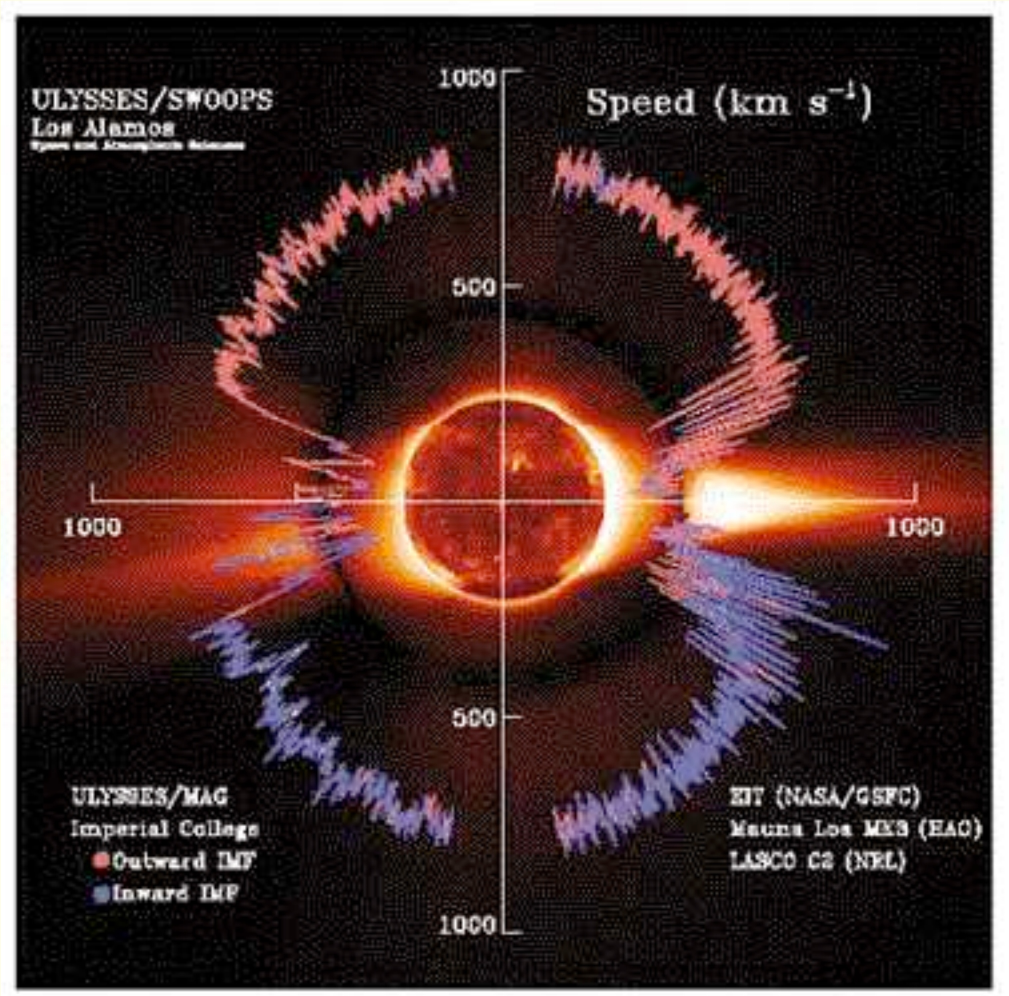
Ian Parrish
UC Berkeley

Collaborators: Rémi Lehe (*ENS*), Eliot Quataert (*UCB*)

Einstein Fellows Symposium
October 27, 2009

Motivation: Solar Wind





McComas, D.J., et al., Geophys. Res. Lett., 25, 1-4, 1998

Solar wind at 1 AU:
•Fairly collisionless
•MHD turbulence observed

$$\begin{aligned} n &\sim 10\ \mathrm{cm}^{-3} \\ T &\sim 10^5\ \mathrm{K} \\ \lambda_{\mathrm{mfp}} &\sim 10^7\ \mathrm{km} \\ v_{\mathrm{flow}} &\sim 700\ \mathrm{km\,s}^{-1} \end{aligned}$$

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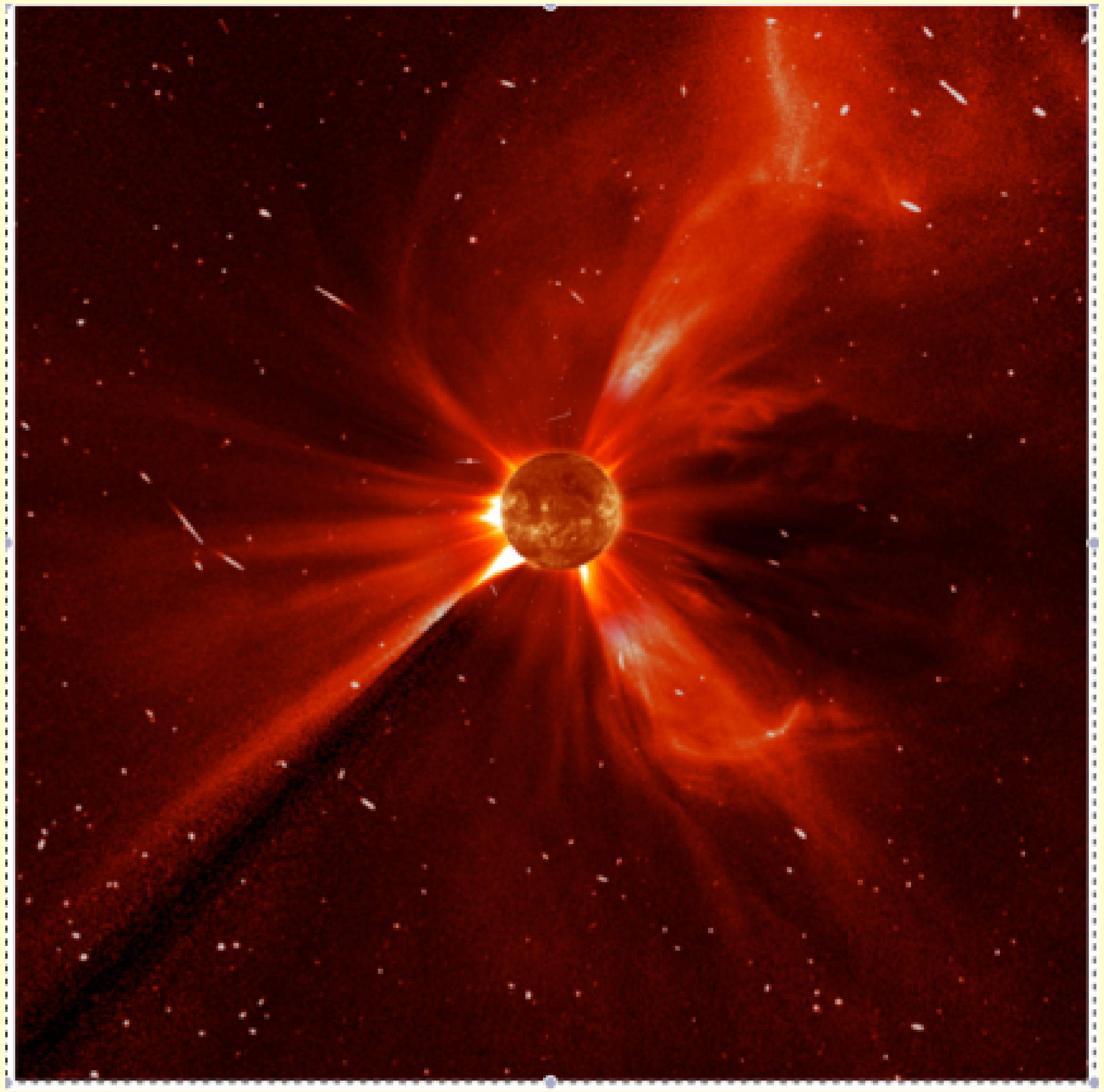

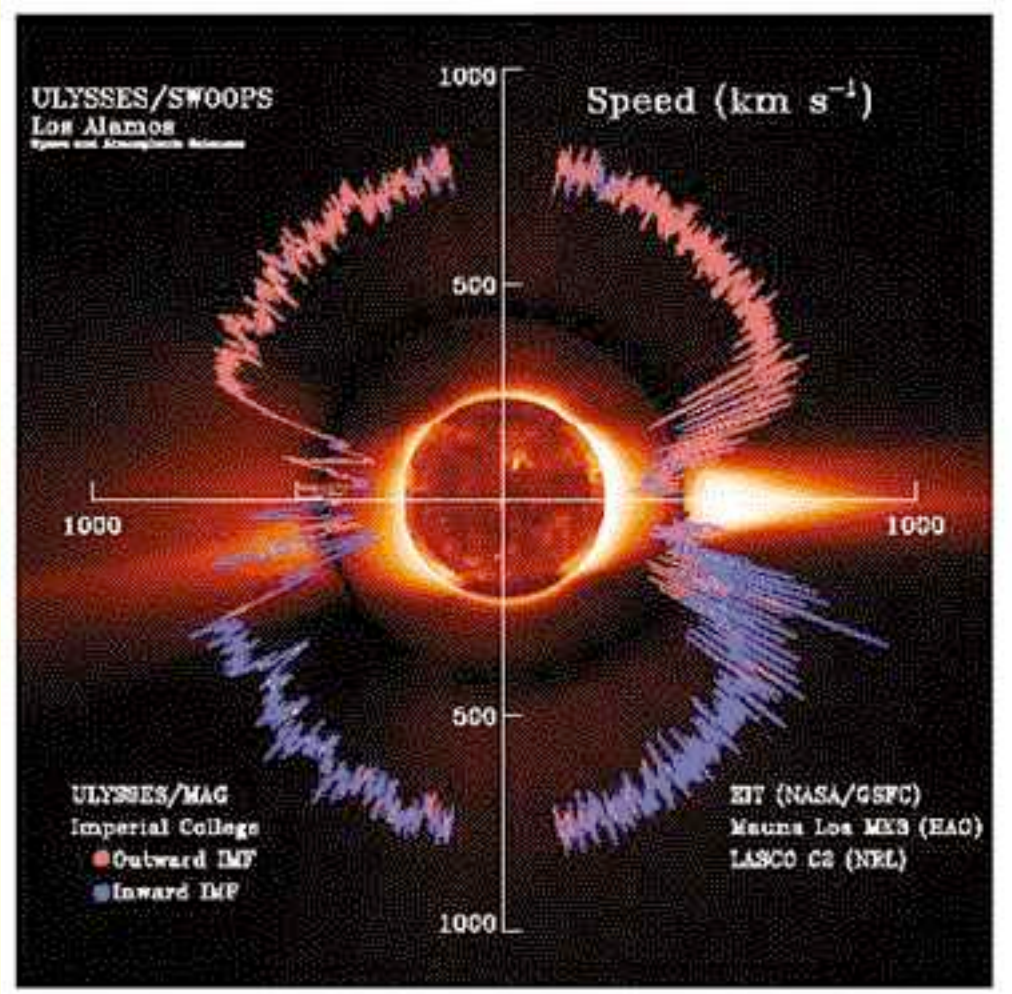

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Also applies to accretion disk coronae

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$$T \sim 10^5\ \mathrm{K}$$
$$\lambda_{\mathrm{mfp}} \sim 10^7\ \mathrm{km}$$
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Presentation Outline

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- Motivation: The Solar Wind

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- **MHD Turbulence**

  Theory and Observations

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MHD Turbulence Theory

Hydro Turbulence: $P(k) \propto k^{-5/3}$ (Kolmogorov)

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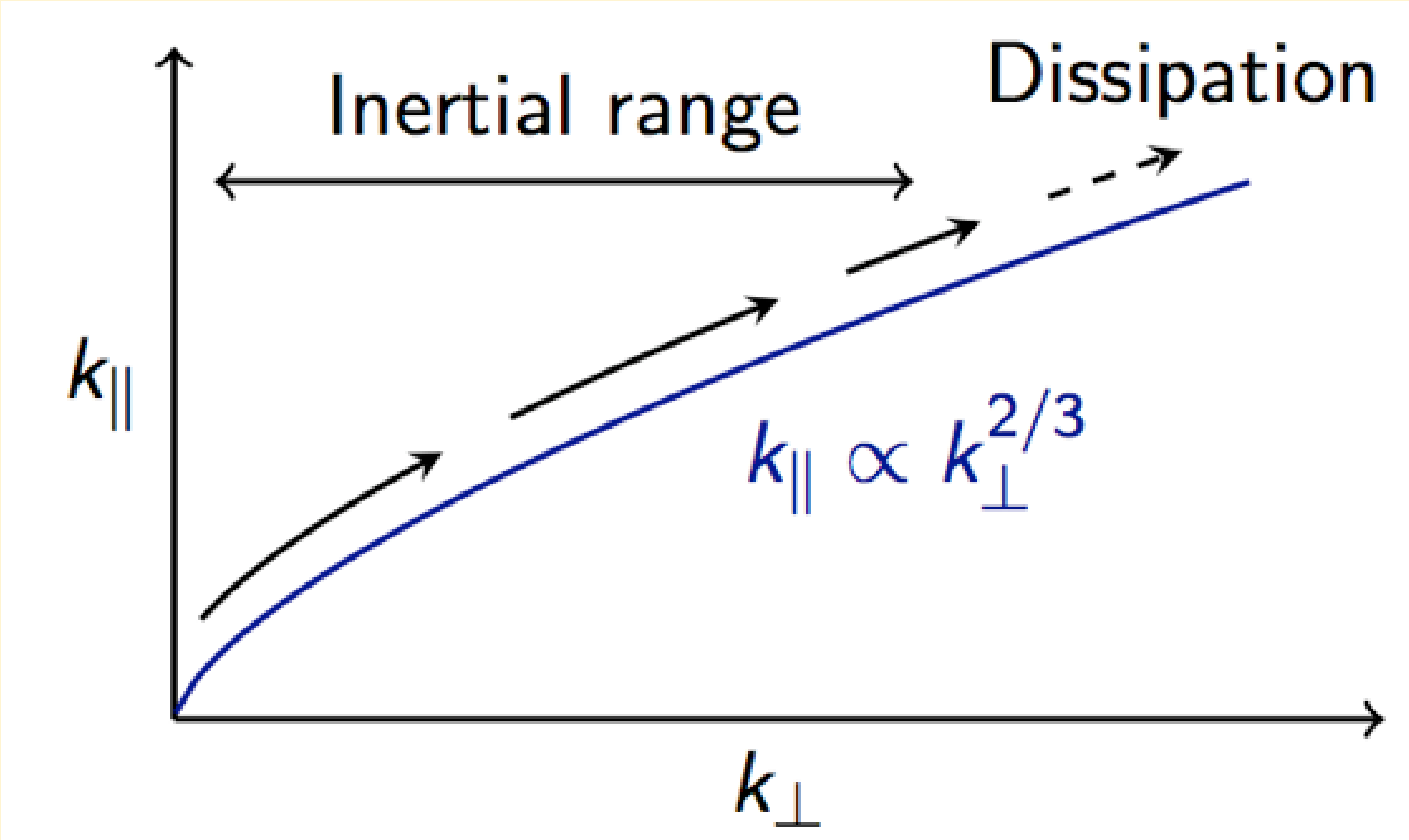
Goldreich-Sridhar Theory



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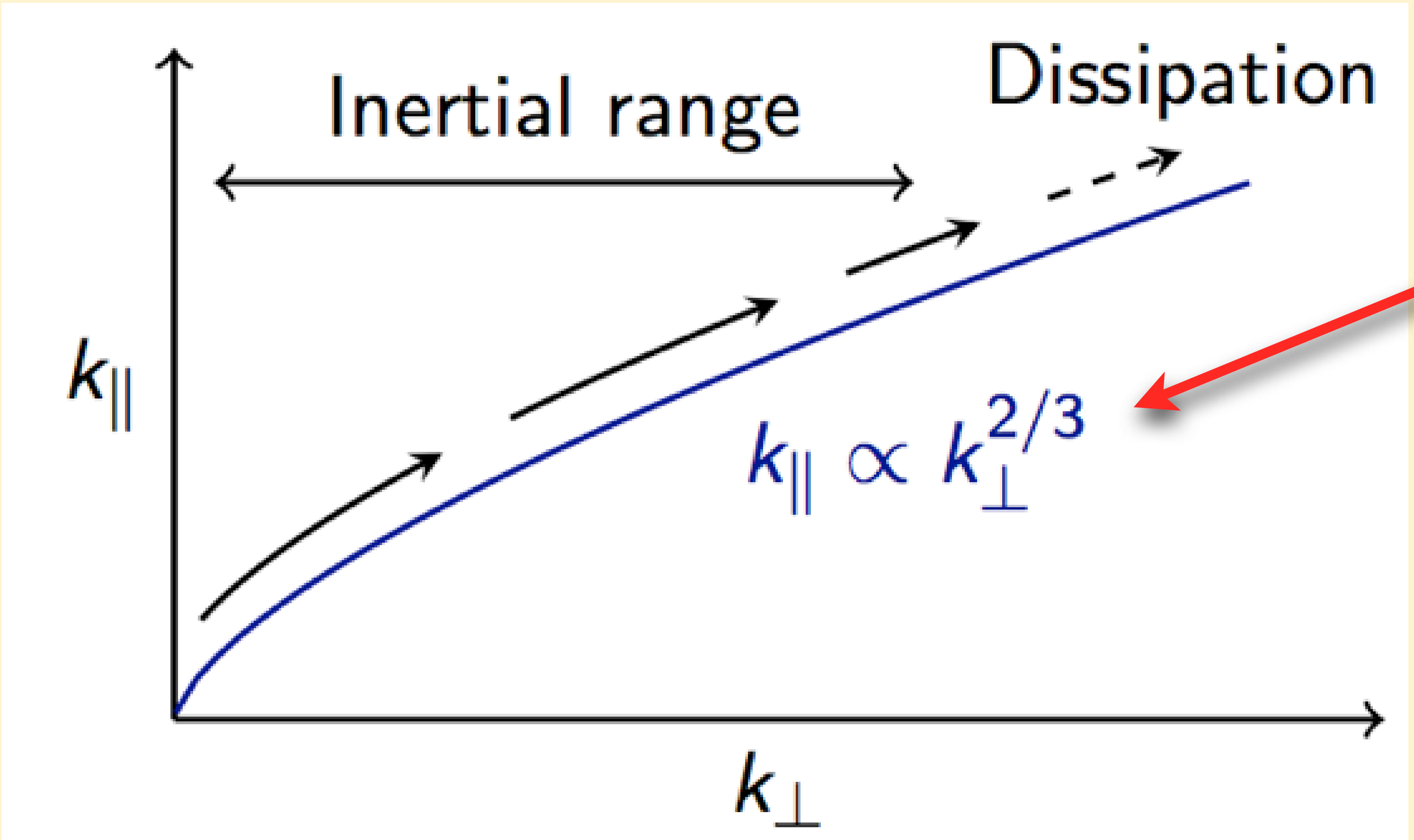
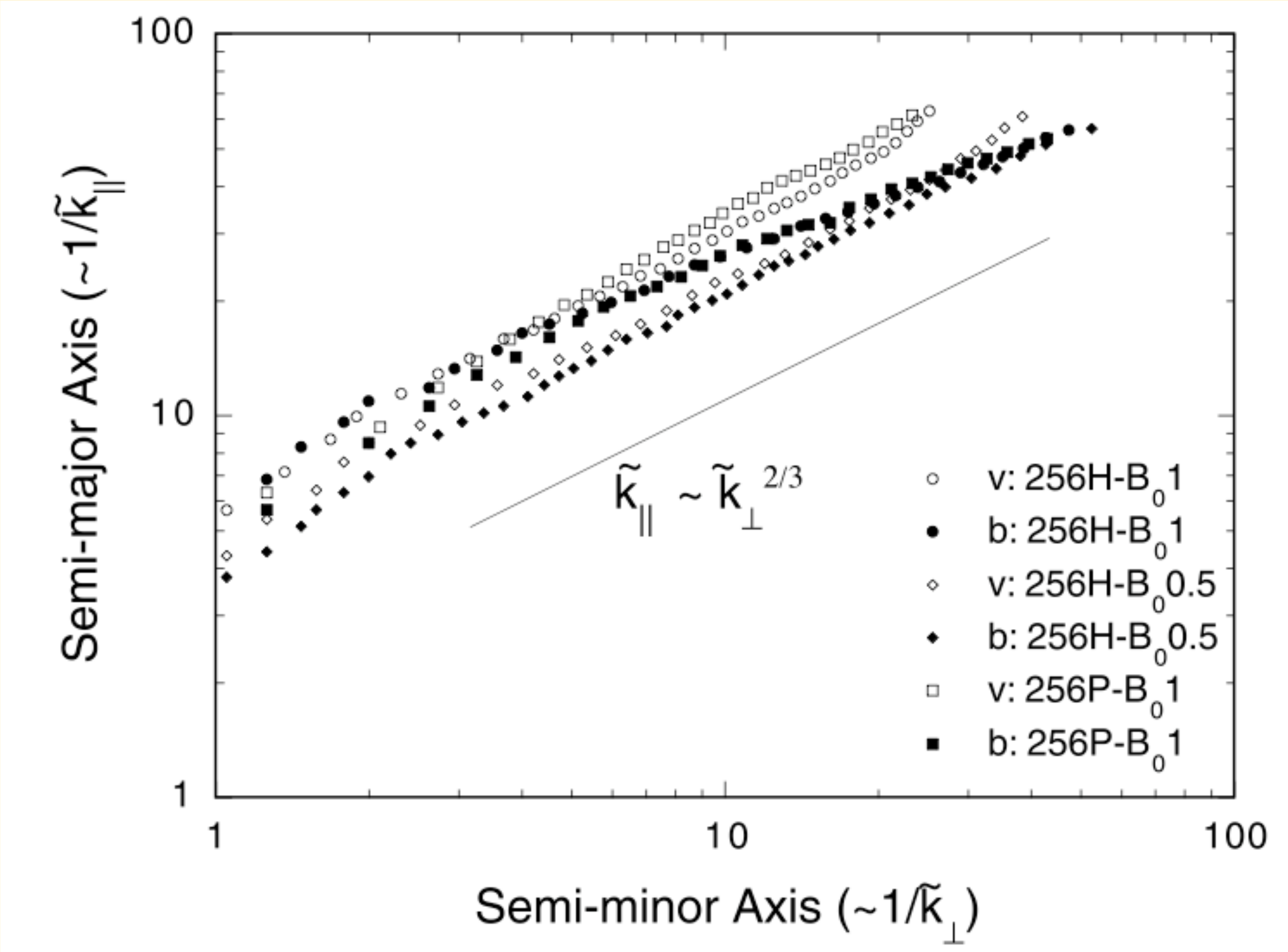


