Heating and Acceleration in Alfvenic Turbulence

Rahul Kumar

PRINCETON UNIVERSITY

MPPC Max-Planck-Princeton Center for Plasma Physics

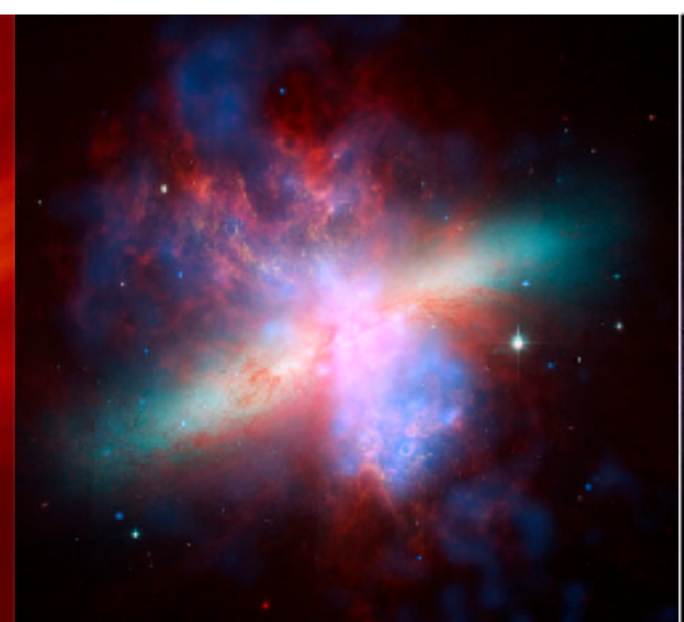
Turbulence in Magnetized Plasmas

Heliosphere: Turbulent heating of Solar corona and wind

Astrophysics: Transport and heating properties of plasma in interstellar medium, galaxy clusters, …

Sun and Heliosphere

Galactic wind



Galaxy Clusters

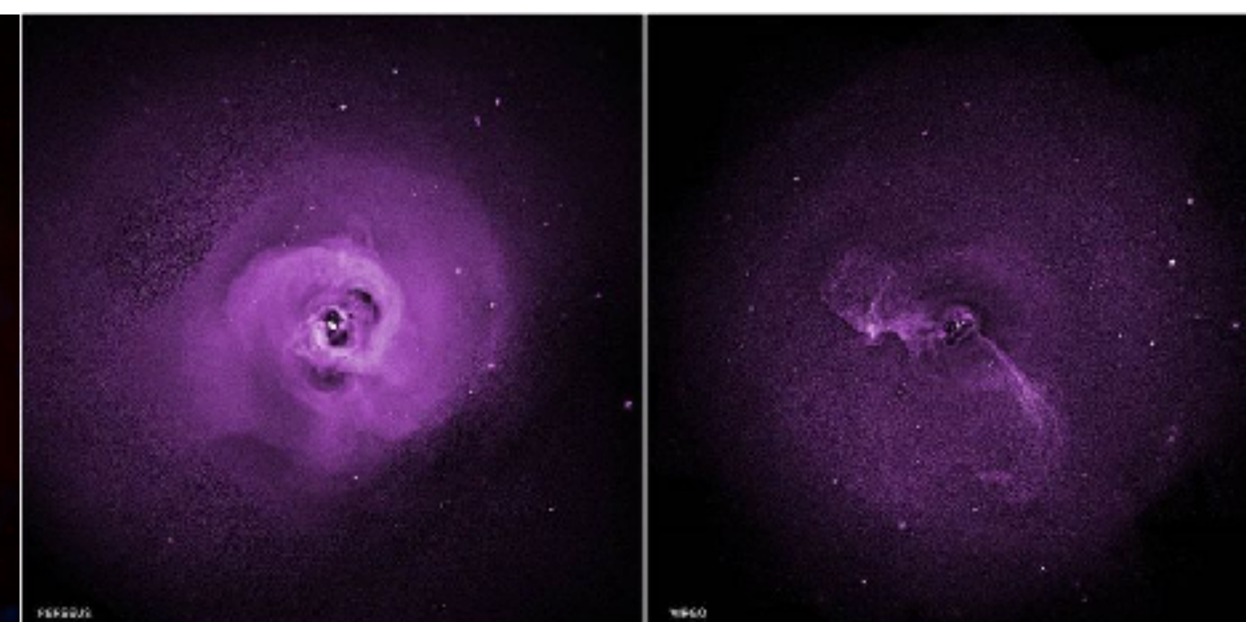


Image source: web

Questions

Nature of turbulence

Spectrum of fluctuations: $\delta B, \delta\rho, ..$

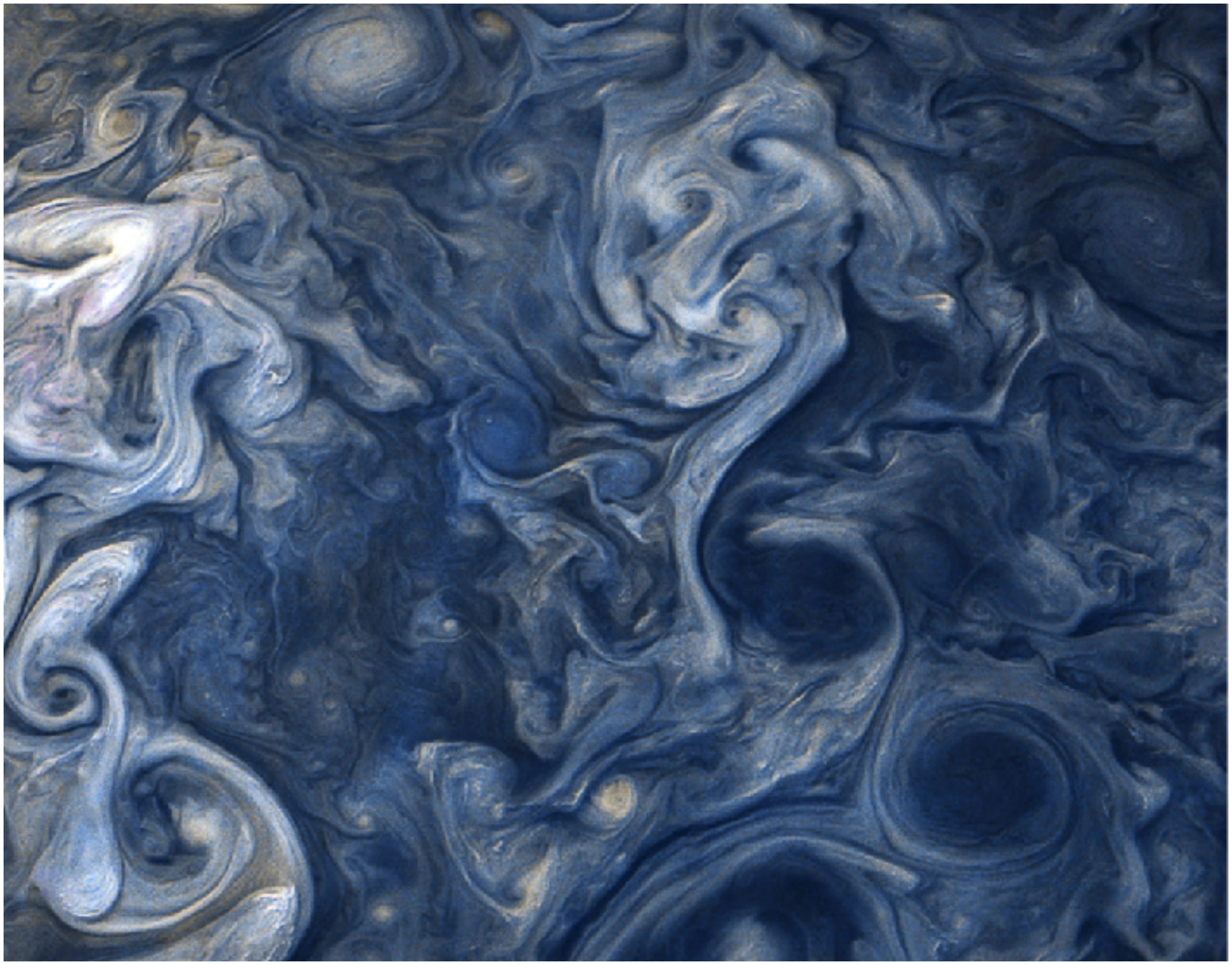
Energy dissipation precesses

Cyclotron damping, transit time damping, reconnection ..

For collisionelss plasmas dissipation occurs at the kinetic scales of the ions and electrons

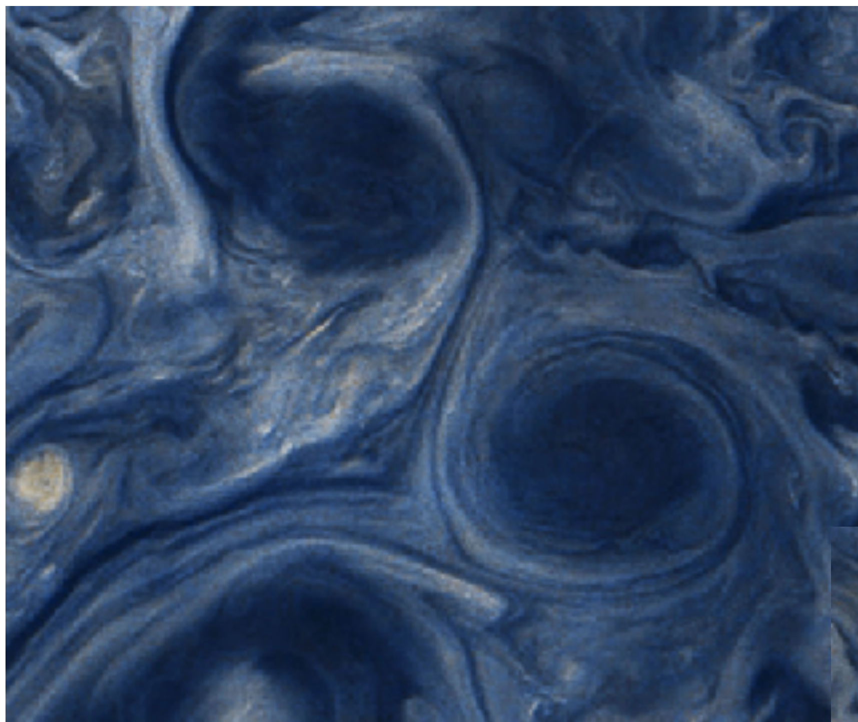
This talk: Heating and acceleration of heavy ions

Hydrodynamical Turbulence



Polar vortices on Jupiter

Kolmogorov Turbulence



Interaction time $\tau \sim l/v$

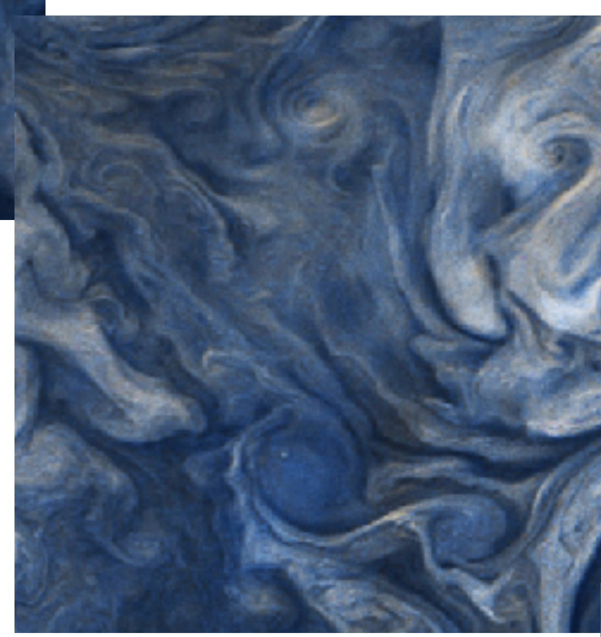
Energy transfer rate $\sim v^2/\tau \sim v^3/l$