"Critical Balance"

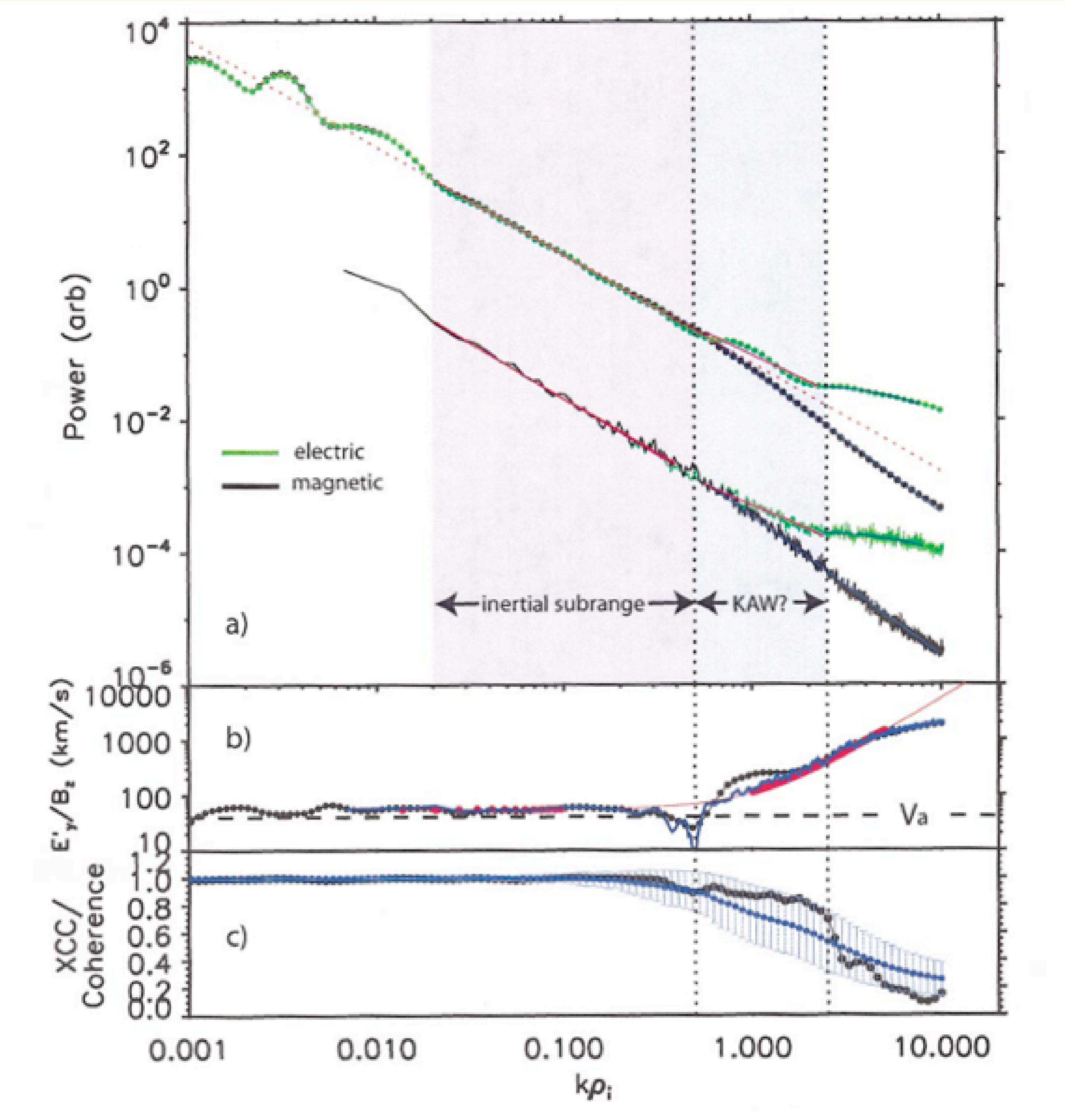
Energy cascades primarily perpendicular to magnetic field.

MHD Turbulence: Simulations



(Cho & Vishniac, 2000)

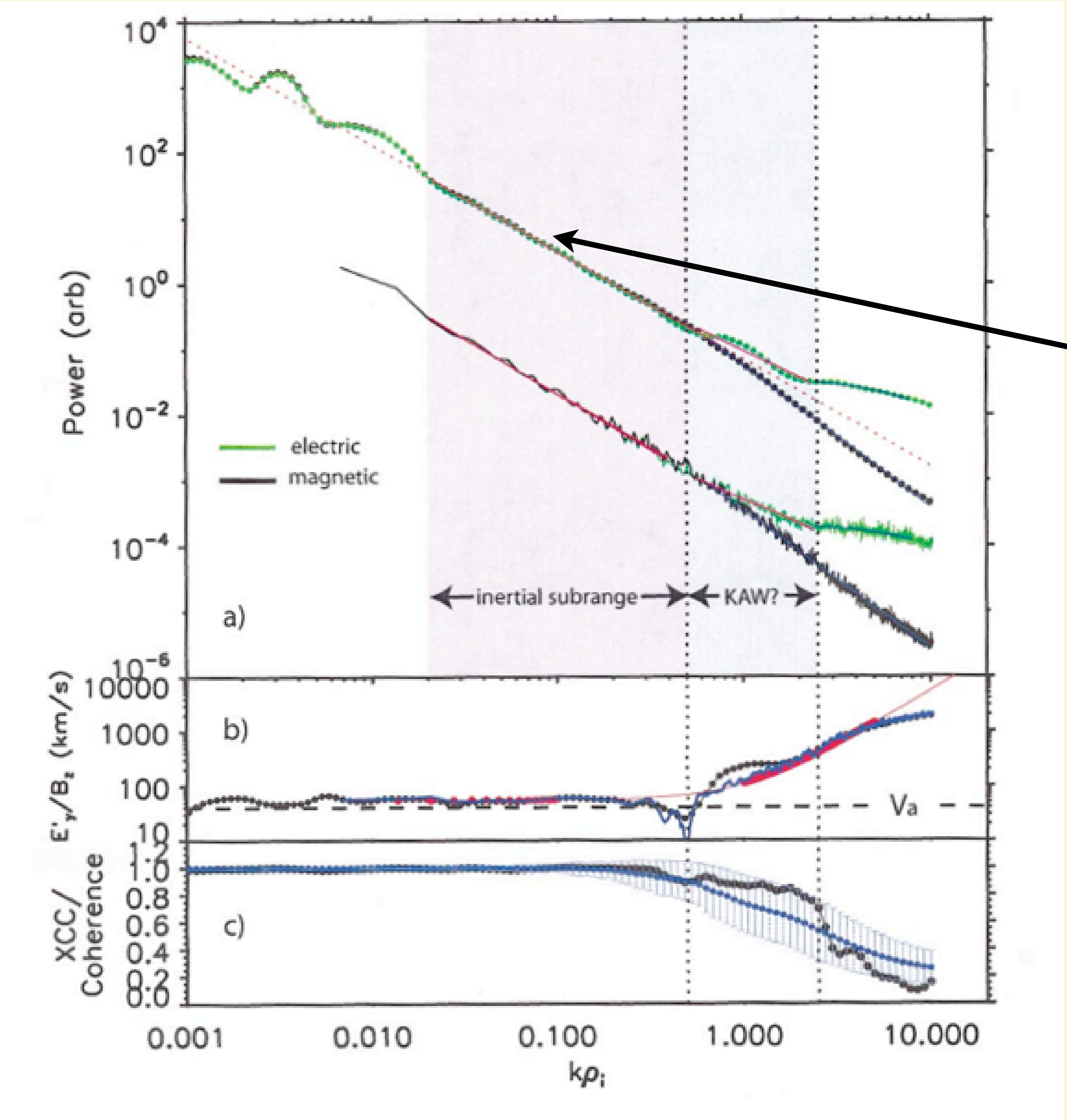
MHD Turbulence: Observations



Cluster spacecraft
in situ fields measurements

(Bale, 2005)

MHD Turbulence: Observations



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Inertial Range:

$$P \propto k^{-5/3}$$

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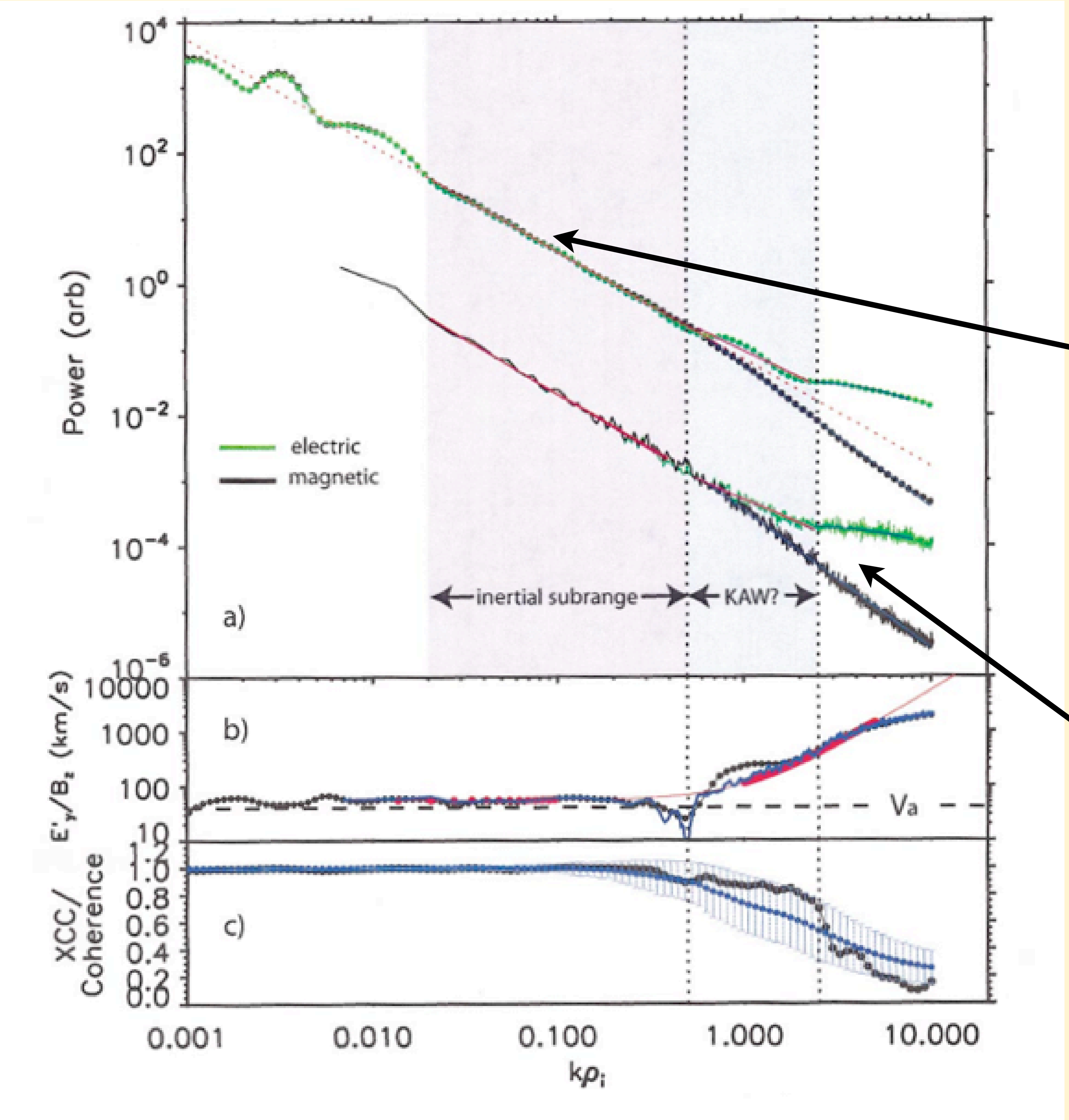

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Cluster spacecraft
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Inertial Range:
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Below Ion Gyroradius:
Kinetic Alfvén Wave?

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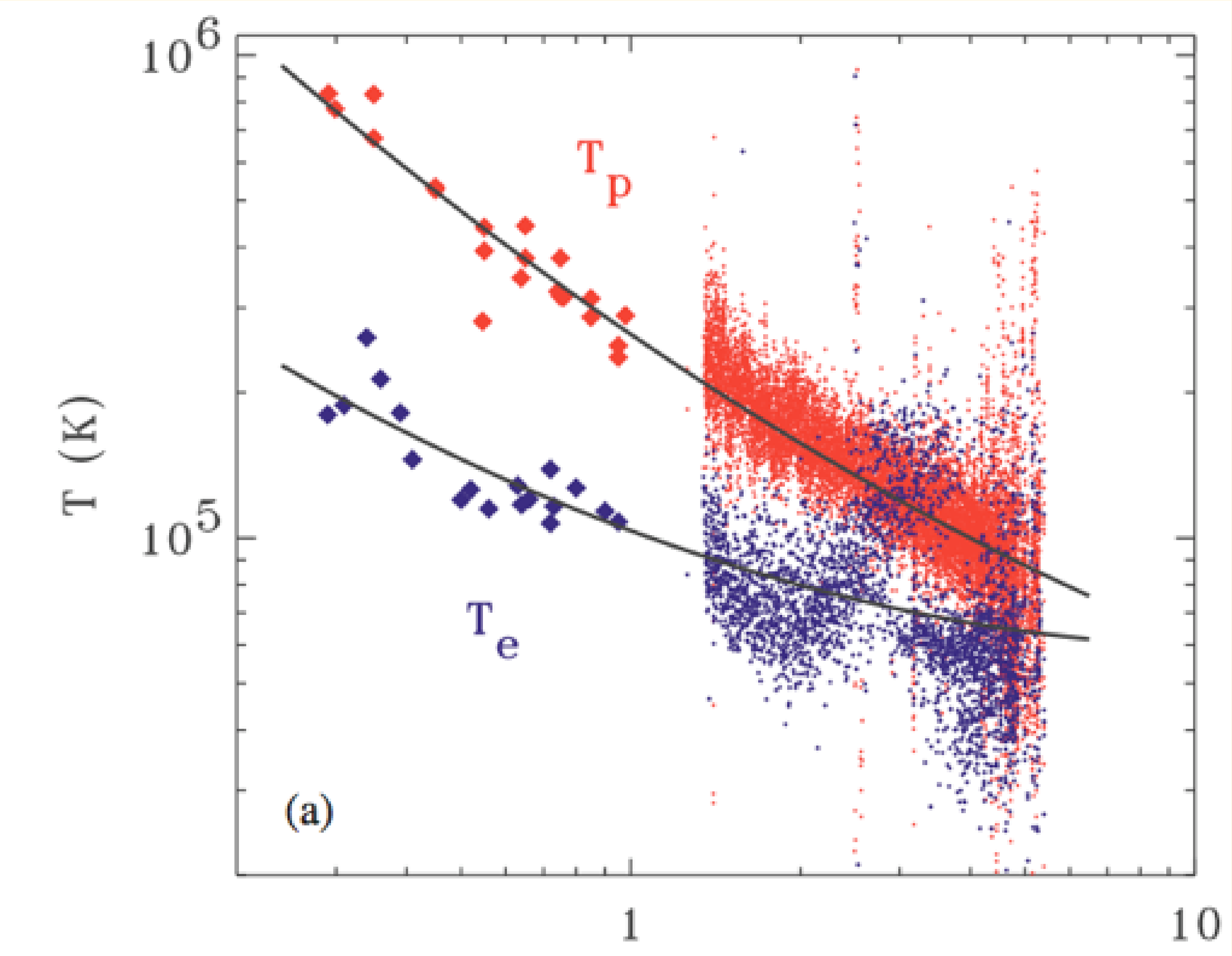
Evidence for Heating in Solar Wind

Helios Data Ulysses Data



(Cranmer, et al, 2009) r (AU)