$\shortparallel$

constant = the dissipation rate

Kolmogorov's Hypothesis

⇘



$$v \sim l^{1/3}$$

or

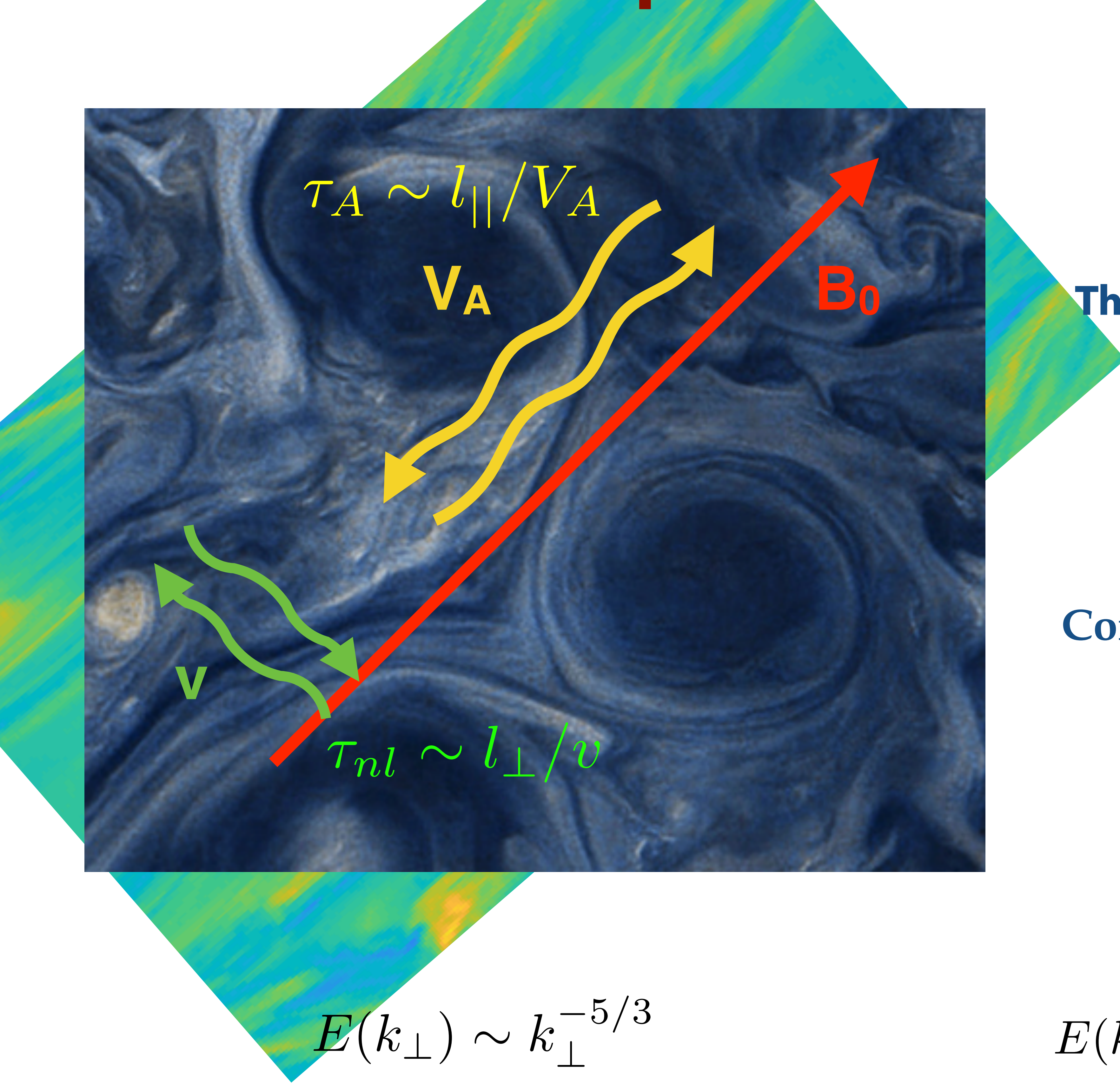
$$E(k) \sim k^{-5/3}$$

Energy cascade

k

Dissipation

Anisotropic MHD Turbulence



The critical balance hypothesis

Goldreich & Sridhar

$$\tau_{nl} \sim \tau_A$$

Consequently,

$$l_\perp \sim l_{||} v / V_A$$

$$E(k_\perp) \sim k_\perp^{-5/3}$$

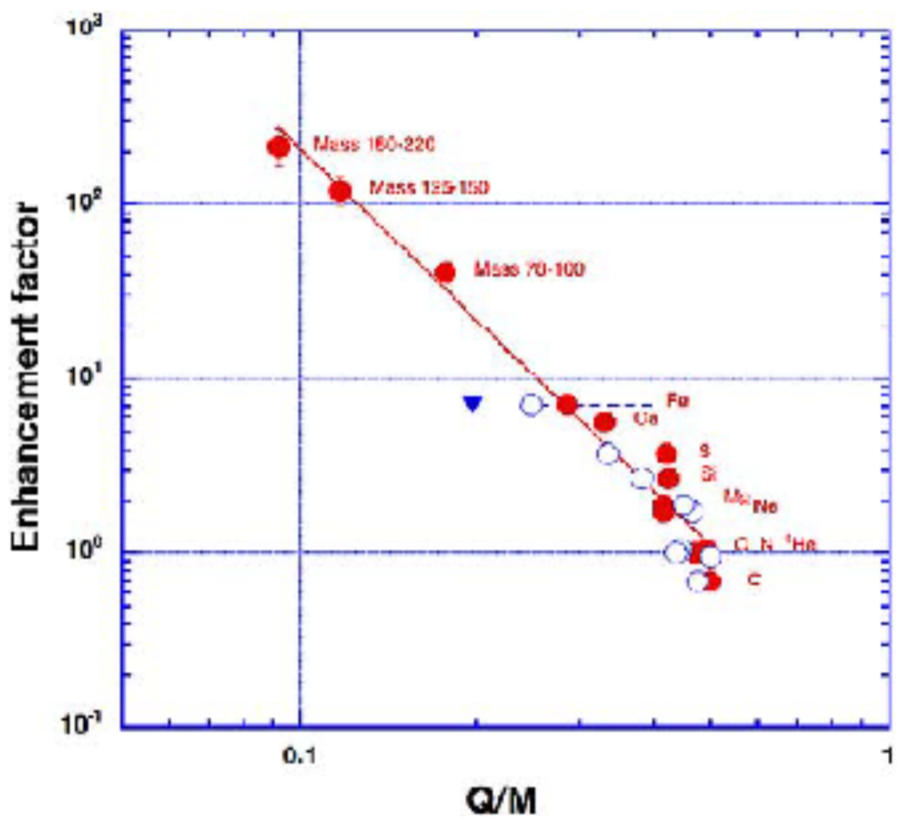
Perpendicular power spectrum

$$E(k_{||}) \sim k_{||}^{-2}$$

Parallel power spectrum

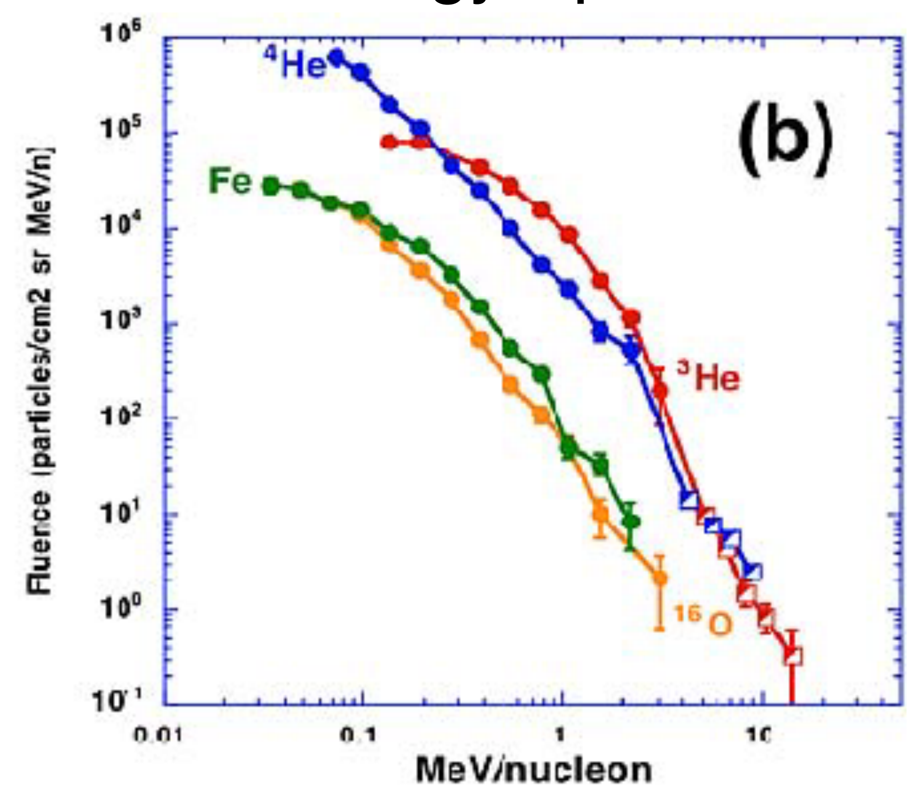
Heating and Acceleration of Heavy Ions

Impulsive Solar Flares



Mason et al., ApJ 2004

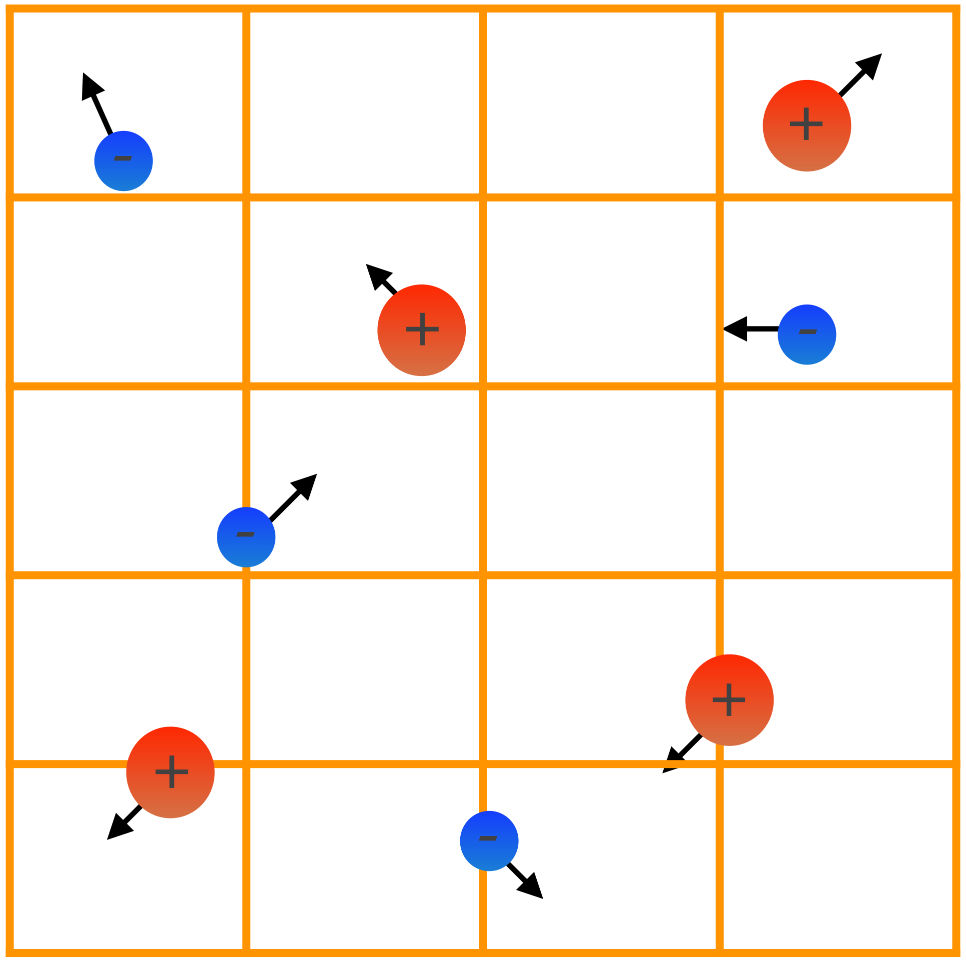
Energy Spectrum



Mason et al., ApJ 2002

Is it due to Cyclotron damping of Alfvenic turbulence?

Particle-in-Cell Method



Maxwell's equations

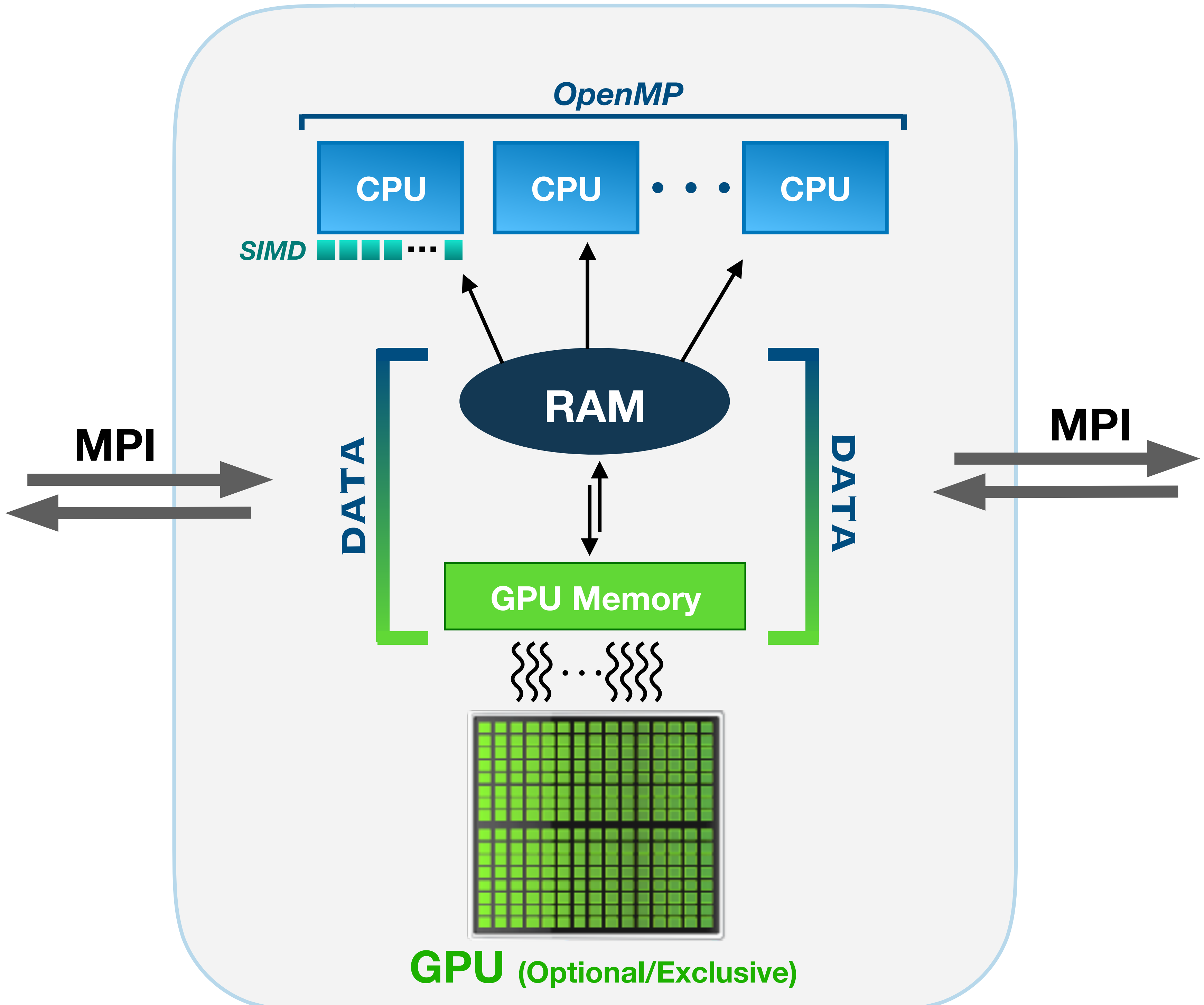
$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}\right)$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho \qquad \nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

Lorentz force

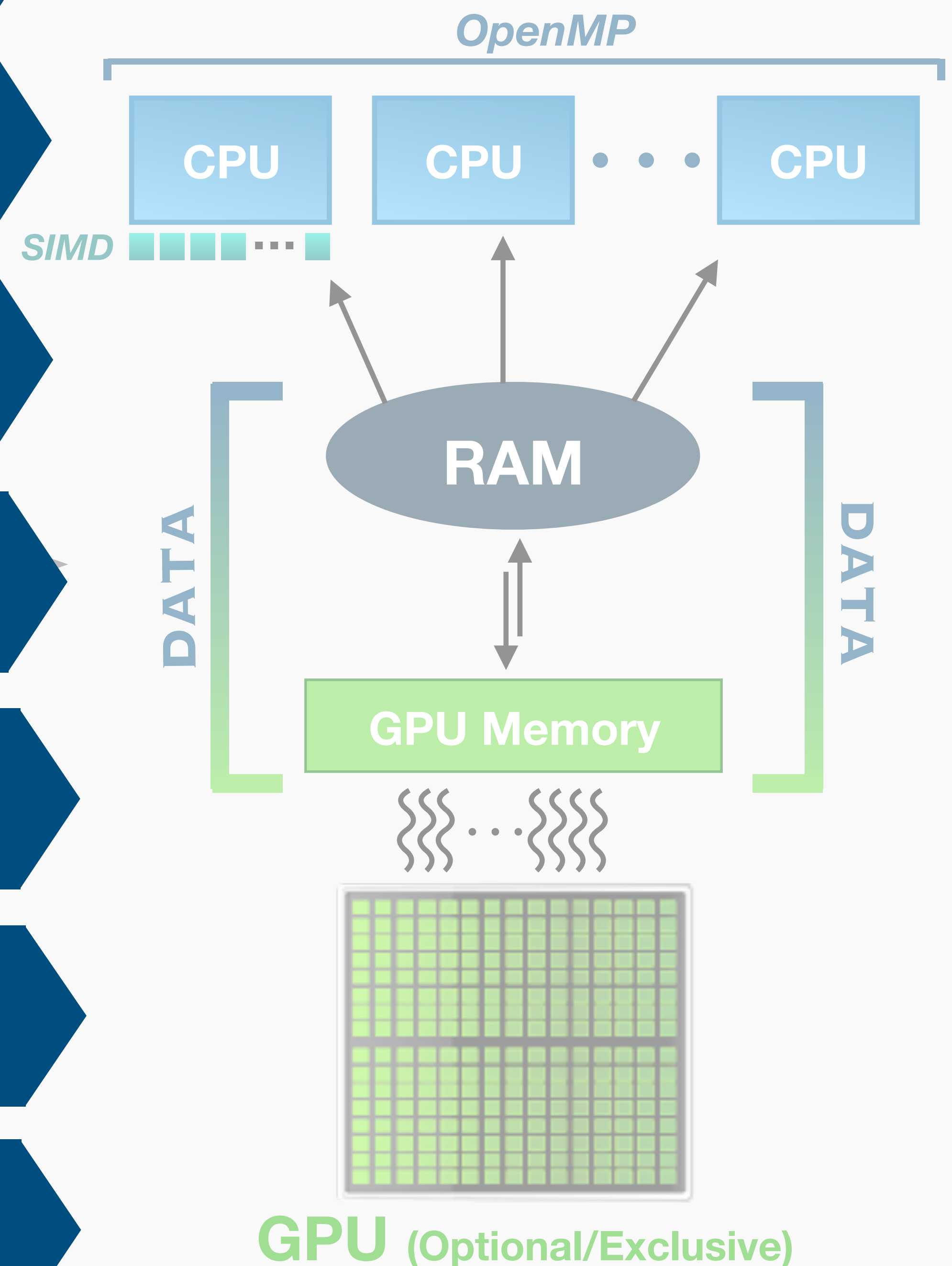
$$\vec{F} = q(\vec{E} + \frac{\vec{v}}{c} \times \vec{B})$$

PICTOR Particle-in-Cell Code



PICTOR Particle-in-Cell Code

- Precision Control
- Dynamic Load Balancing
- Machine Level Optimization
- Cache Usage Optimization
- Memory Usage Optimization
- OpenMP+SIMD+GPU
- MPI + Parallel HDF5



- Multiple Species
- Test Particles
- Particle Tracking
- Moving/Fixed Boundaries
- Comprehensive Output
- Simple/Flexible Setup
- Shock, Turbulence, ..

Numerical Simulation

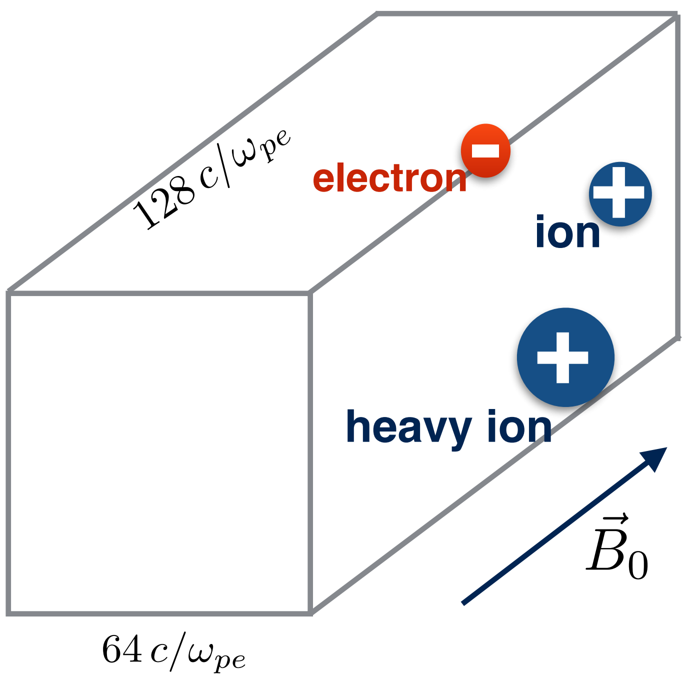
Three dimensional electromagnetic
particle-in-cell simulations

Counter propagating shear Alfven waves
(six modes)

electron-positron plasma + Heavy ions

Heavy ions are treated as test particles

Initial velocity distribution is
Maxwellian + local drift (ExB and
polarization drift)