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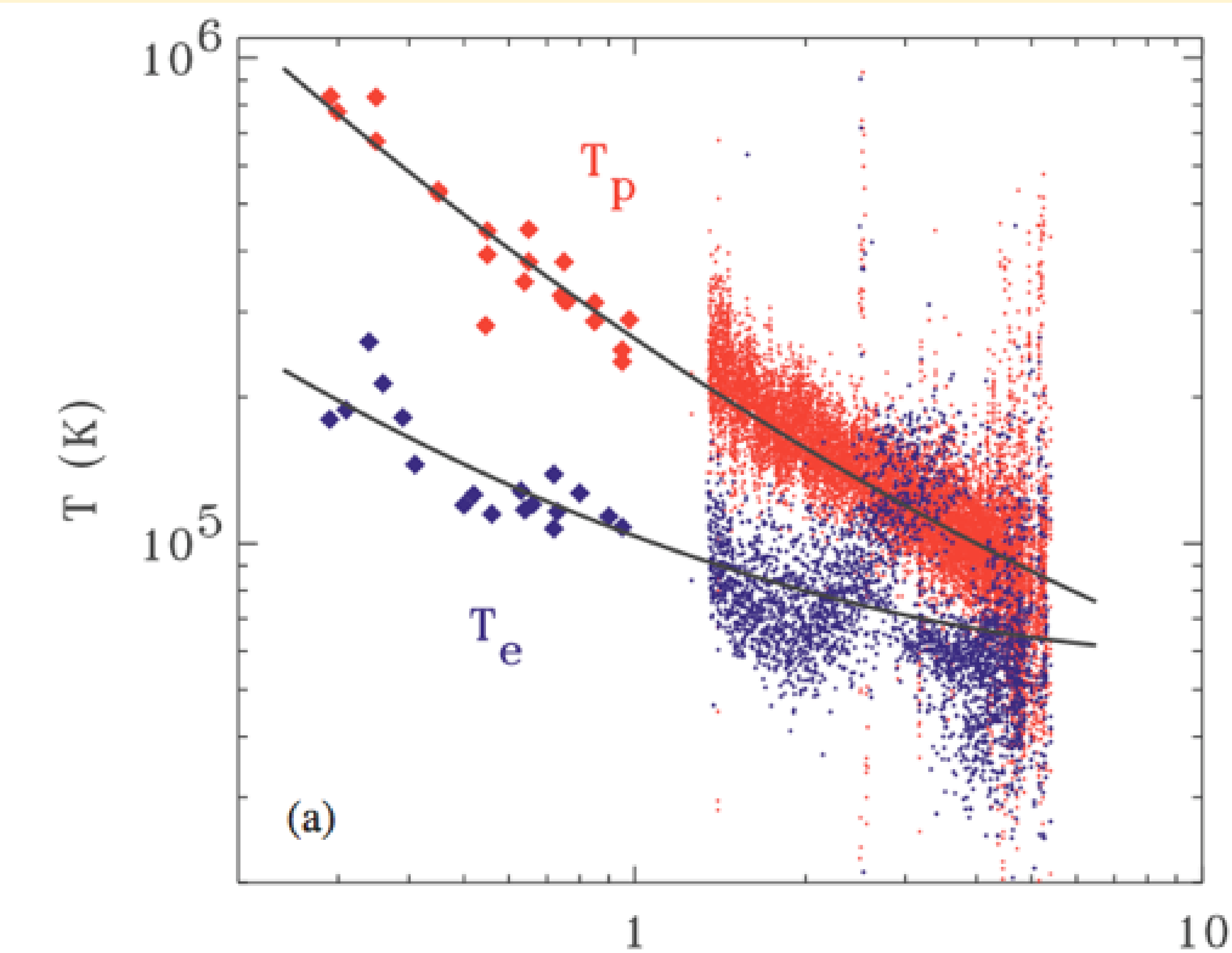

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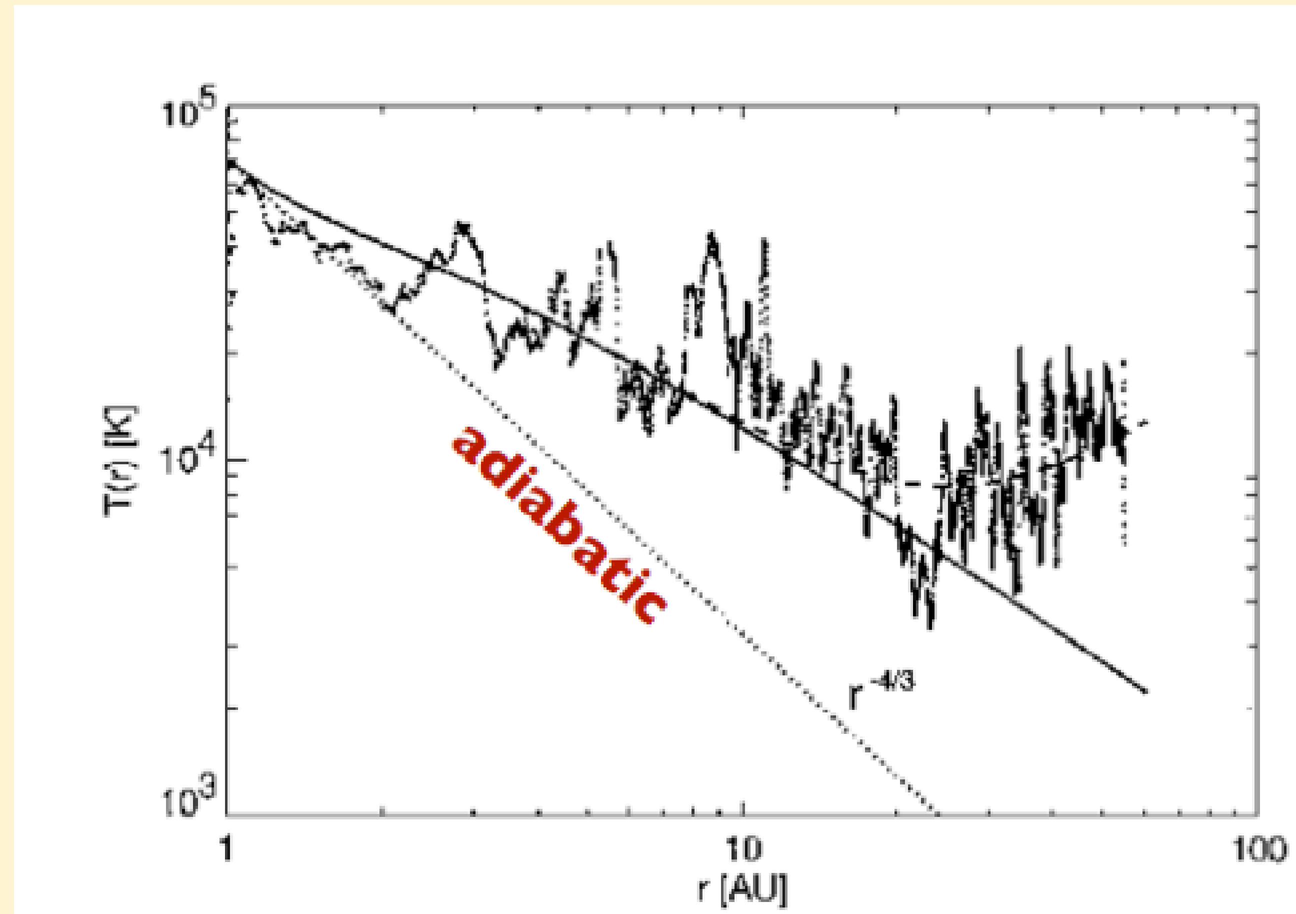
Voyager Data



(Matthaeus, et al, 1999)

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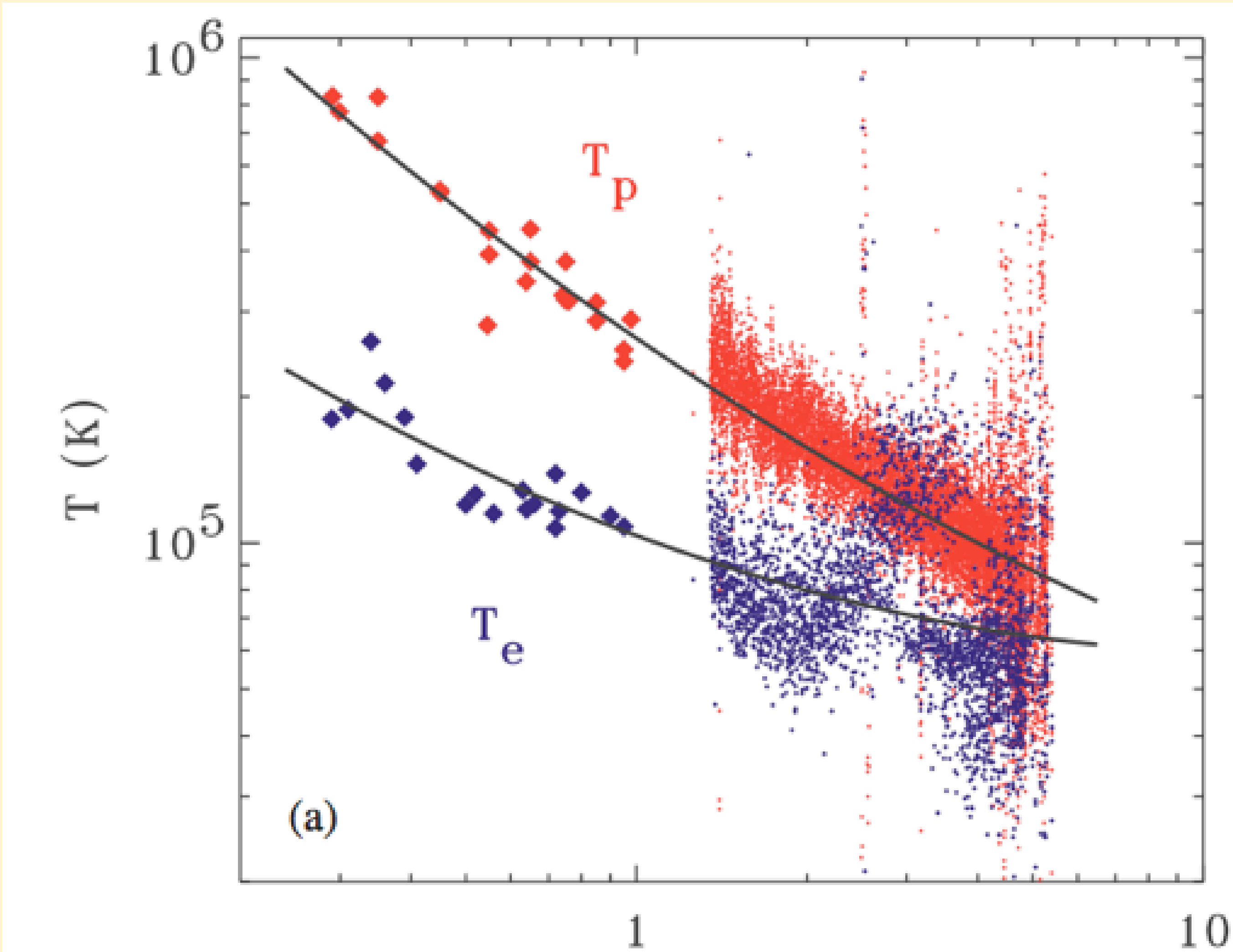

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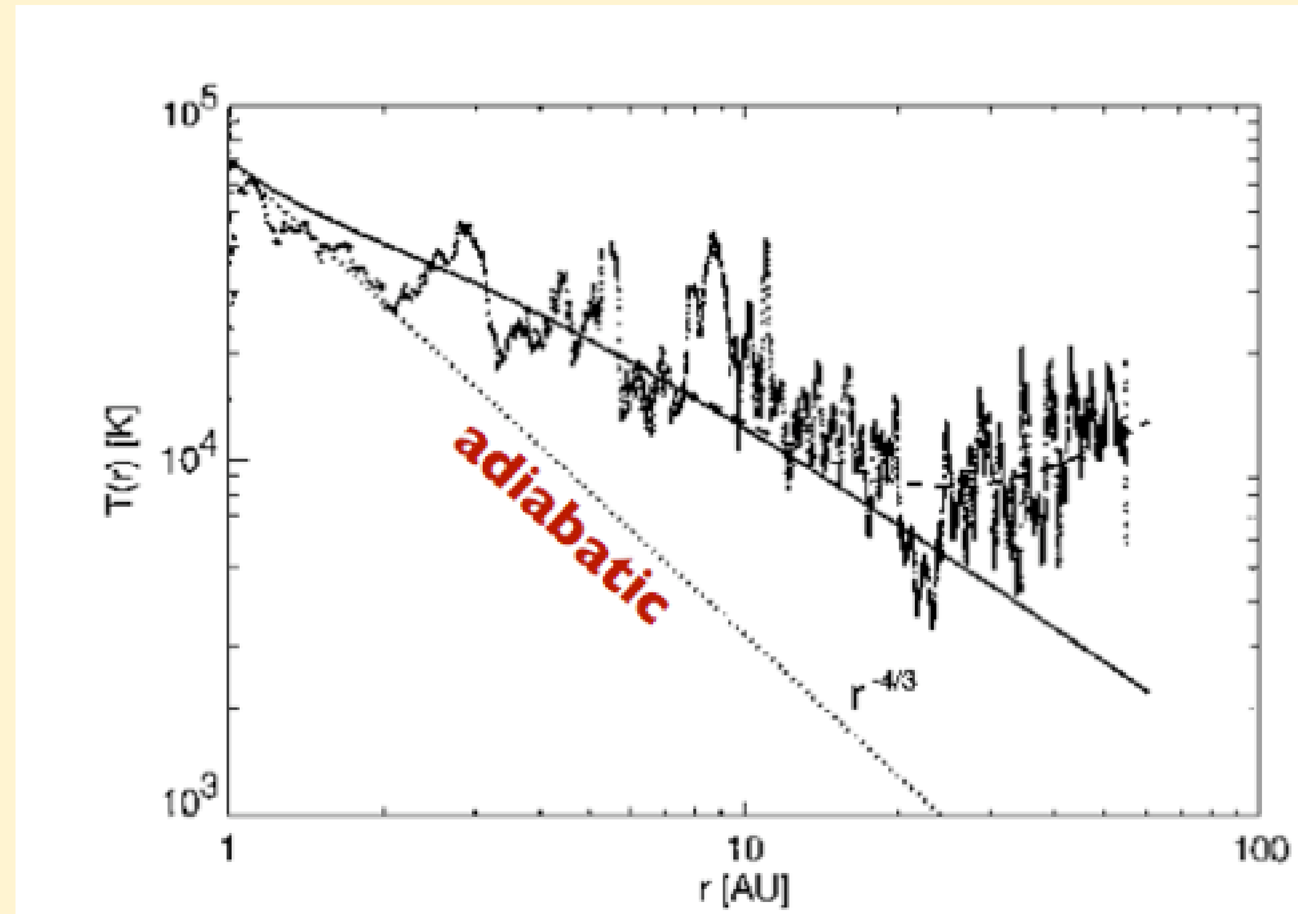

(Matthaeus, et al, 1999)

- Evidence for extended heating favors waves.

Evidence for Heating in Solar Wind

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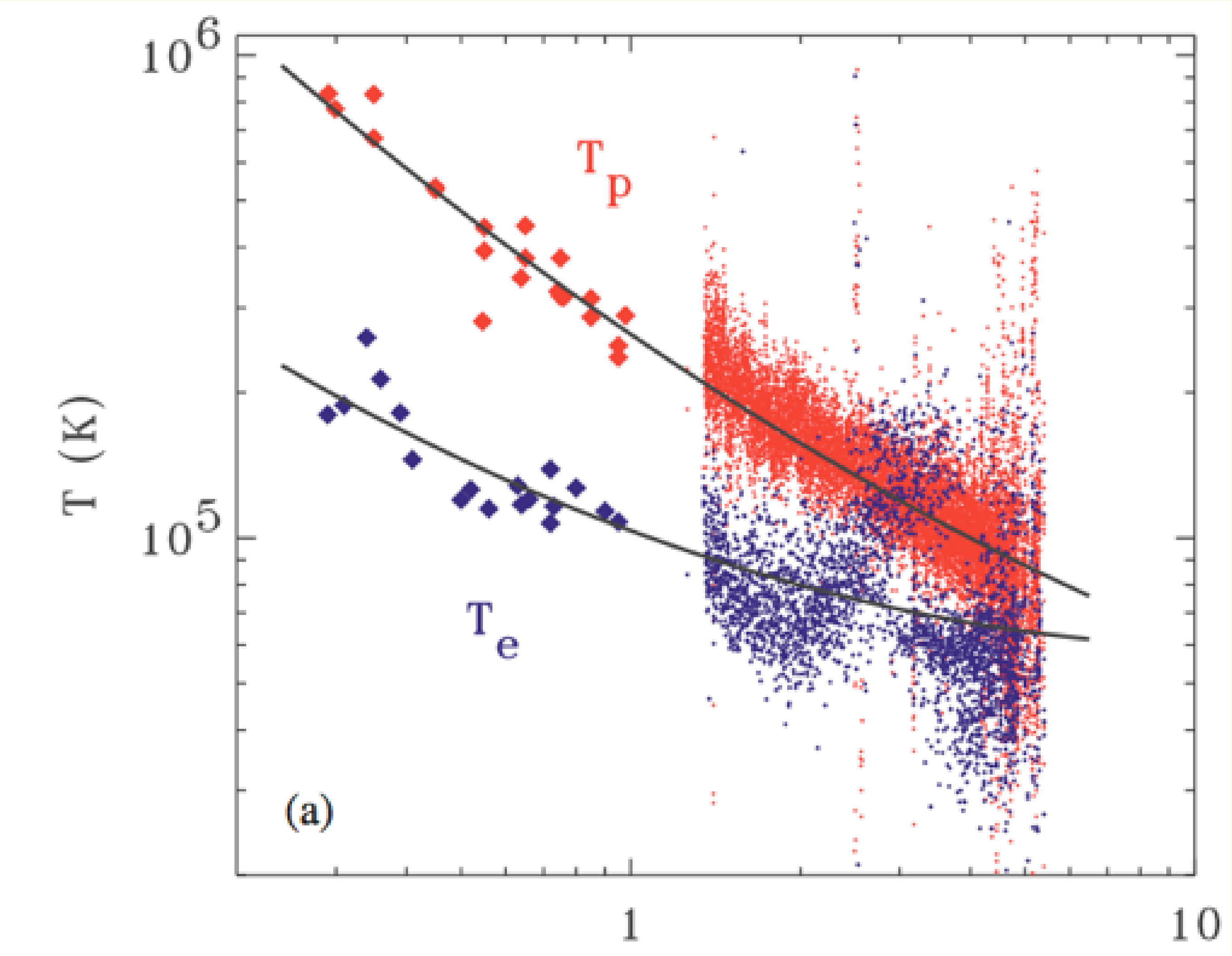