$$\delta B_{rms}/B_0 = 1/3$$

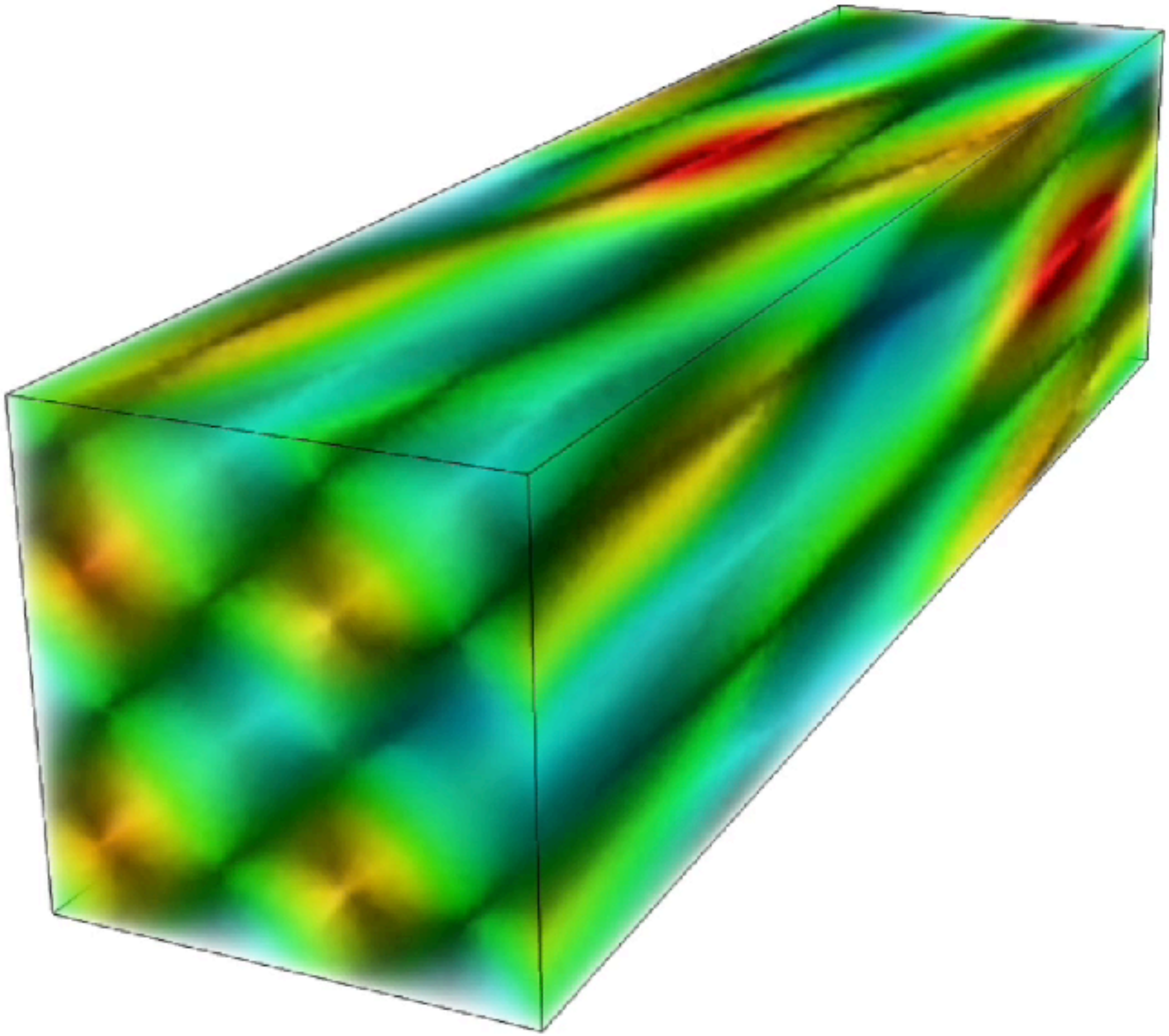
$$V_A = 0.1\,c$$

pasma beta =1/3

12 particles/cell-species

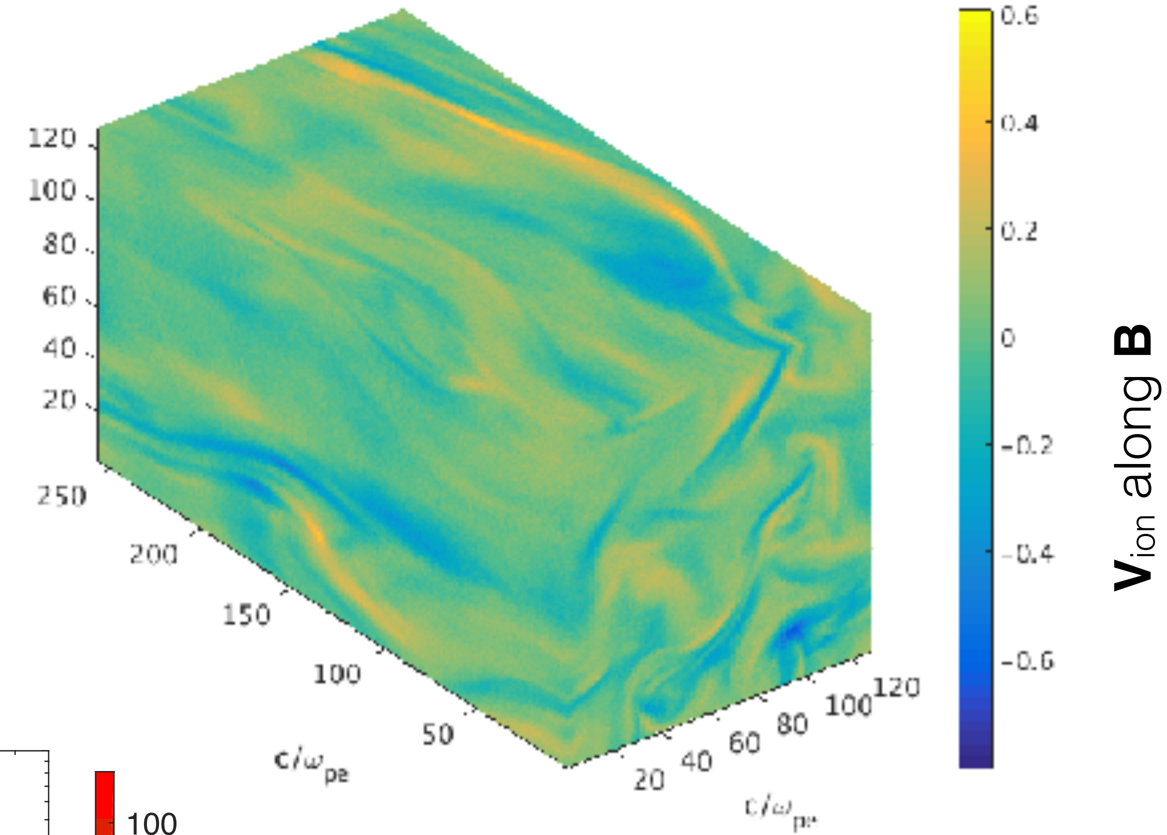
Anisotropic Turbulent Cascade

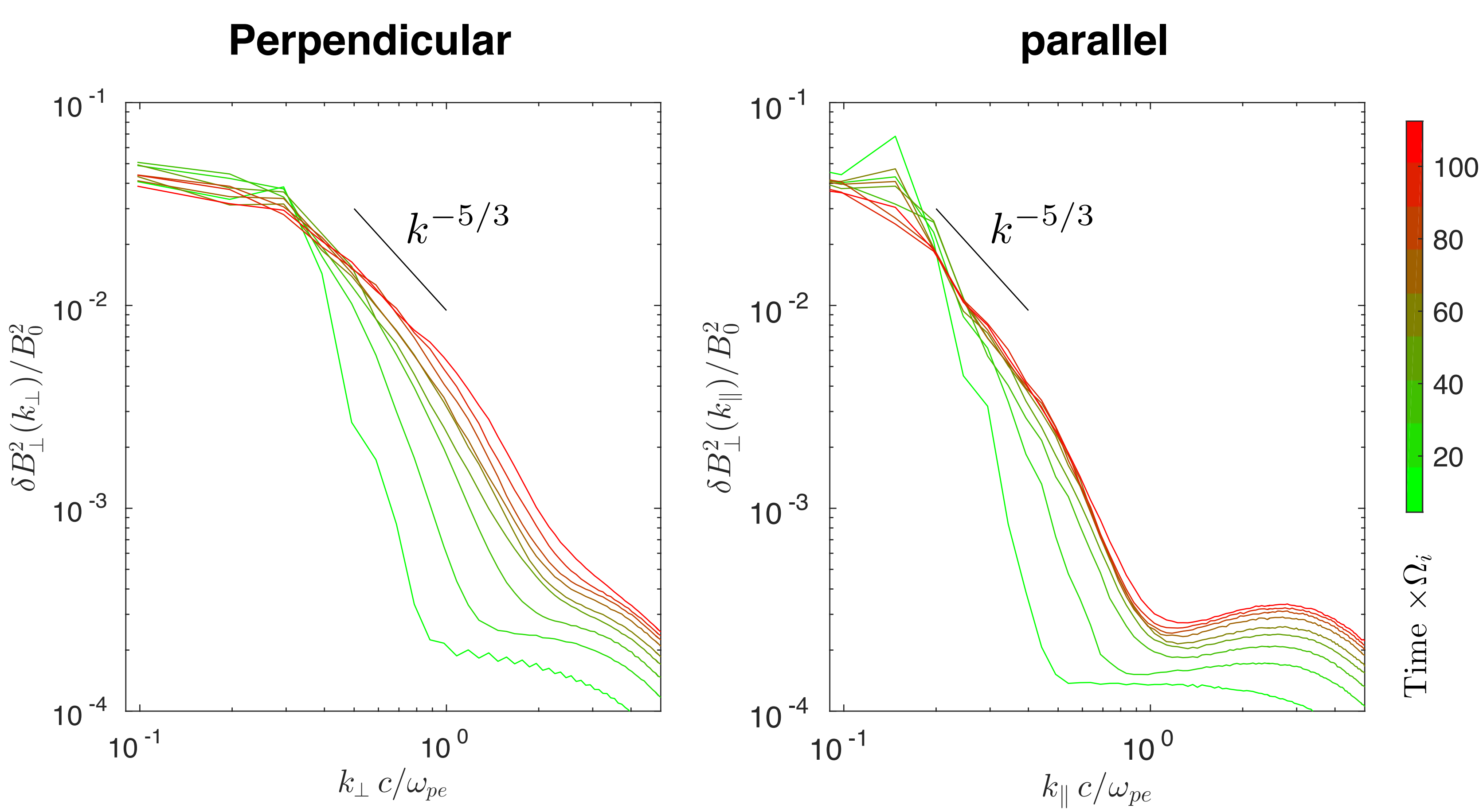
Parallel Velocity



Anisotropic turbulence

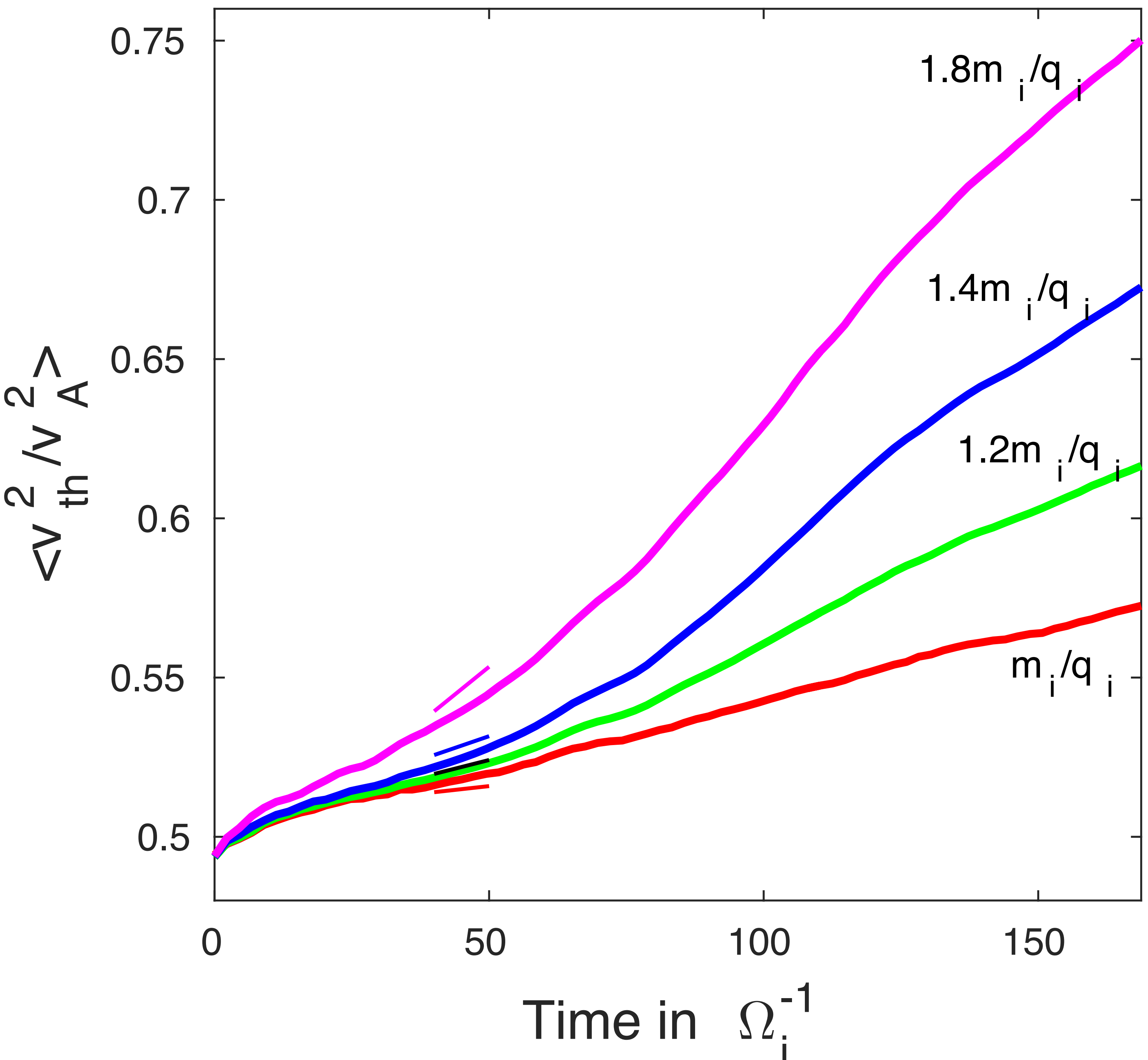
Energy cascade generates elongated turbulent eddies parallel to the mean magnetic field





One dimensional power spectrum is steeper along the mean magnetic field !

Average Energy/Mass Vs. Time



$$\vec{v}_{th} = \vec{v} - \vec{E} \times B_0 \hat{x} / B_0^2$$

Resonance Condition

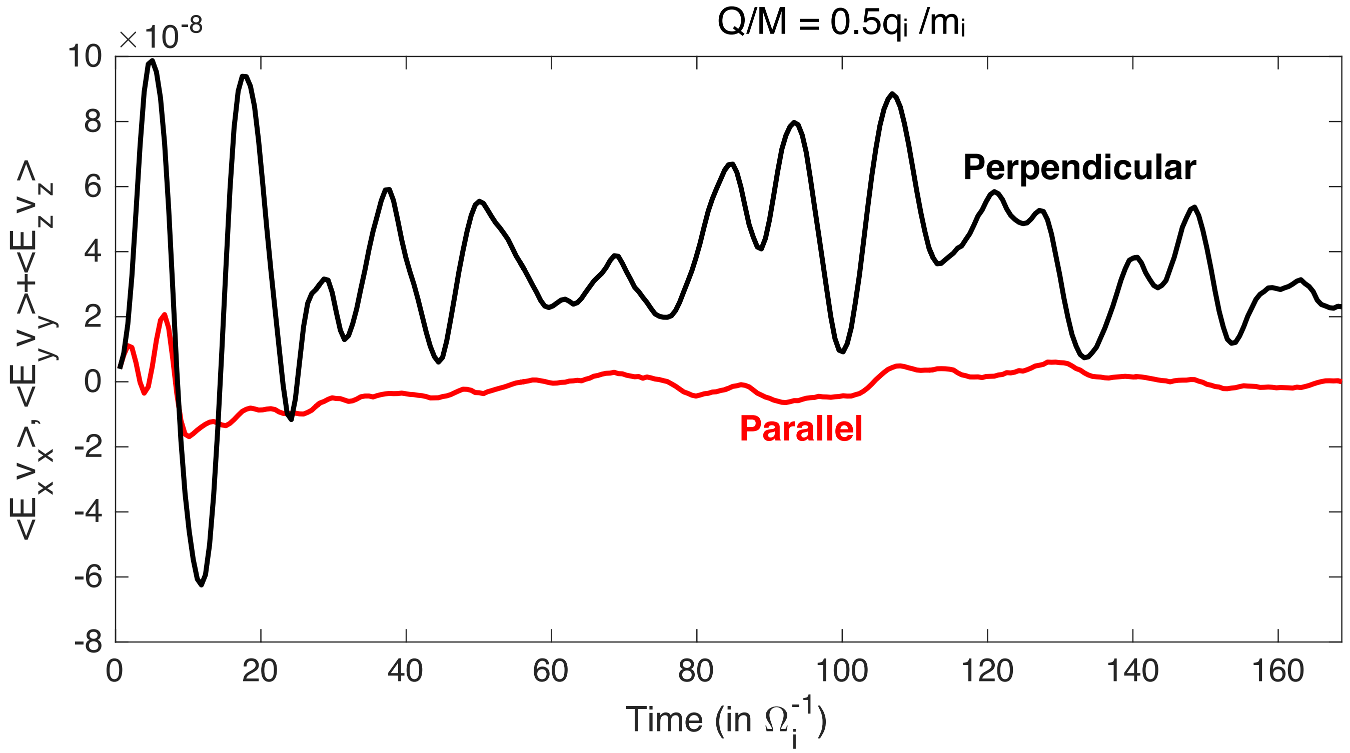
$$\omega \pm k_{\parallel} v_{\parallel} = \omega_c$$

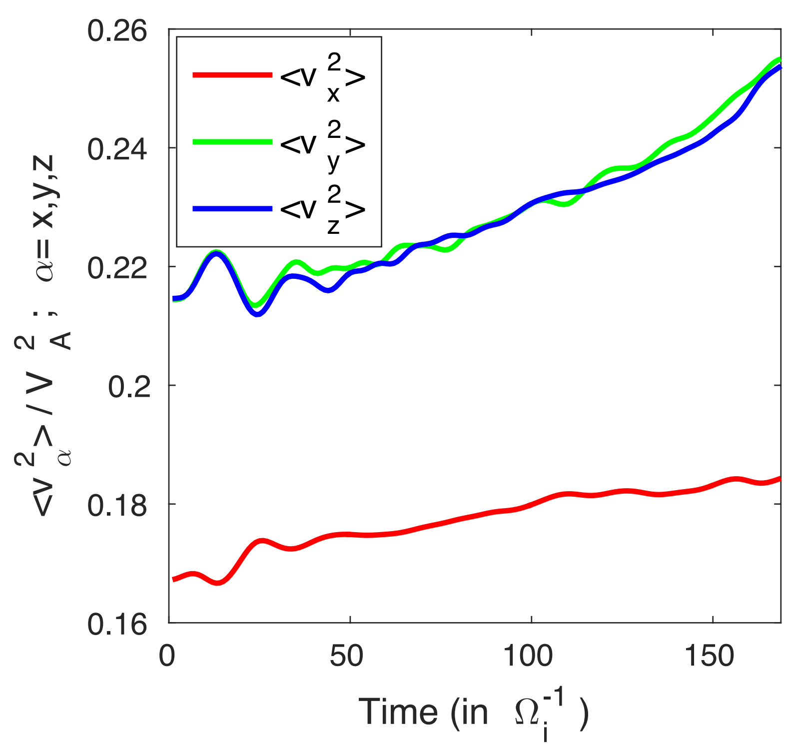
Heavier ion species (smaller Q/M) heat up at faster rate!