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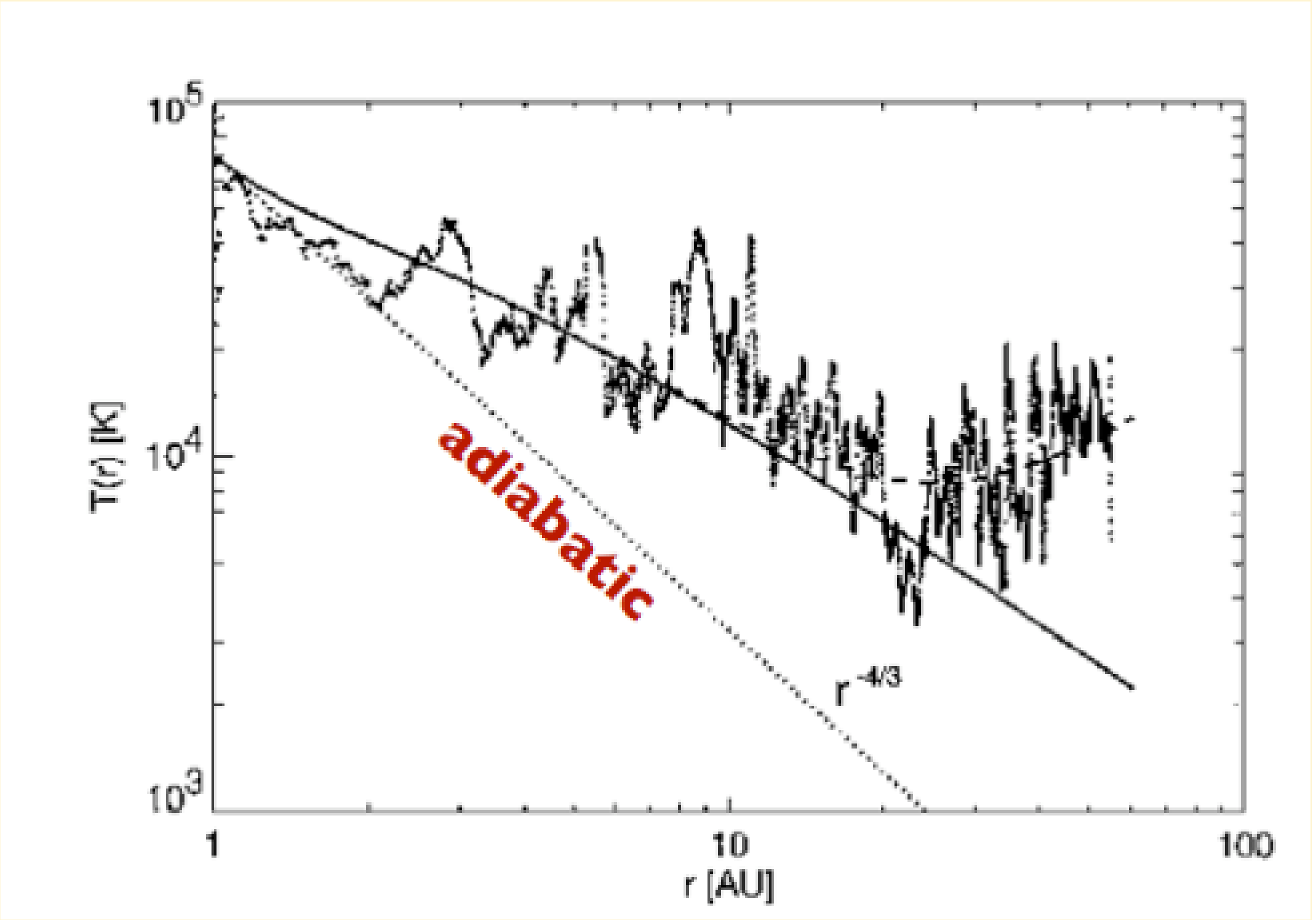


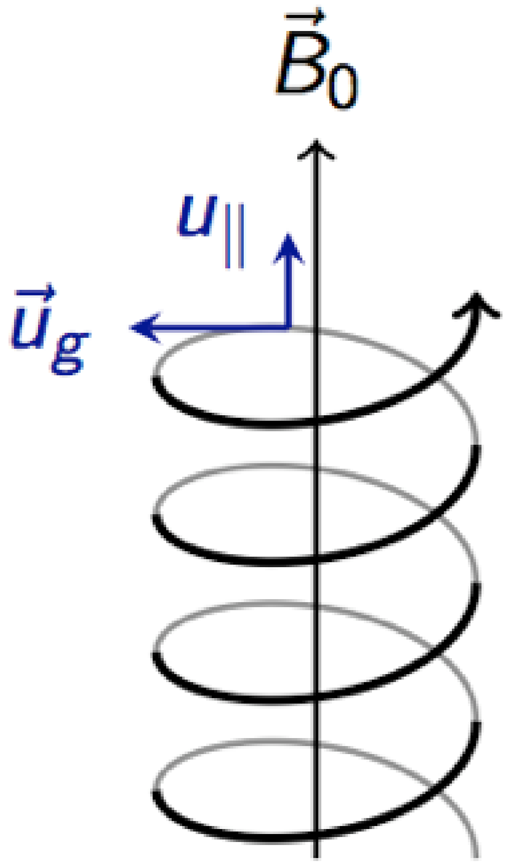
(Matthaeus, et al, 1999)

- Evidence for extended heating favors waves.
- Interesting heating signatures: $T_{\rm ion} \gg T_p > T_e$

$$T_\perp > T_\parallel$$

Cyclotron Resonance

Gyromotion



$$\Omega = \frac{qB_0}{mc}$$

Cyclotron Resonance

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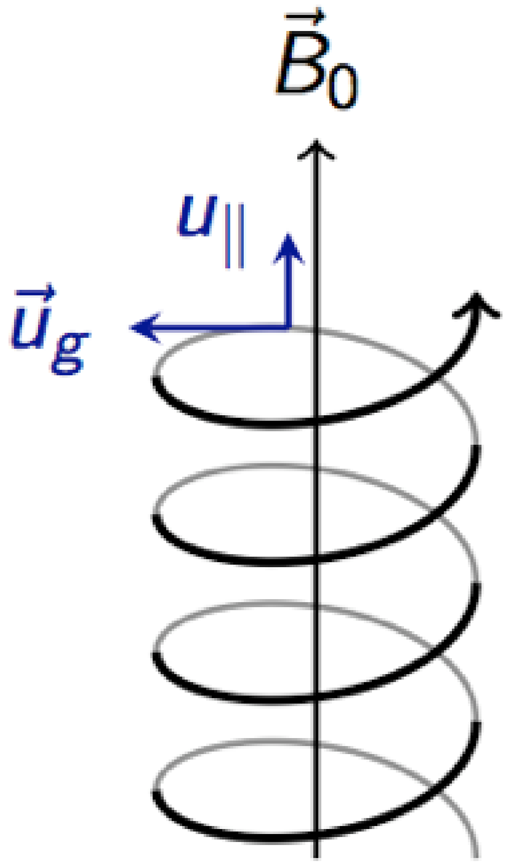

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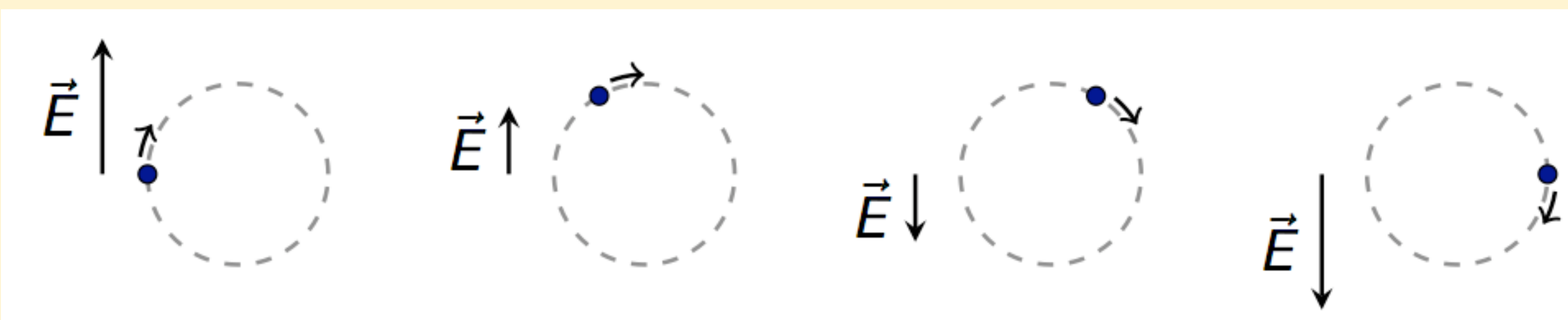
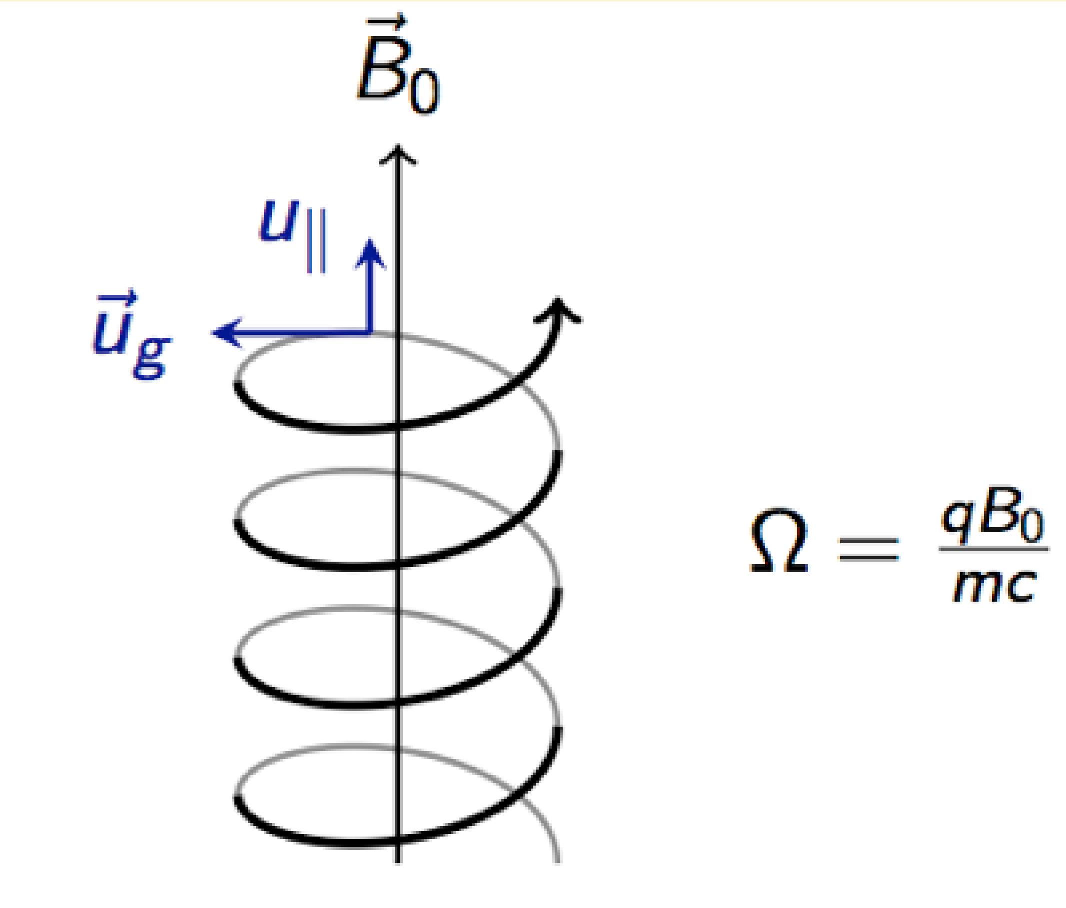


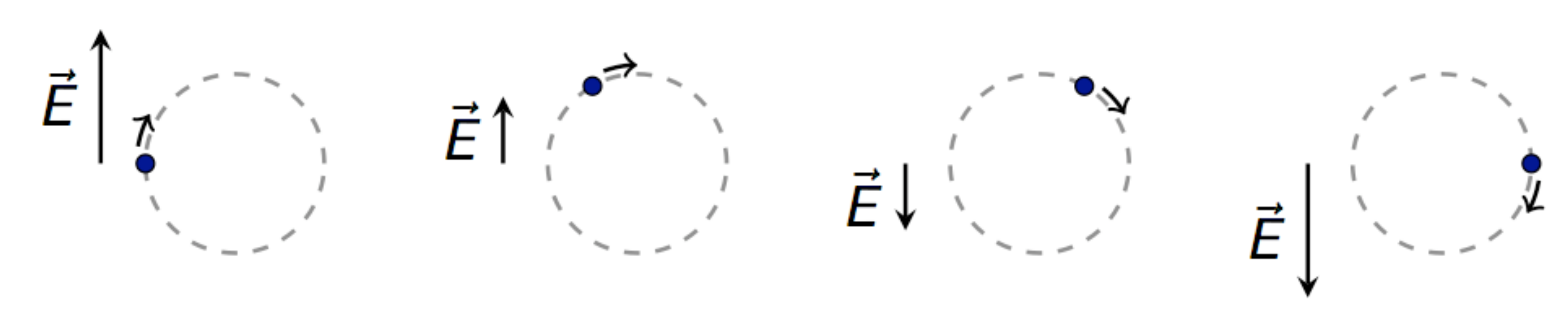
Electric field in phase with cyclotron motion.

Cyclotron Resonance

Gyromotion



Resonance Condition:
$$\omega - k_{\|} u_{\|} = \pm\Omega$$



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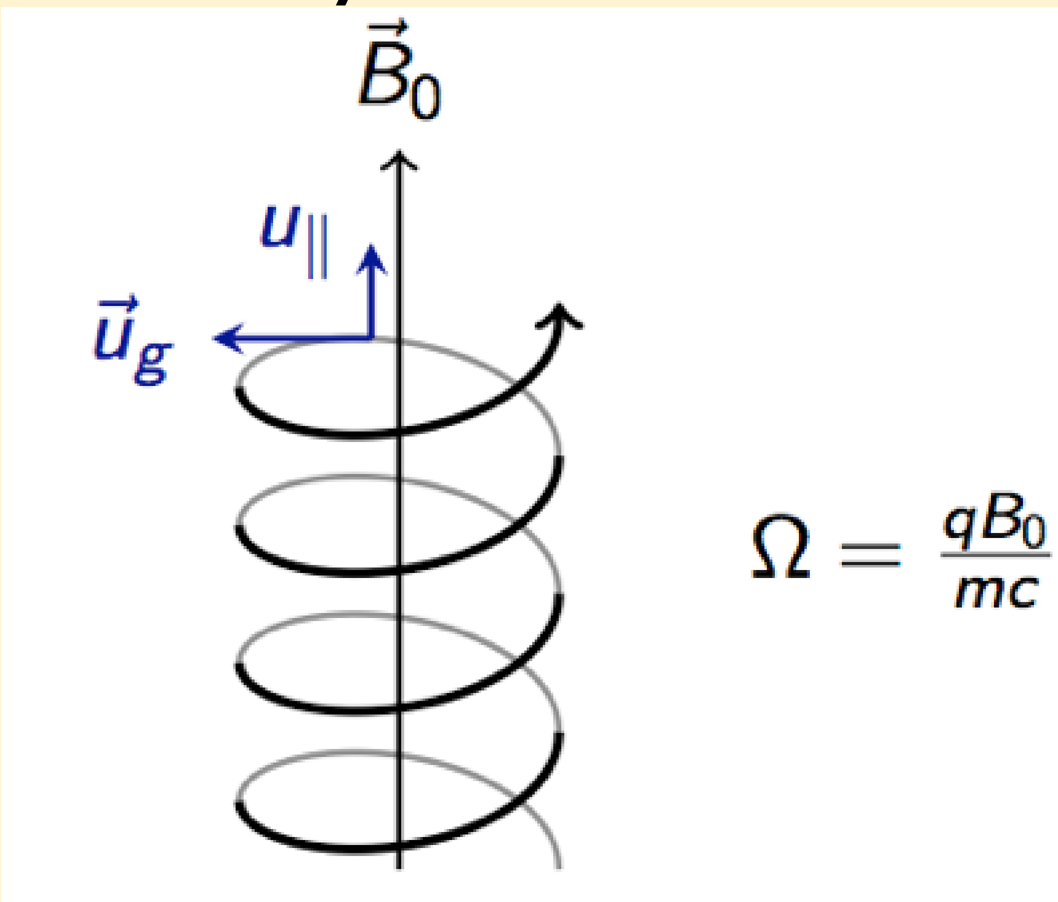

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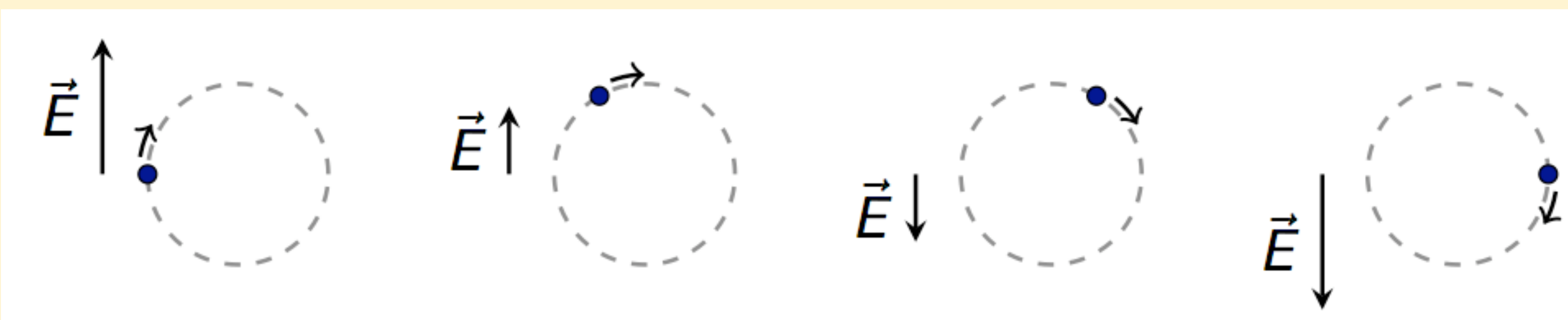
Leads to *Perpendicular* Heating



Electric field in phase with cyclotron motion.

Landau Damping and Transit Time Damping

Parallel Dynamics:

$$\frac{du_\parallel}{dt} = \frac{q}{m} E_\parallel - \mu \nabla_\parallel B$$

Landau Damping and Transit Time Damping

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Magnetic Moment:

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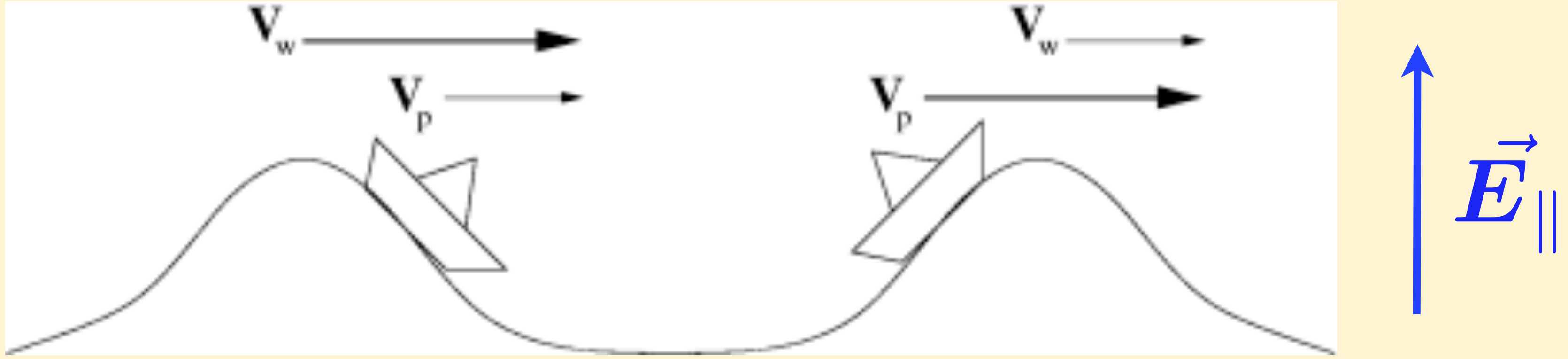

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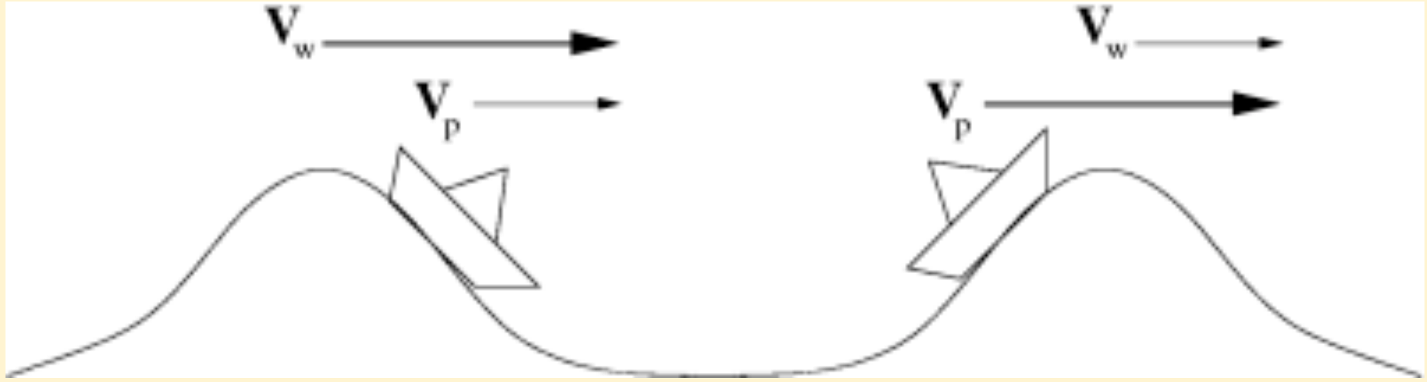