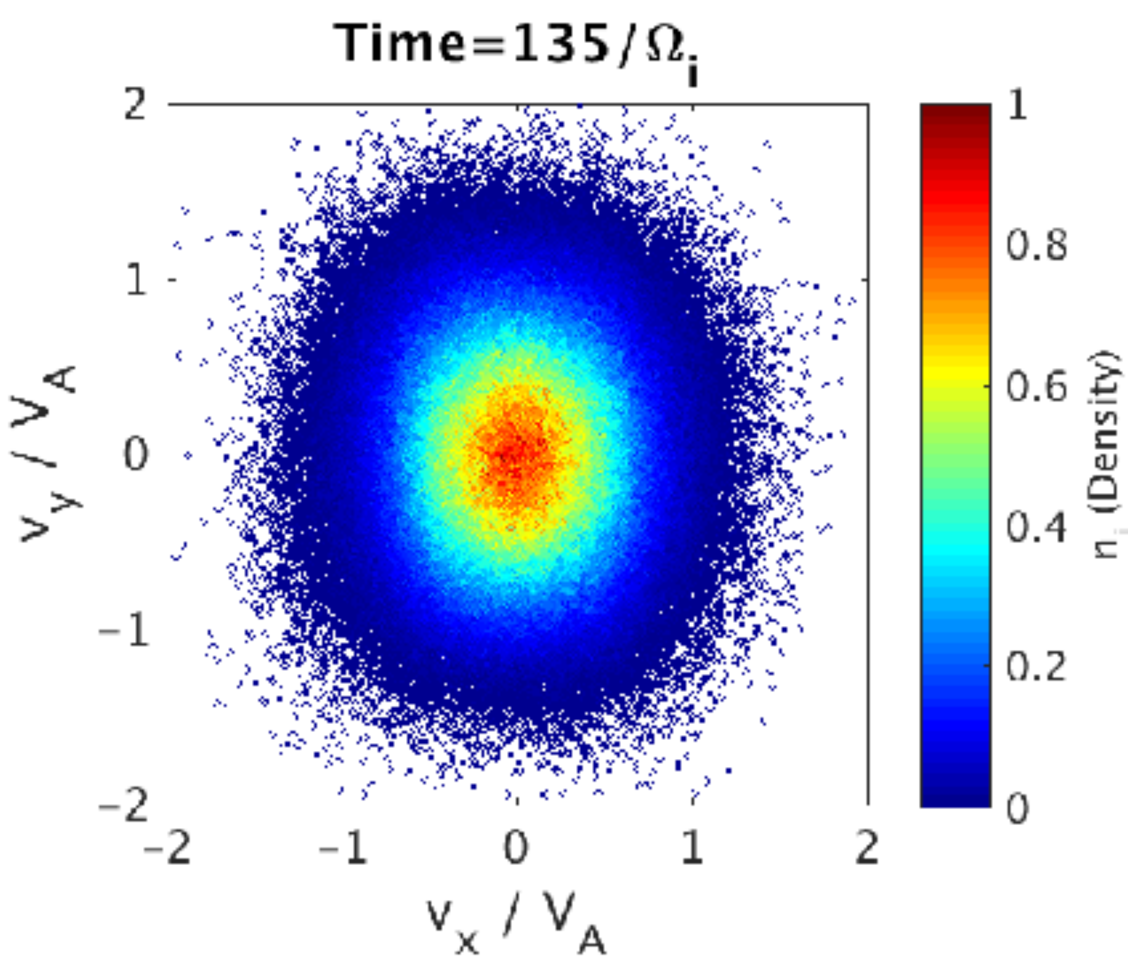
Perpendicular Heating

Heating is mostly due to the transverse electric field

Velocity space distribution is anisotropic, $T_{\perp} > T_{\|}$

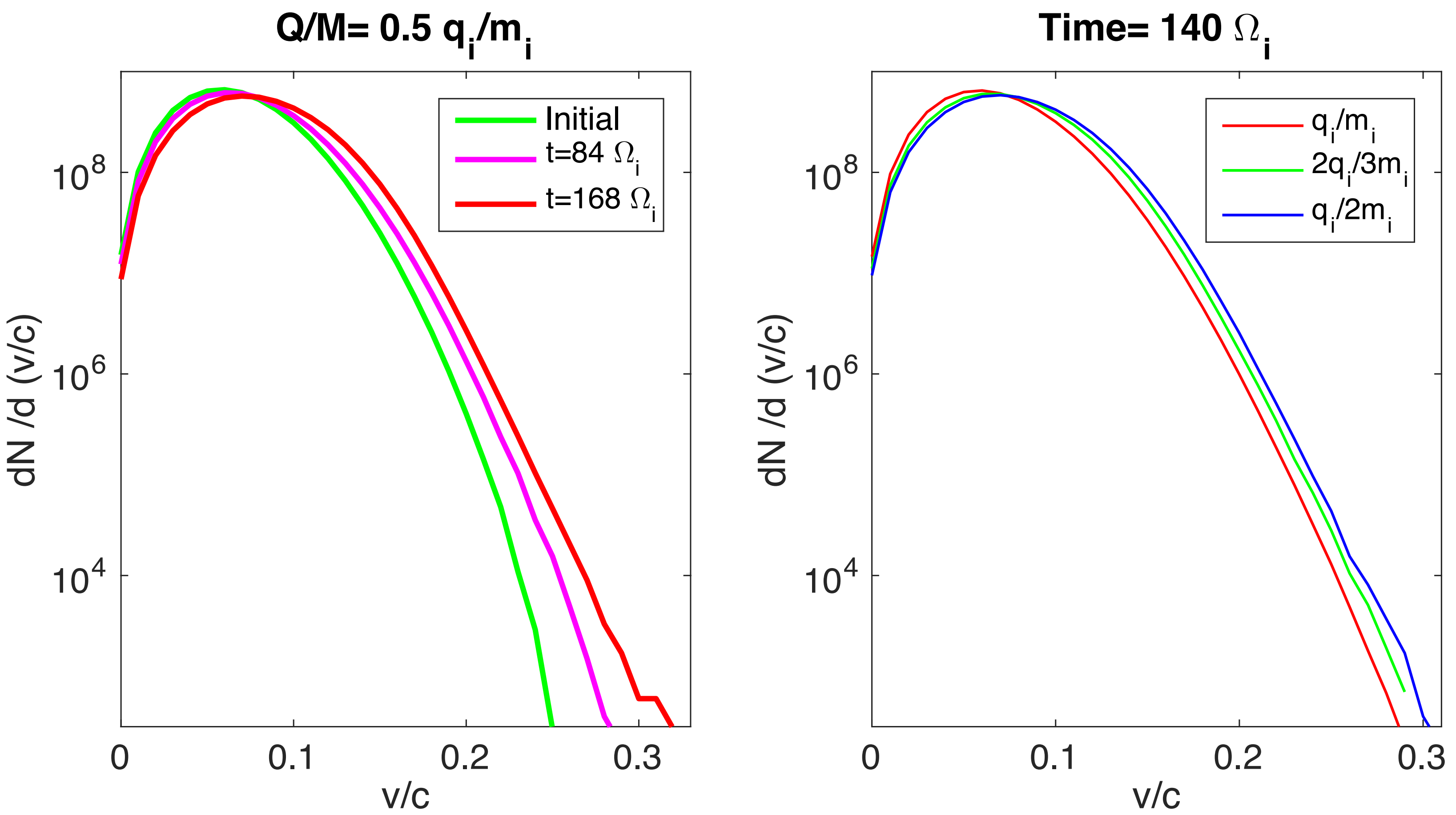






Acceleration to non-thermal energies

Some particles are accelerated to non thermal energies



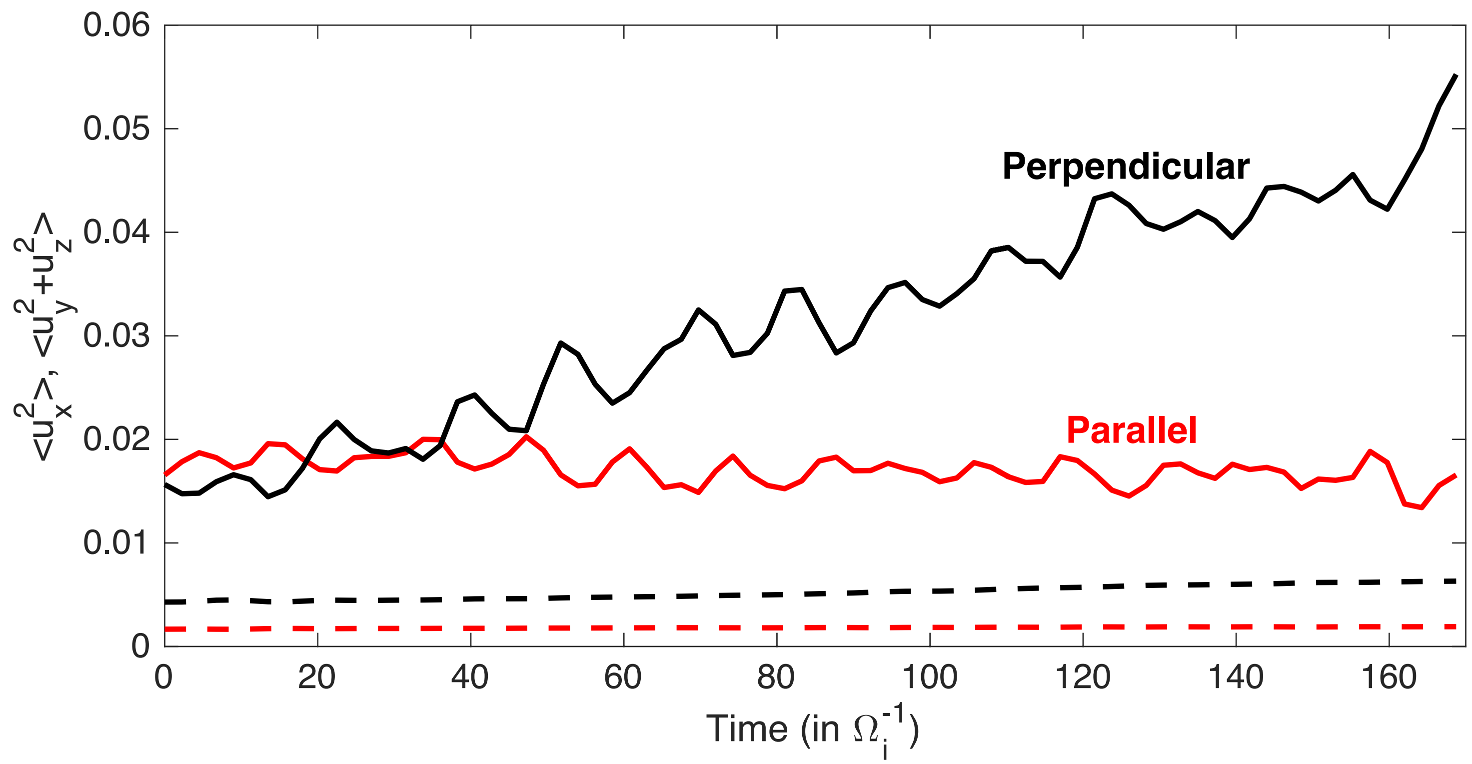
Heavier ions are accelerated to slightly higher energies

Acceleration to non-thermal energies

What is so special about the accelerated particles?

Resonance Condition : $\omega \pm k_{\|} v_{\|} = \omega_c$

Particles that end up in the non-thermal tail vs. all



Accelerated particles had relatively large *initial speed* to begin with!