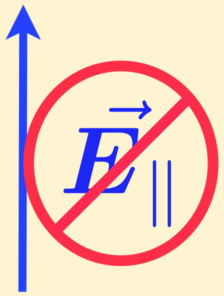

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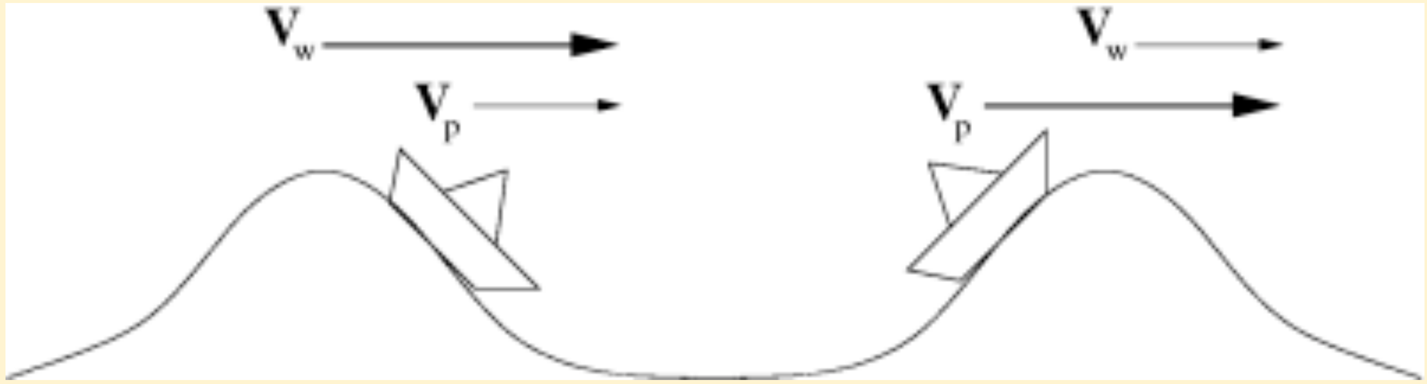

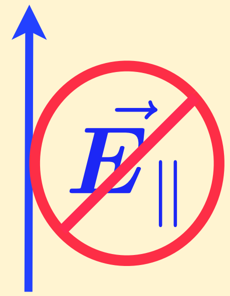

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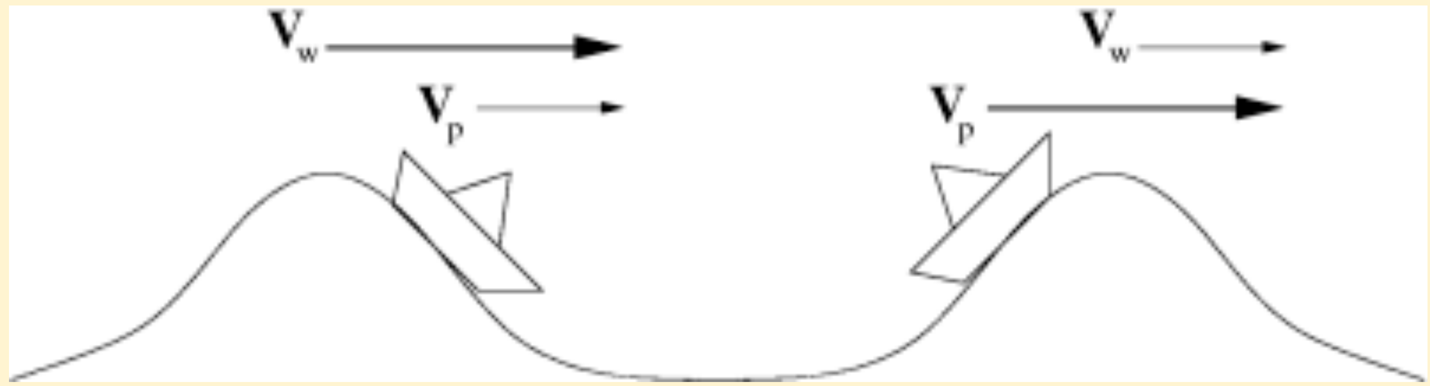

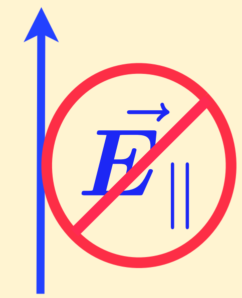

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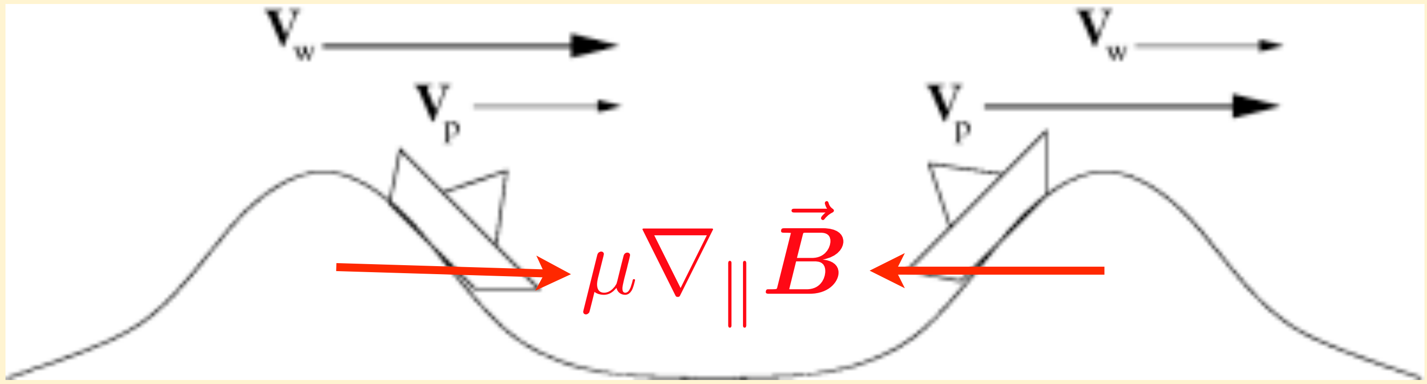

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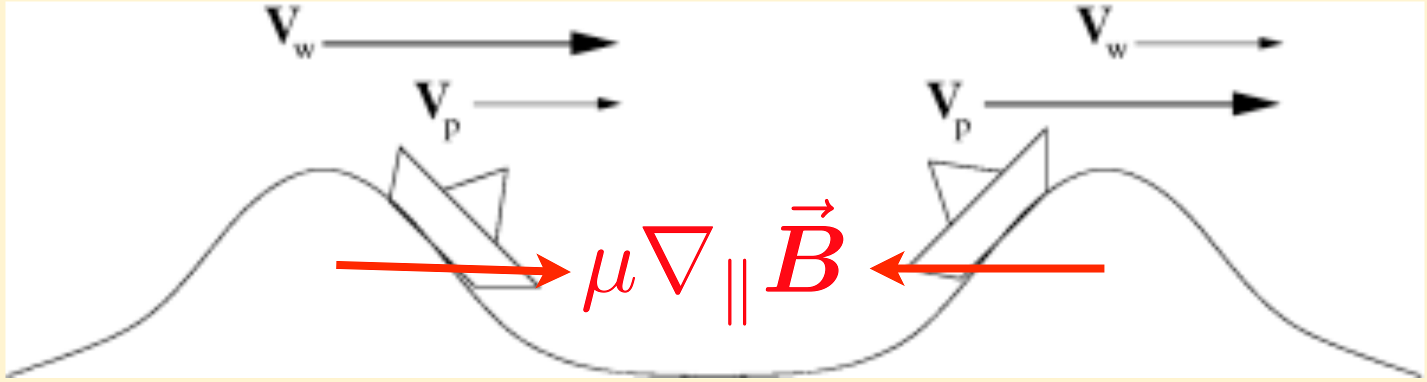

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  - Results in *parallel* heating.

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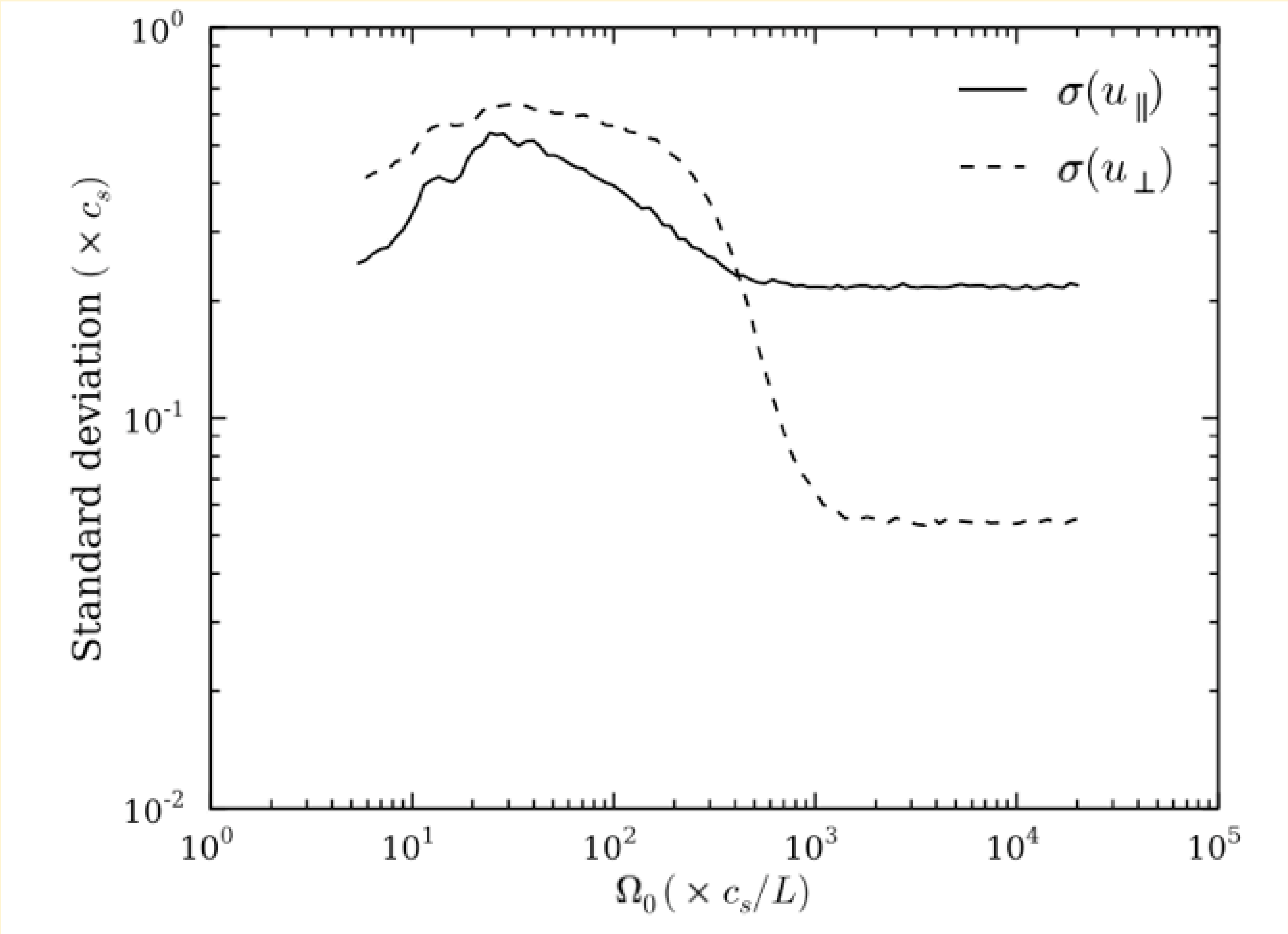
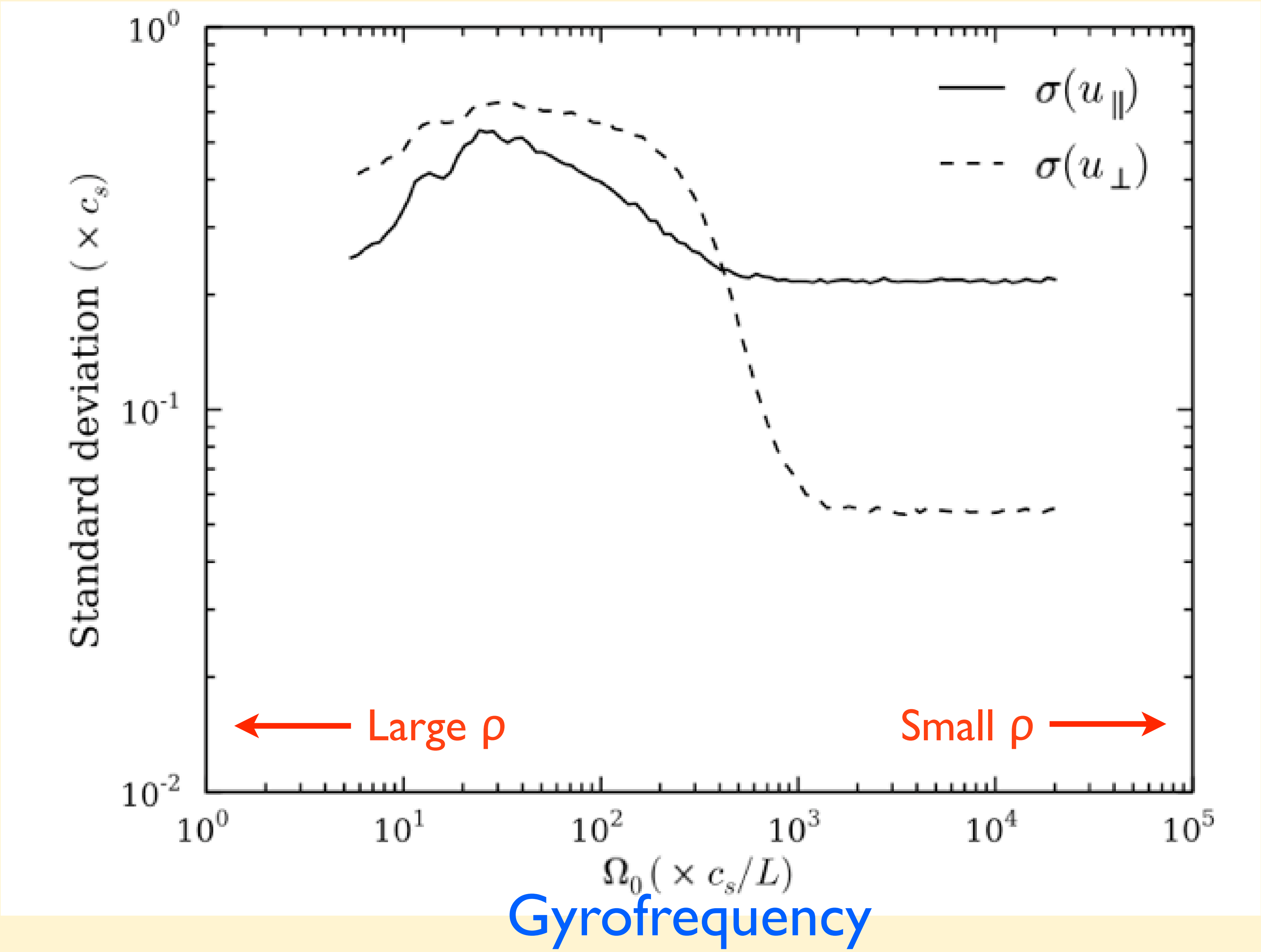
Results: Heating



MHD Simulations (Athena) with test particles:

- MHD: Evolves turbulent cascade $(256)^3$ or $(512)^3$
- Particles feel Lorentz Force: $\dfrac{d\boldsymbol{v}}{dt} = \dfrac{q}{m}\left(\boldsymbol{E} + \dfrac{\boldsymbol{v} \times \boldsymbol{B}}{c}\right)$

Results: Heating



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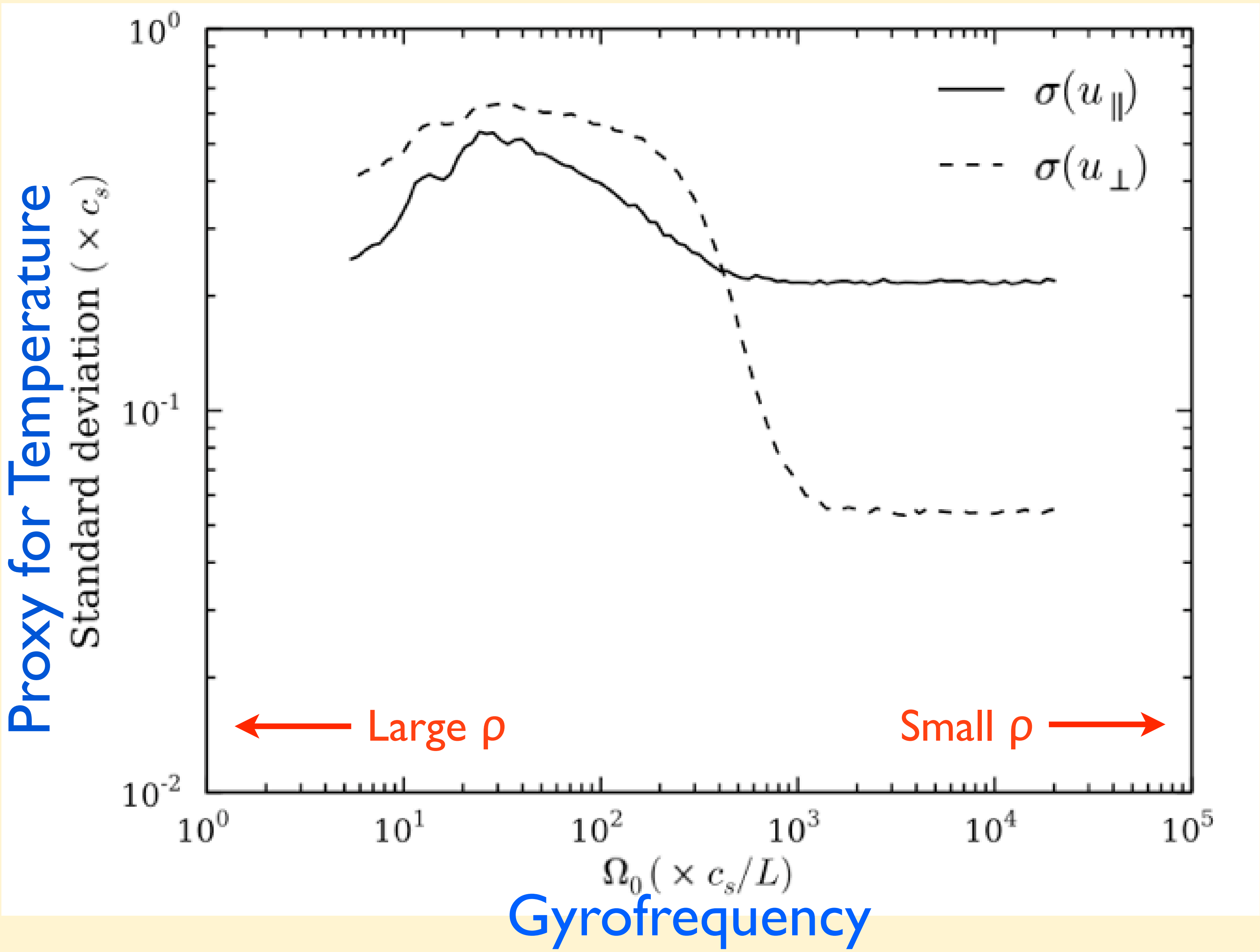

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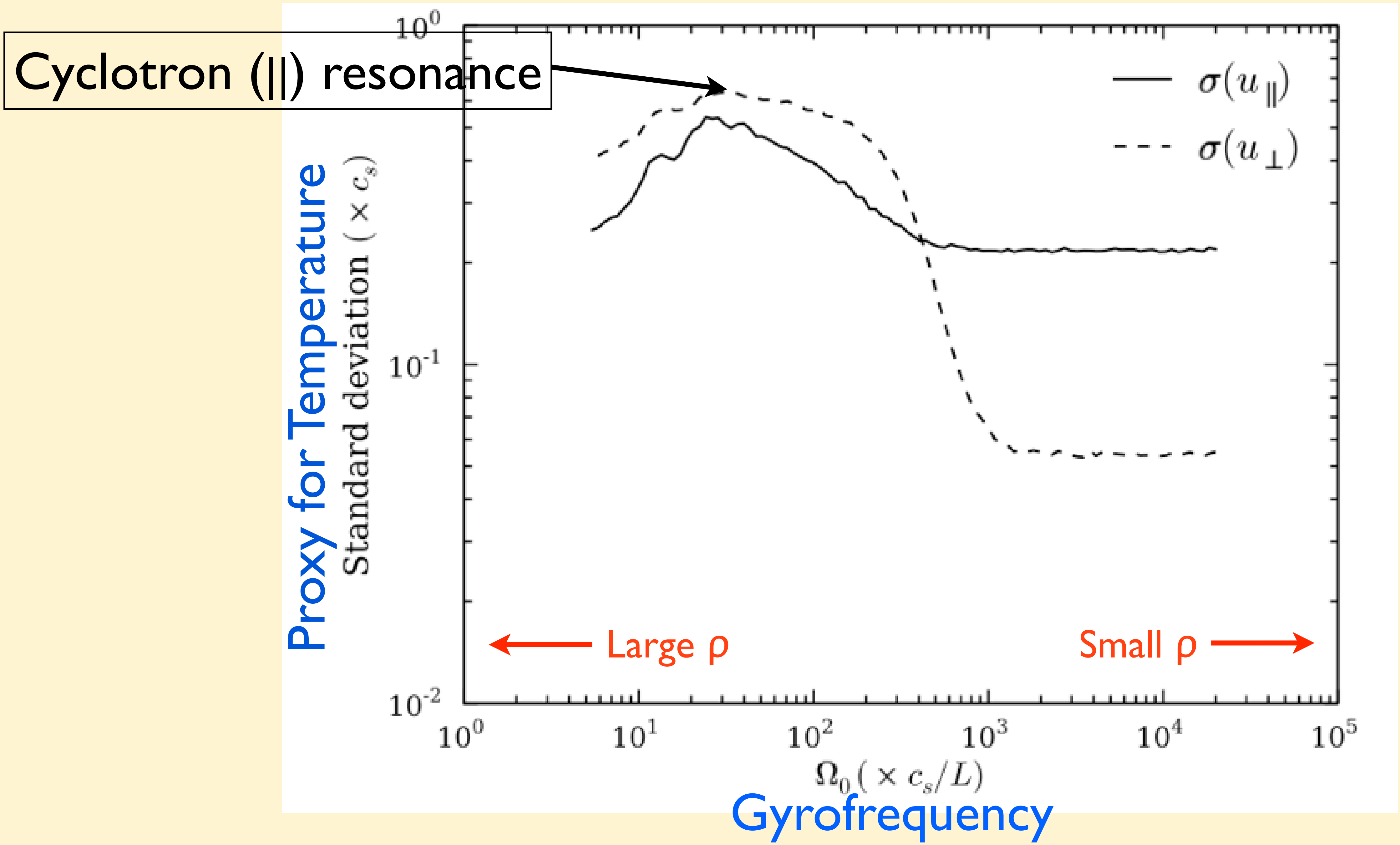

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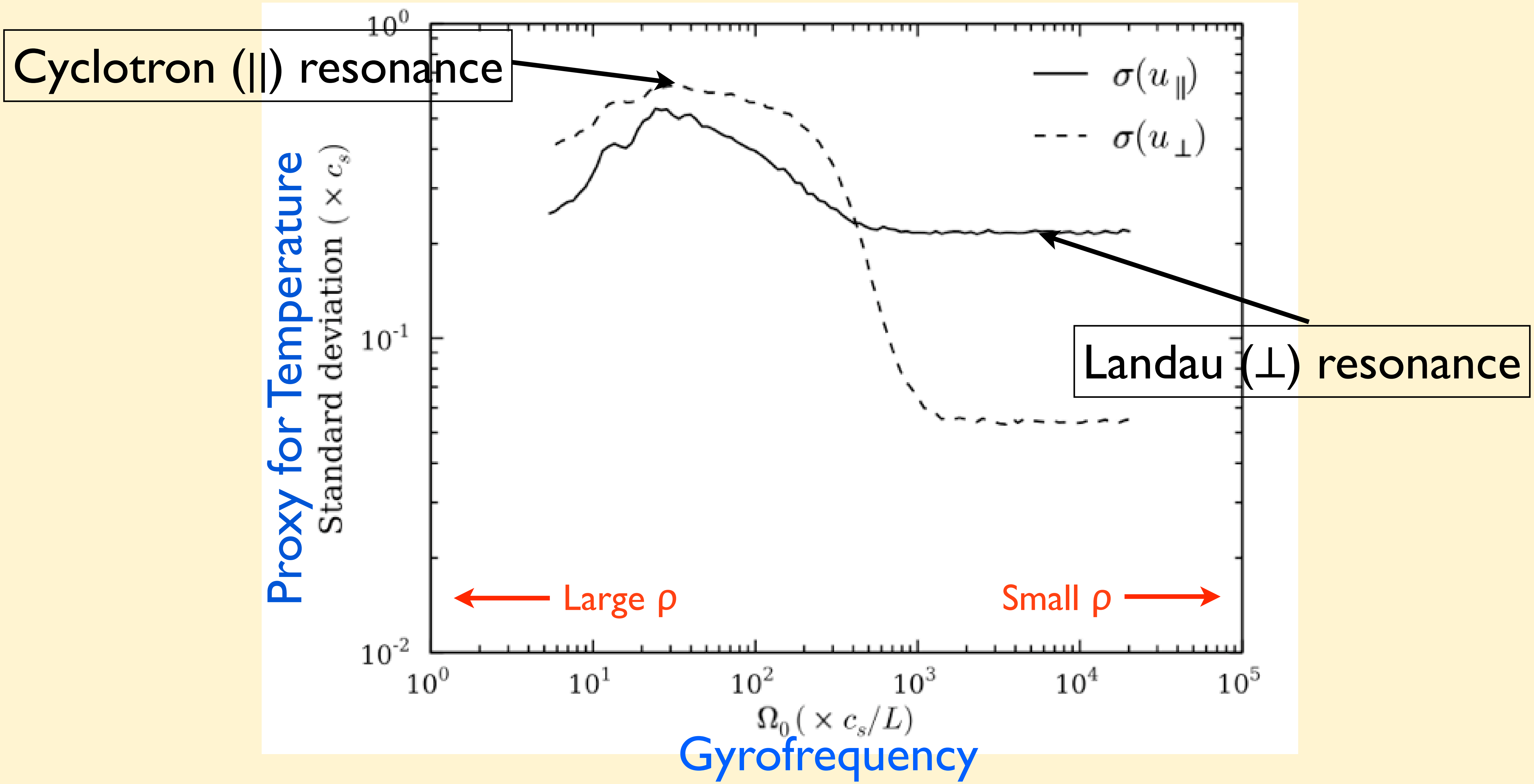

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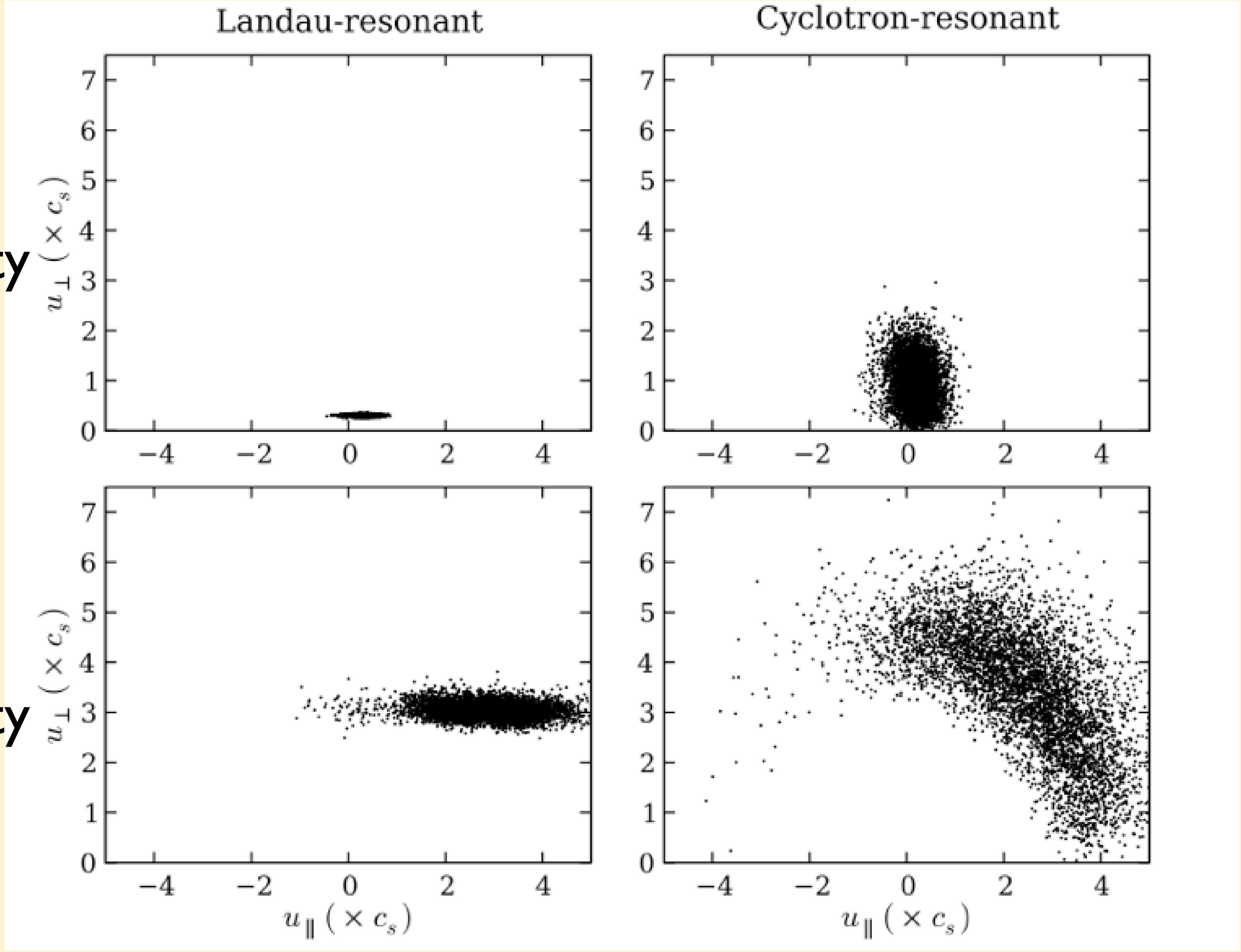
Results: Scattering

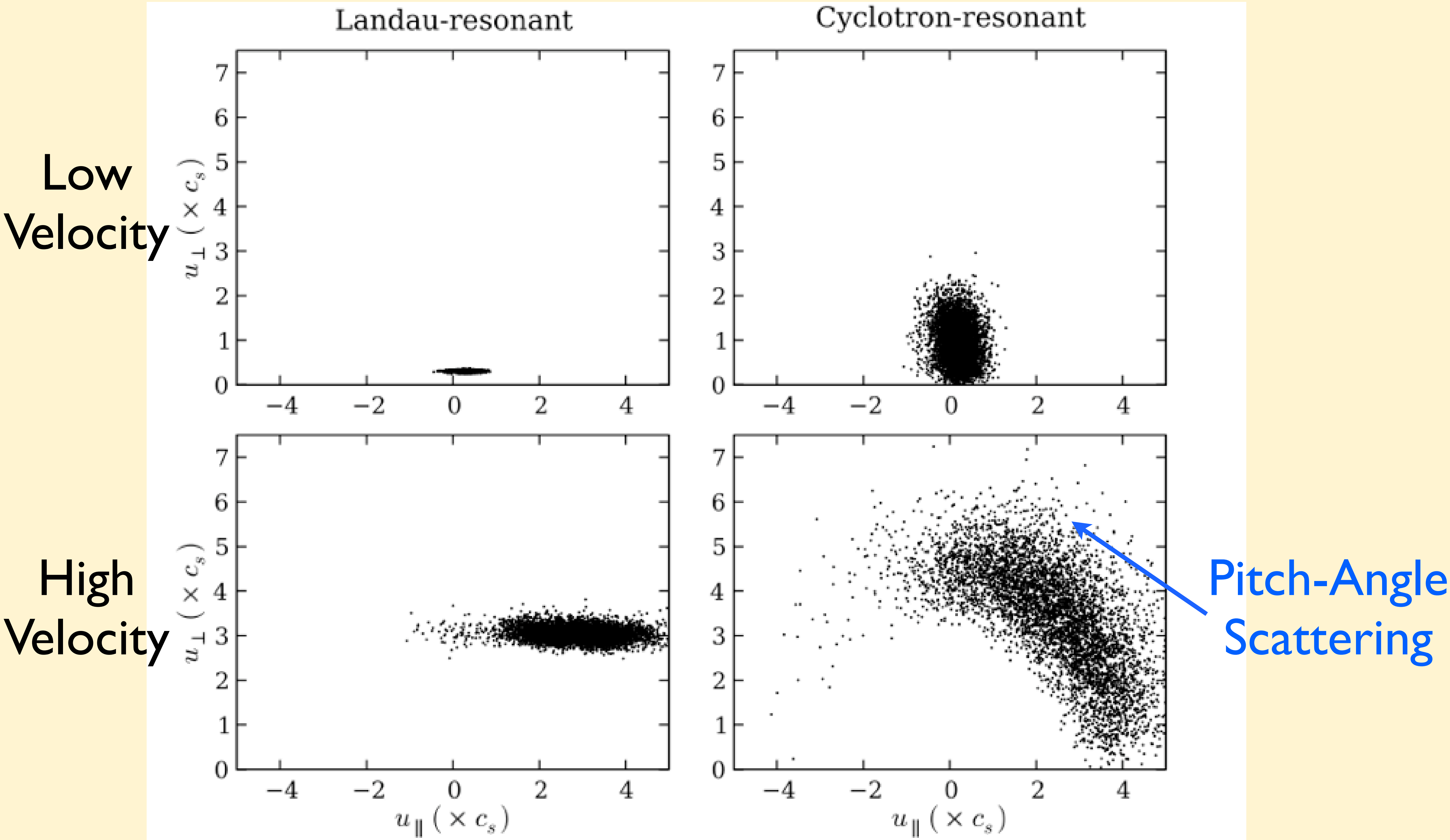
Low Velocity

High Velocity



Initial Condition: Delta Function in $u_\perp$, $u_\parallel$.

Results: Scattering



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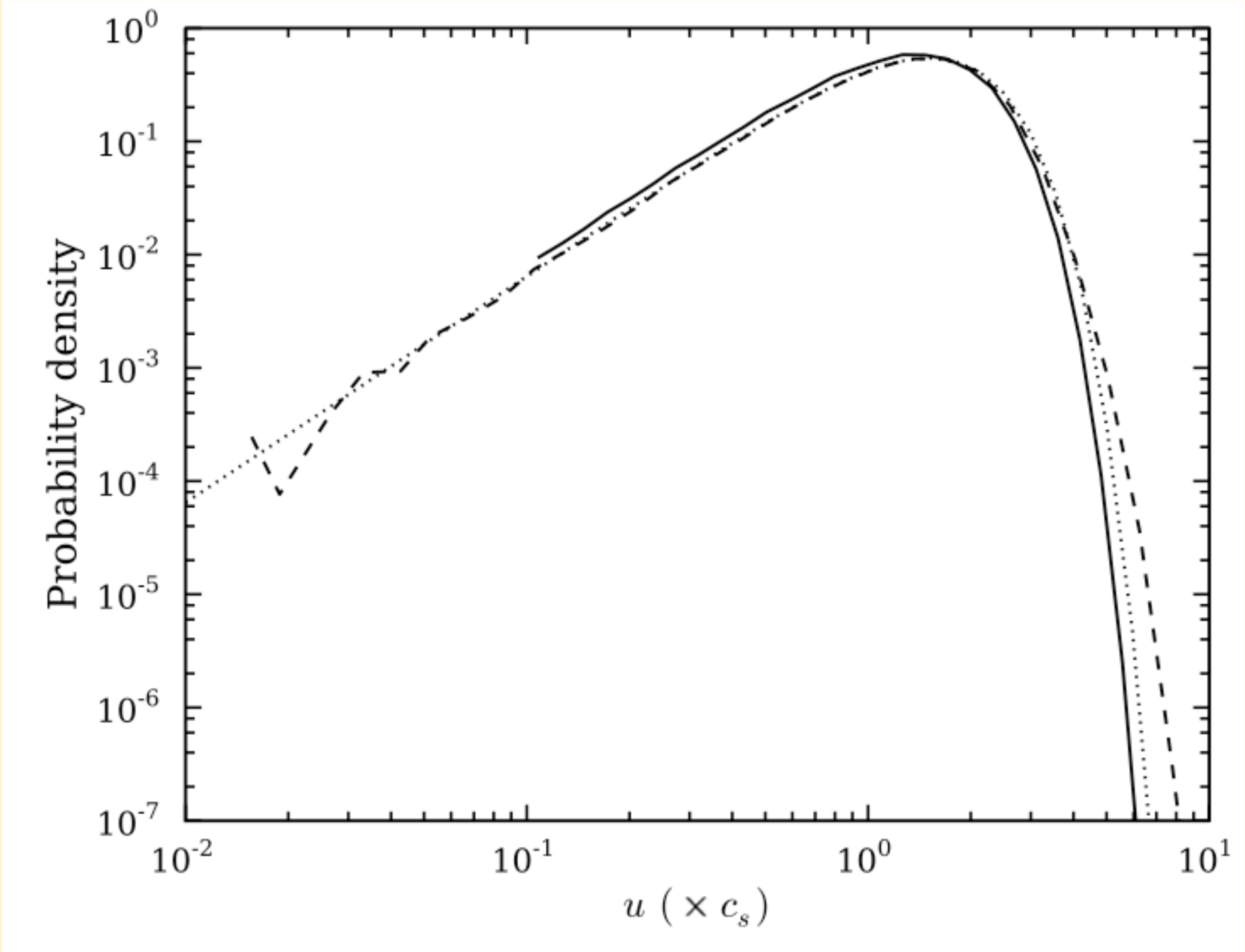
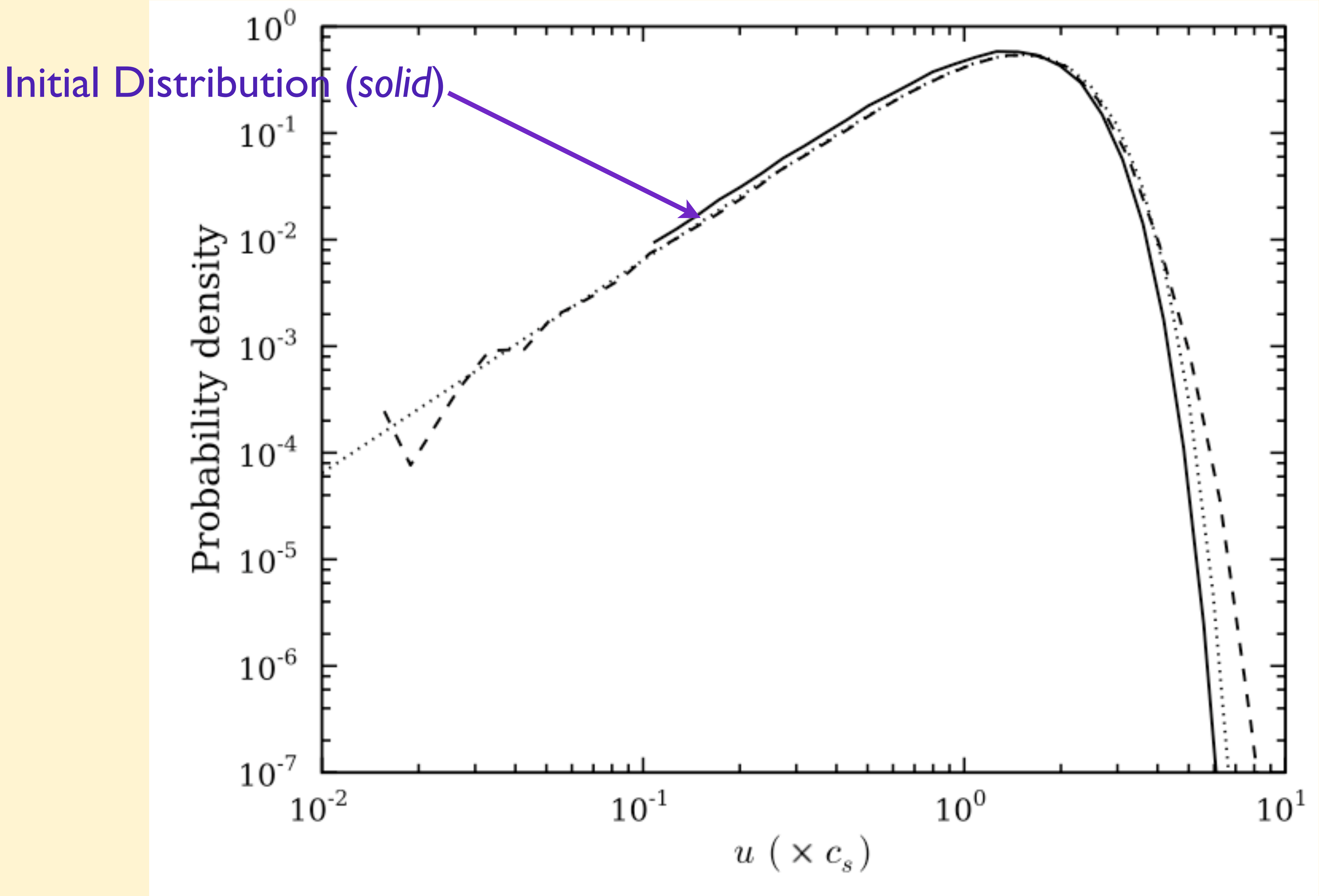
Results: Non-thermal Heating