Cyclotron resonance (Analytical estimate)

Considering perpendicular energization of particles

$$\Delta v^2 = 2Q\vec{E}_\perp \cdot \vec{v}_\perp \Delta t/M = 2Q(\delta\vec{u}_\perp \times \vec{B}_0) \cdot \vec{v}_\perp/M$$

In Fourier space,

$$\Delta v^2 = 2Q/M \,(\sum_{\vec{k}} \delta\vec{u}_\perp(k_x, k_y, k_z) \times \vec{B}_0) \cdot \vec{v}_\perp$$

Counting only resonate modes ($\omega \pm k_\| v_\| = \omega_c$) we can compute diffusion rate in the momentum space

$$D \simeq \frac{2\pi Q(1+v_\|/V_A)}{M} \times \sum_{k_y,k_z} \frac{J_1(Mk_r v_\perp/QV_A)}{k_r^2} \times (B_y^2(k_\|^{res}, k_y, k_z) + B_z^2(k_\|^{res}, k_y, k_z))/B_0^2$$

↔

Can be computed in the numerical simulation

Cyclotron resonance (Analytical estimate)

$$D \simeq \frac{2\pi Q(1+v_{\parallel}/V_A)}{M} \times \sum_{k_y,k_z} \frac{J_1(Mk_r v_{\perp}/QV_A)}{k_r^2} \times (B_y^2(k_{\parallel}^{res},k_y,k_z)+B_z^2(k_{\parallel}^{res},k_y,k_z))/B_0^2$$

Can be computed in the numerical simulation

Initially, the energy cascade from larger scale to smaller scales

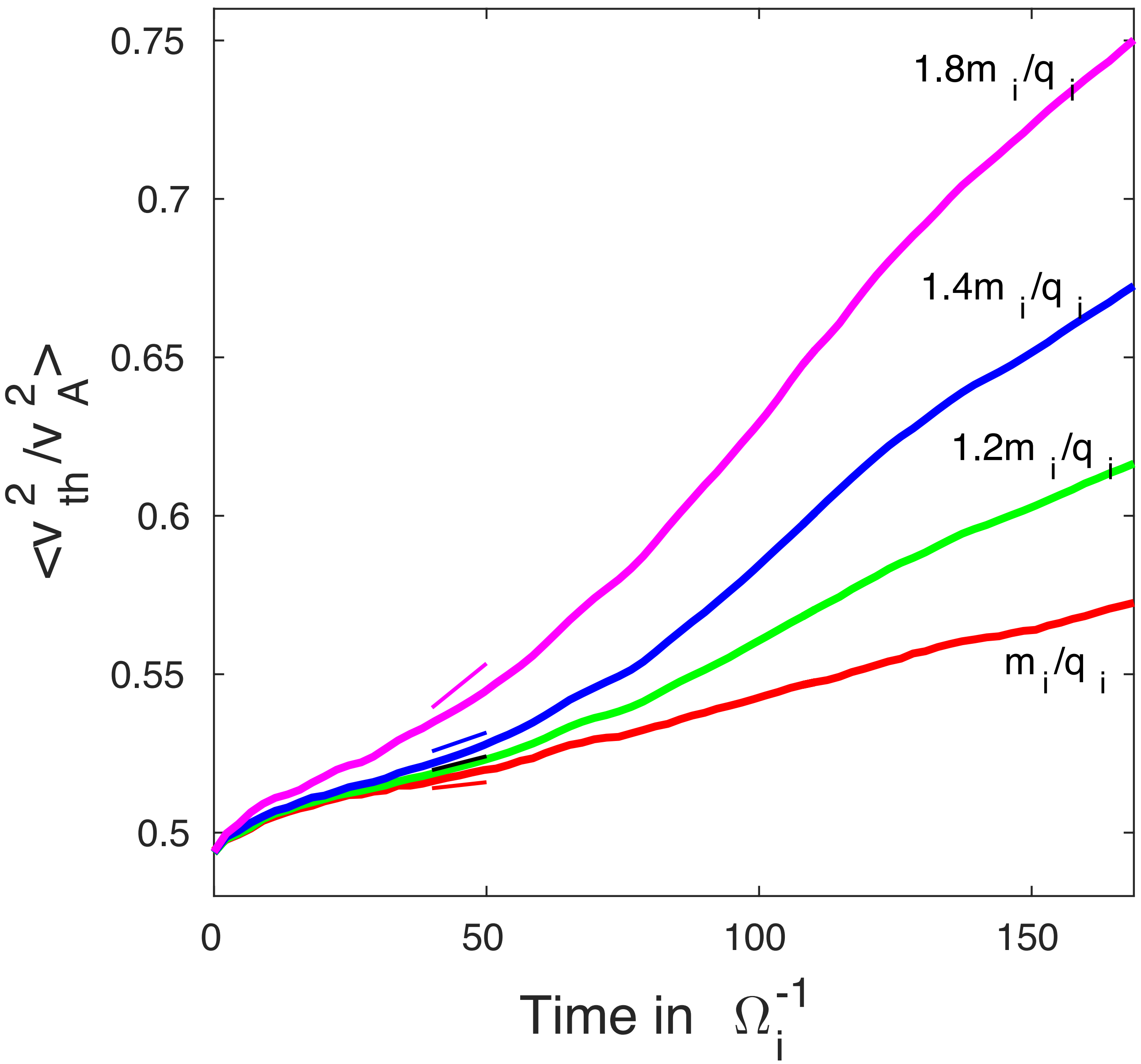
The total power in the resonant modes is increasing: $D = D_0 t$

Thermal energy increases almost linearly with time

$$< \Delta v_{th}^2/V_A^2 > \propto \Delta t$$

Cyclotron resonance (Analytical estimate)

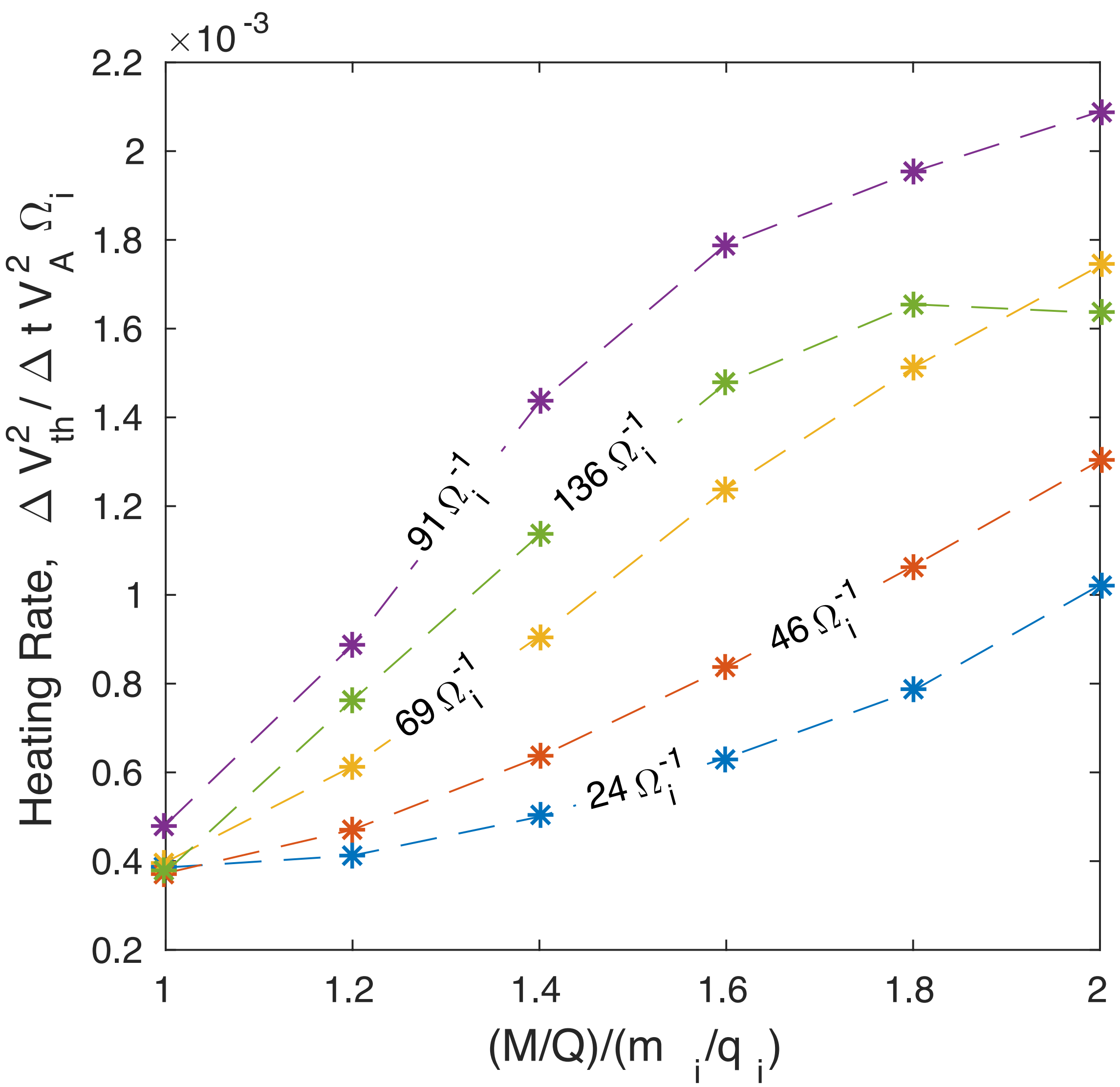
For heavy ions Observed rate of heating agrees well with the estimate!



Most significant contribution from the oblique modes!

Heating Rate Vs. Time

Preferential heating is more pronounced for a steeper spectrum



Isotropic turbulence is not favorable for the preferential acceleration of the heavy ions

Summary and Conclusions

Heavy ions are preferentially heated and accelerated in an anisotropic Aflvenic turbulence

It can be understood as Cyclotron damping of the turbulence by individual ions.

Article: Preferential Heating and Acceleration of Heavy Ions in Impulsive Solar Flares
Rahul Kumar et al 2017 ApJ 835 295