Cyclotron Resonant Particles

Results: Non-thermal Heating



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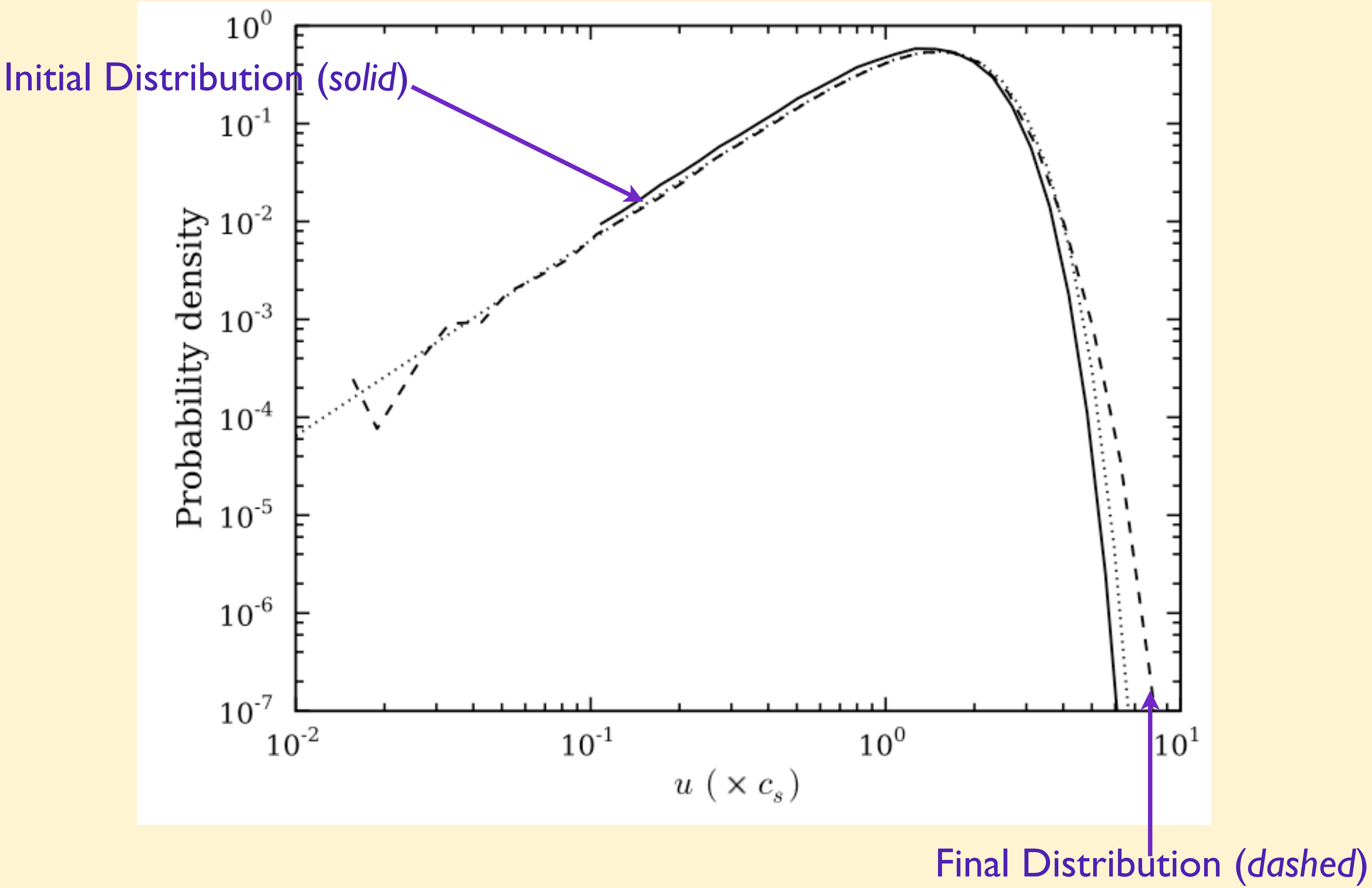

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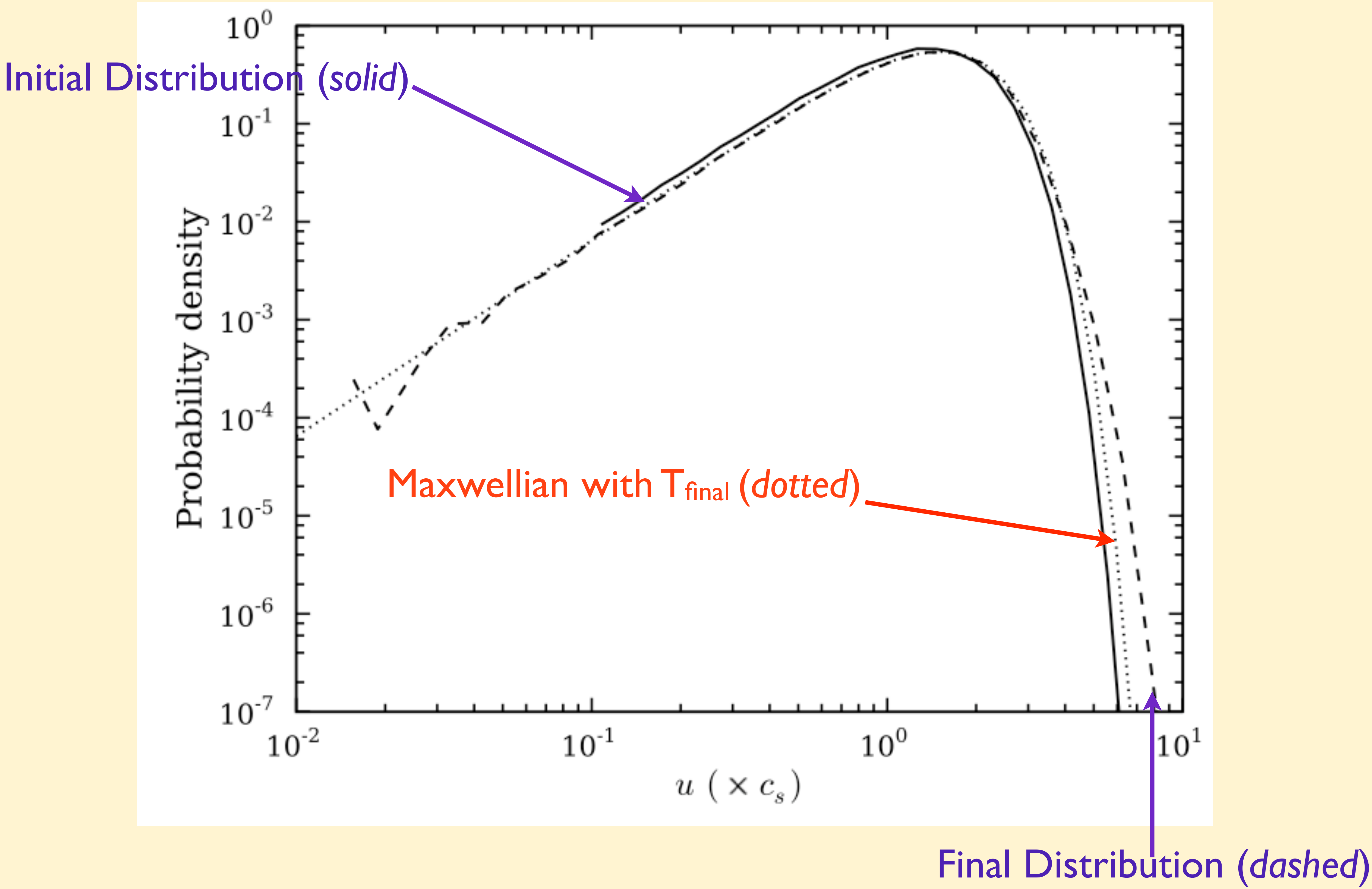
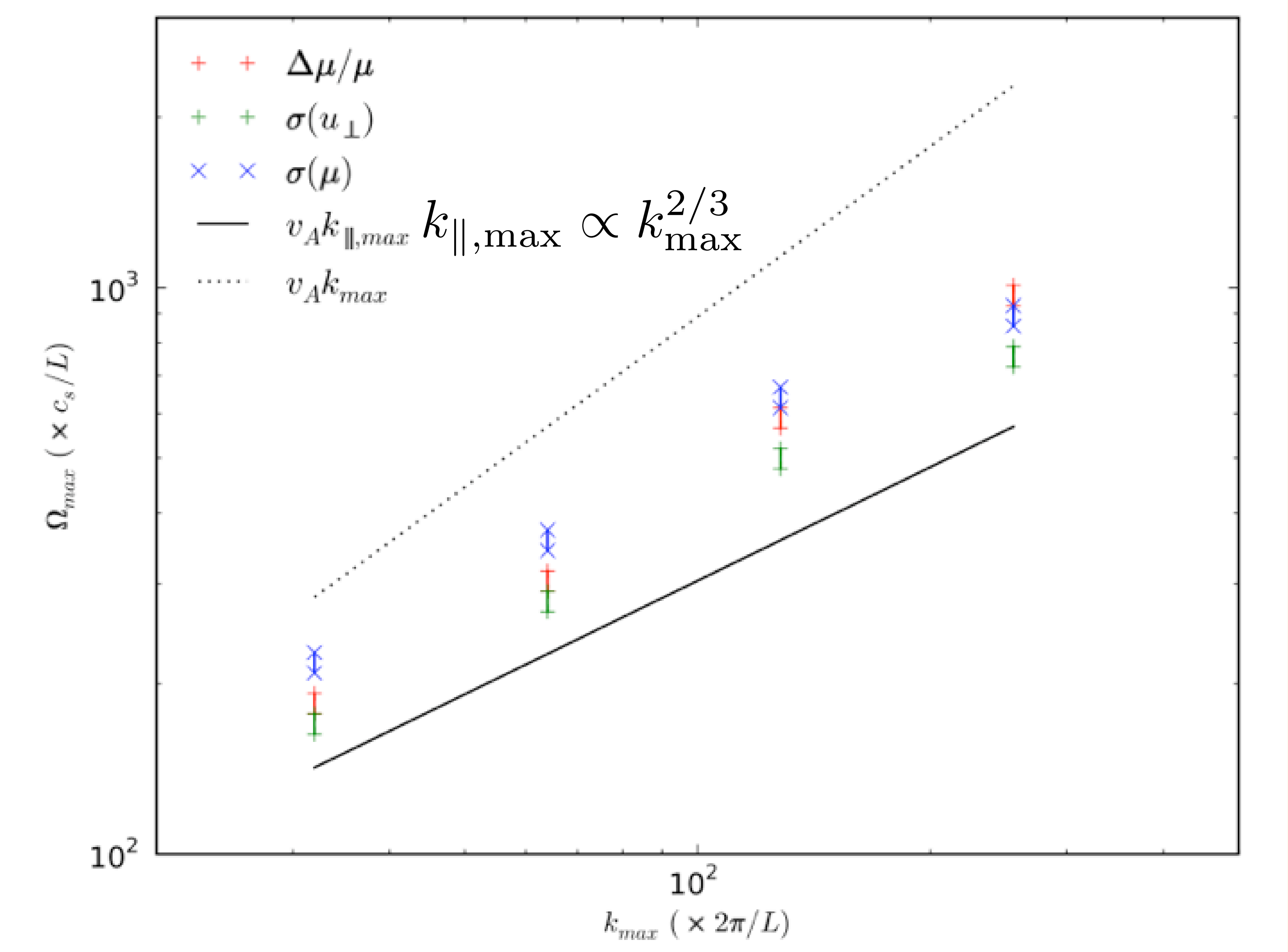


Cyclotron Resonant Particles

Heating in the Solar Wind



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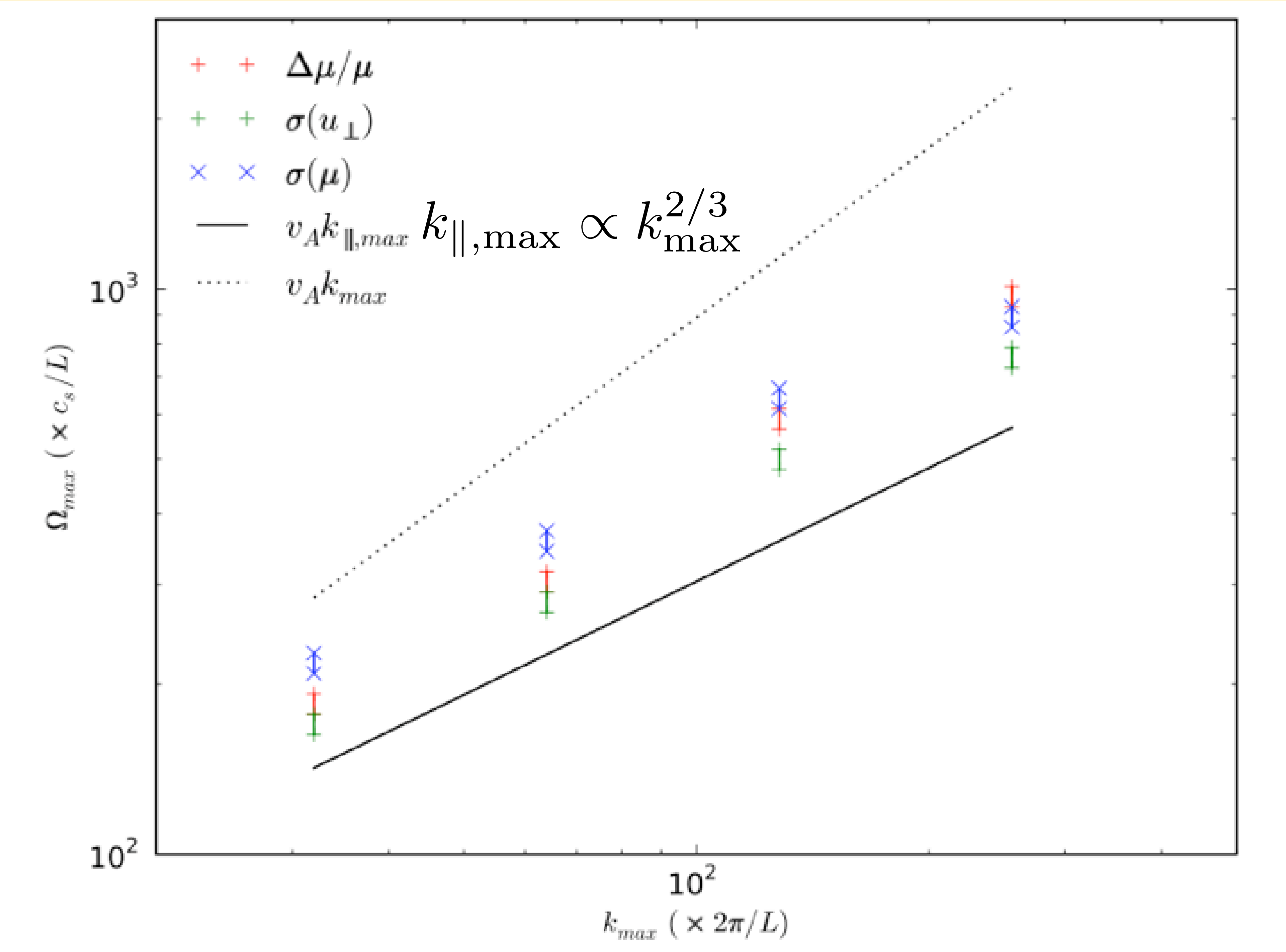
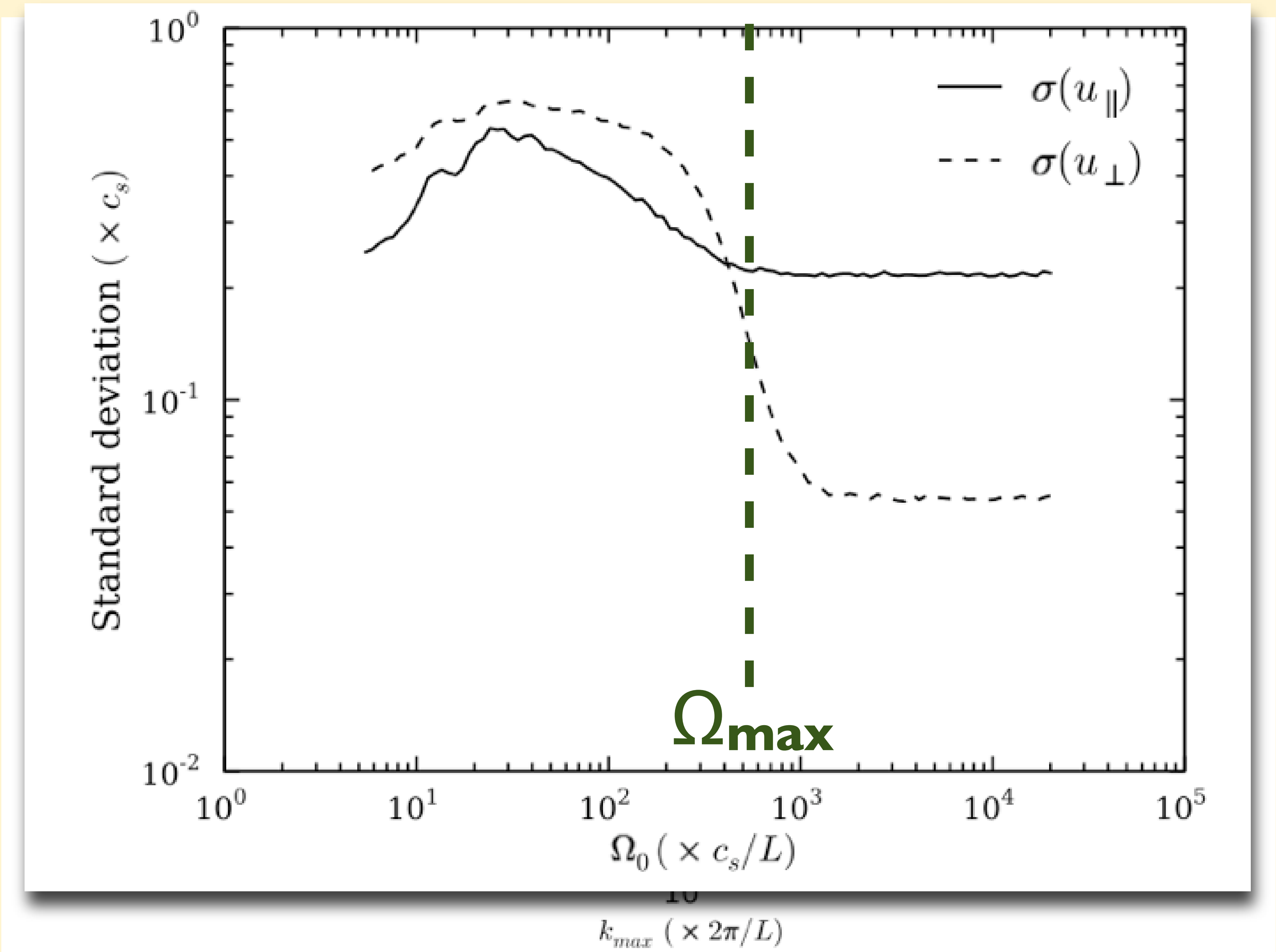


Solar wind near 1 AU: $\rho_p \sim 3 \times 10^6\,\mathrm{cm}; \quad \Omega_p \sim 0.15\,\mathrm{Hz}$

$\rho_e \sim 1 \times 10^5\,\mathrm{cm}; \quad \Omega_e \sim 300\,\mathrm{Hz}$

Heating in the Solar Wind



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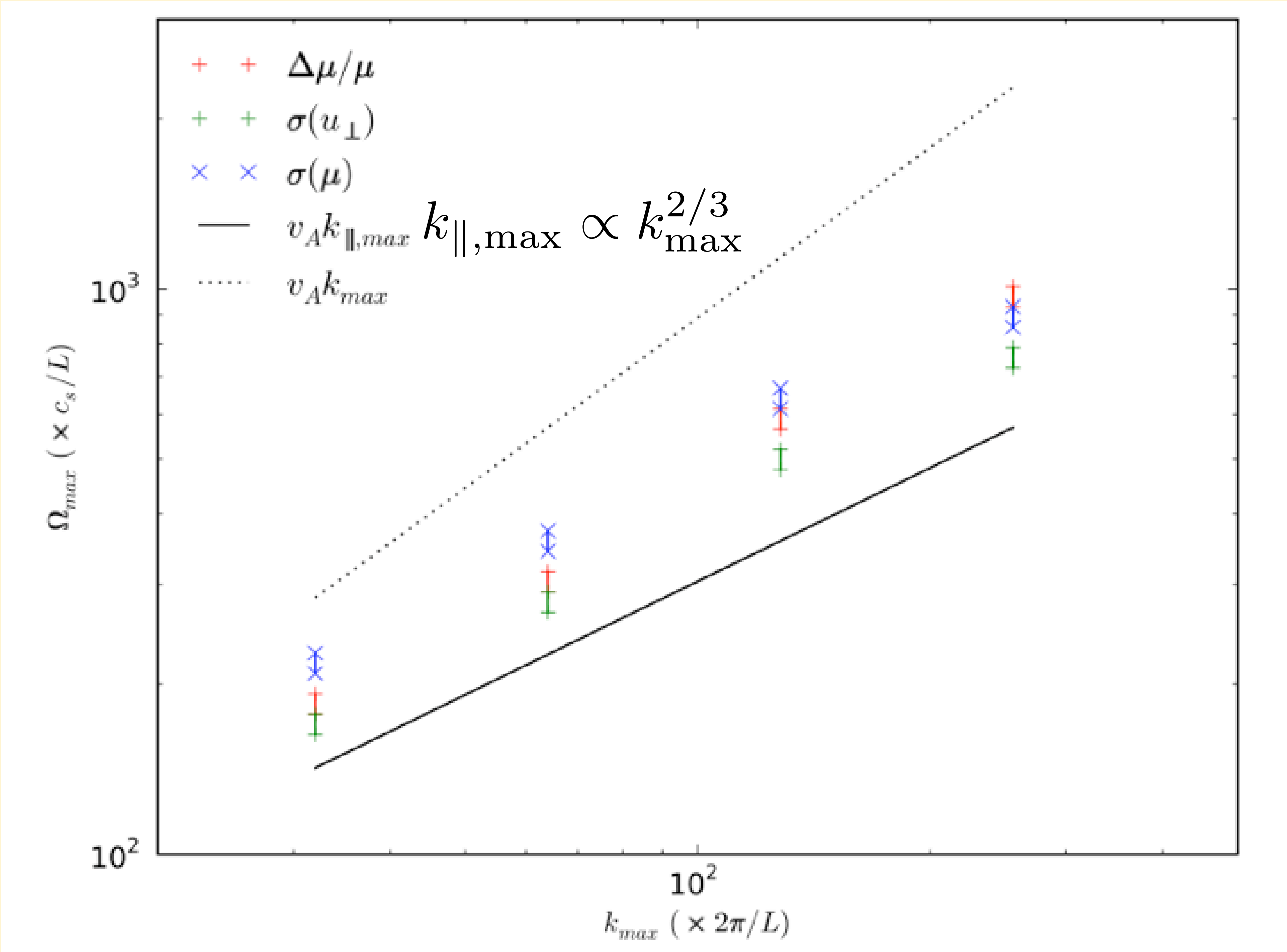
Heating in the Solar Wind



Solar wind near 1 AU: $\rho_p \sim 3 \times 10^6\,\mathrm{cm}; \quad \Omega_p \sim 0.15\,\mathrm{Hz}$

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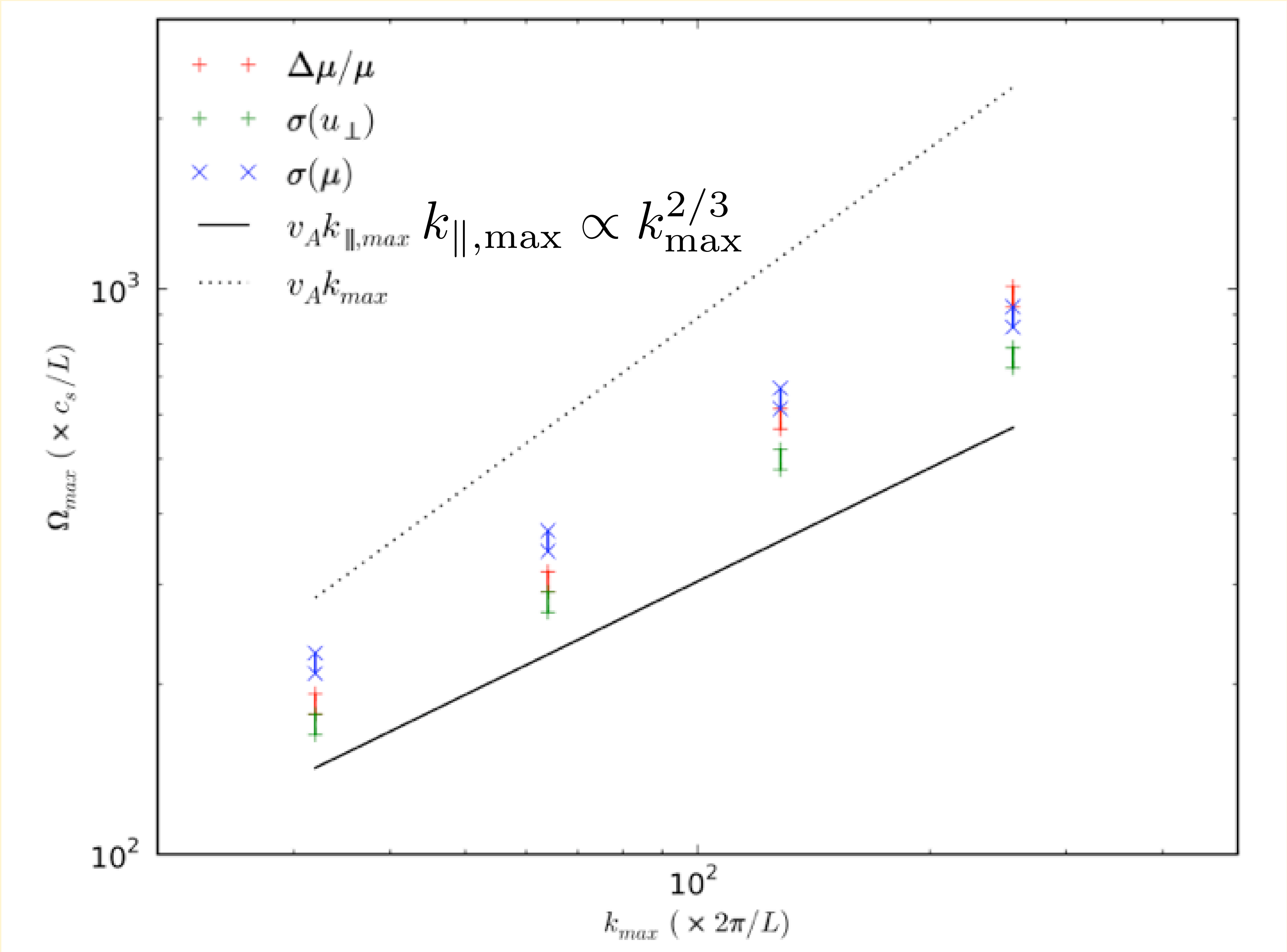

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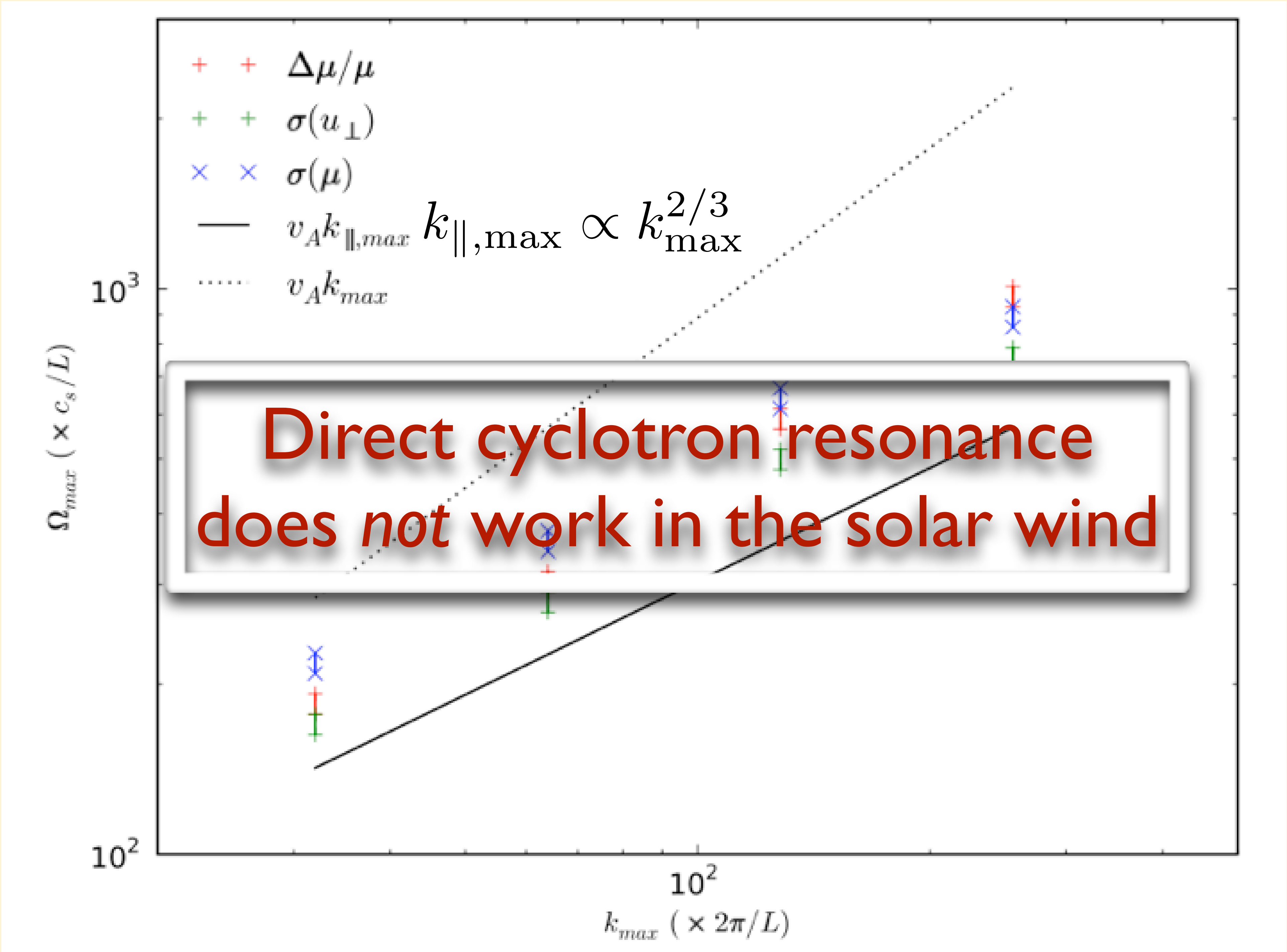

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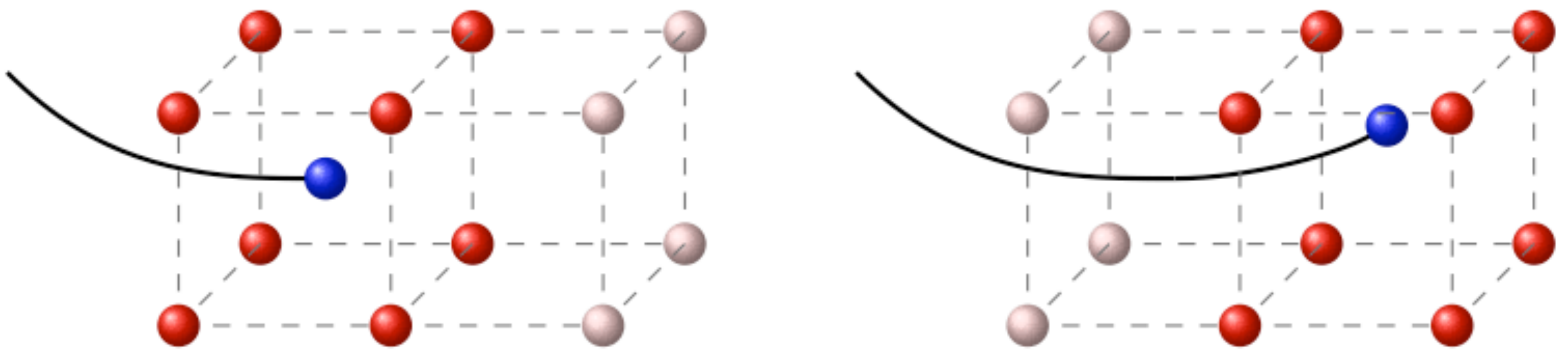
Thanks to:
- Chandra/Einstein Fellowship & Staff
- Teragrid for lots of CPU hours.

Supplemental Material

Interpolation Methods

$\vec{E}$ and $\vec{B}$ are interpolated by averaging over the nearest nodes.



Averaging weights

- Must ensure the continuity of $\vec{E}$ and $\vec{B}$
- TSC method $\Rightarrow \vec{E}, \vec{B}$ are $\mathcal{C}^1$

Parallel component of $\vec{E}$

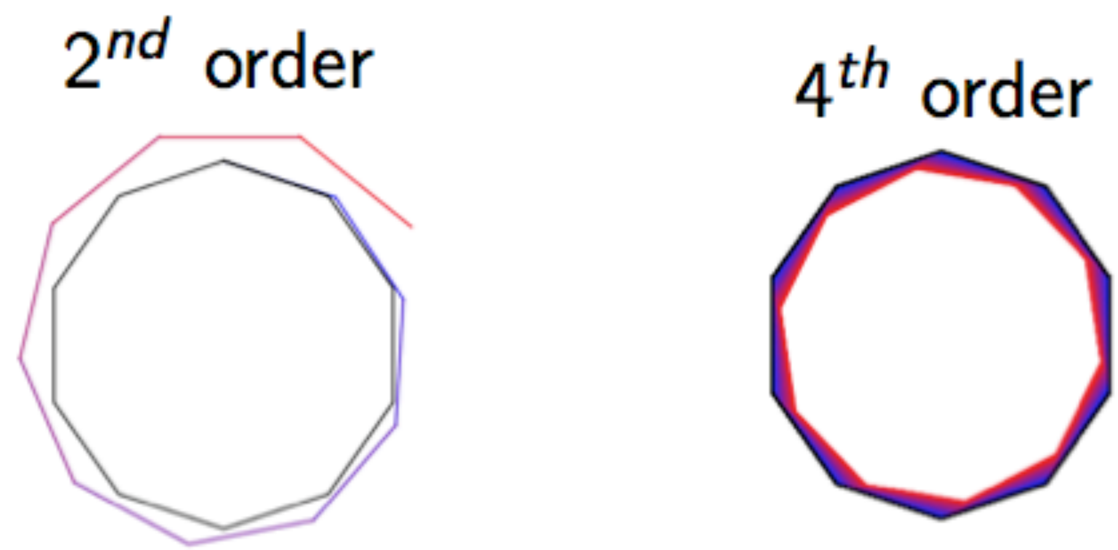
- Ideal MHD: $\vec{E} = -\frac{1}{c}\vec{v} \times \vec{B} \quad \Rightarrow \quad E_{\parallel} = 0$
- One needs to enforce $E_{\parallel} = 0$, after the interpolation.

Particle Integration Method

How to discretize $\frac{d\vec{u}}{dt} = \frac{q}{m}\vec{E} + \frac{q}{mc}\vec{u} \times \vec{B}$?

Runge-Kutta methods

The energy is not conserved!



Boris pusher

- The energy is exactly conserved.
- Only requires 1 interpolation per integration step.