PRINCETON UNIVERSITY

FRONTERA
AST20010

Turbulence, Transport, and Thermodynamics in Collisionless Space and Astrophysical Plasmas

Michael F Zhang

with and on behalf of: Matthew Kunz (PI), Lev Arzamasskiy,
Archie Bott, Alisa Galishnikova, Eliot Quataert, Stephen Majeski,
Alex Schekochihin, Jonathan Squire, Himawan Winarto, Evan Yerger, Muni Zhou

(Frontera users thus far marked in orange)

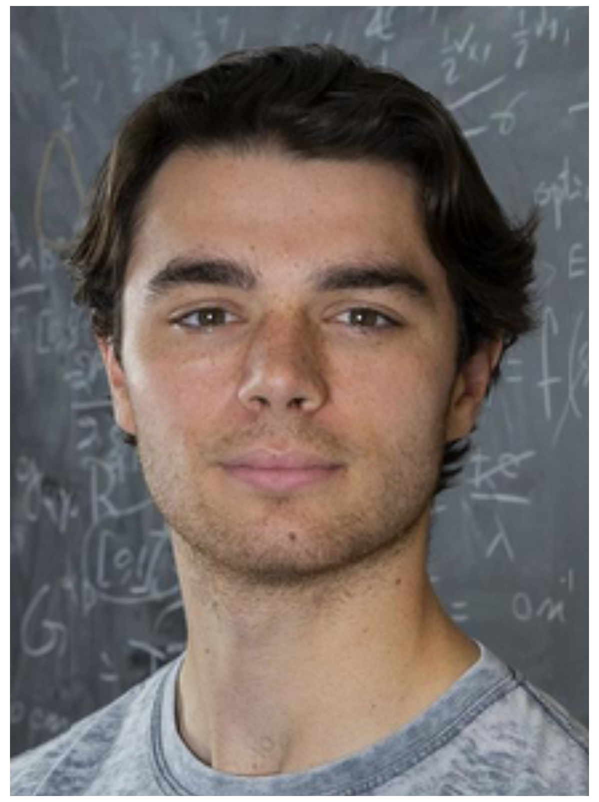
We use kinetic and MHD simulations to study turbulence, transport, and thermodynamics in space/astrophysical plasmas


Matthew Kunz


Lev Arzamasskiy


Archie Bott


Alisa Galishnikova


Stephen Majeski


Eliot Quataert


Alex Schekochihin


Jono Squire


Himawan Winarto

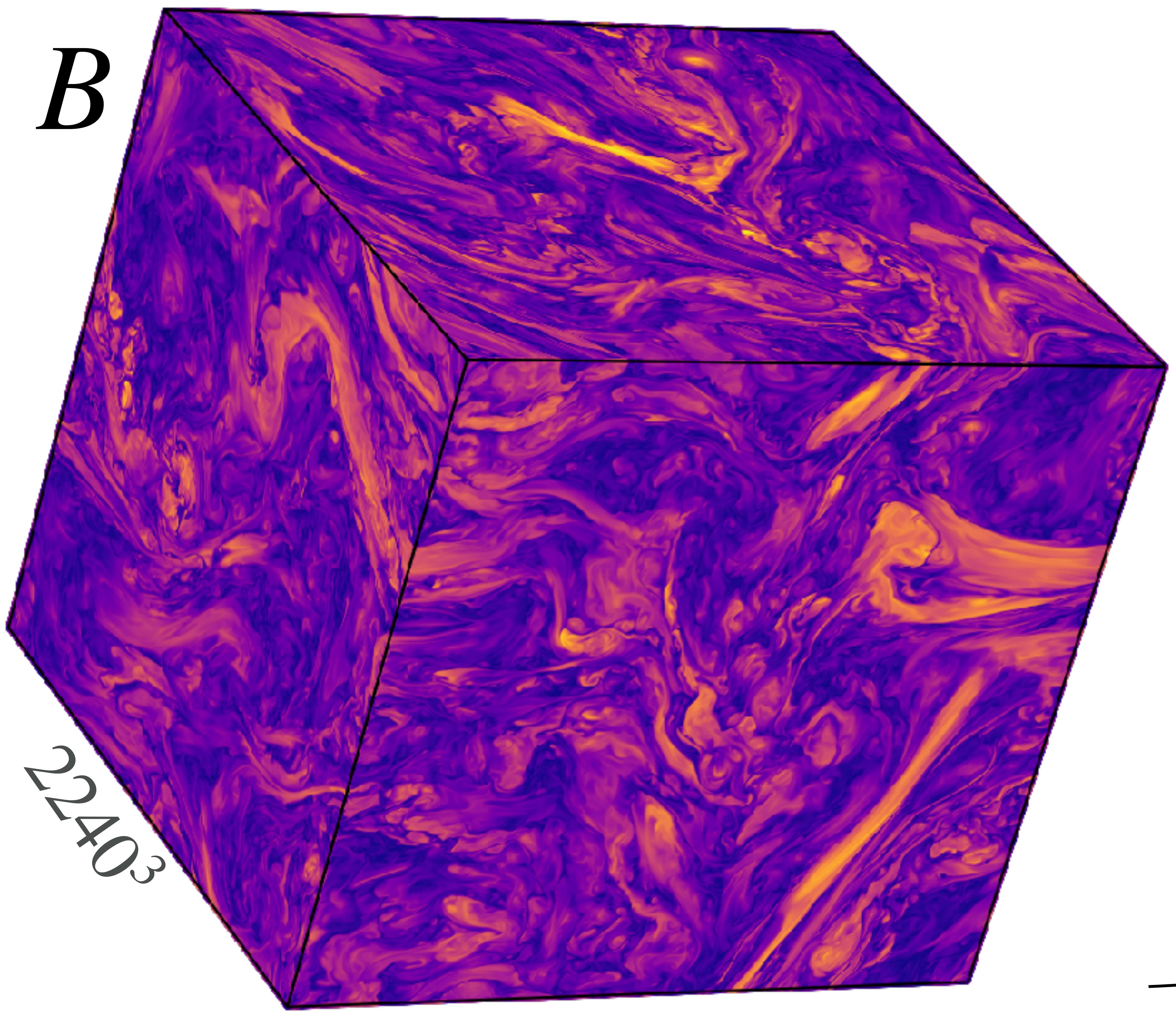

Evan Yerger


Michael Zhang


Muni Zhou

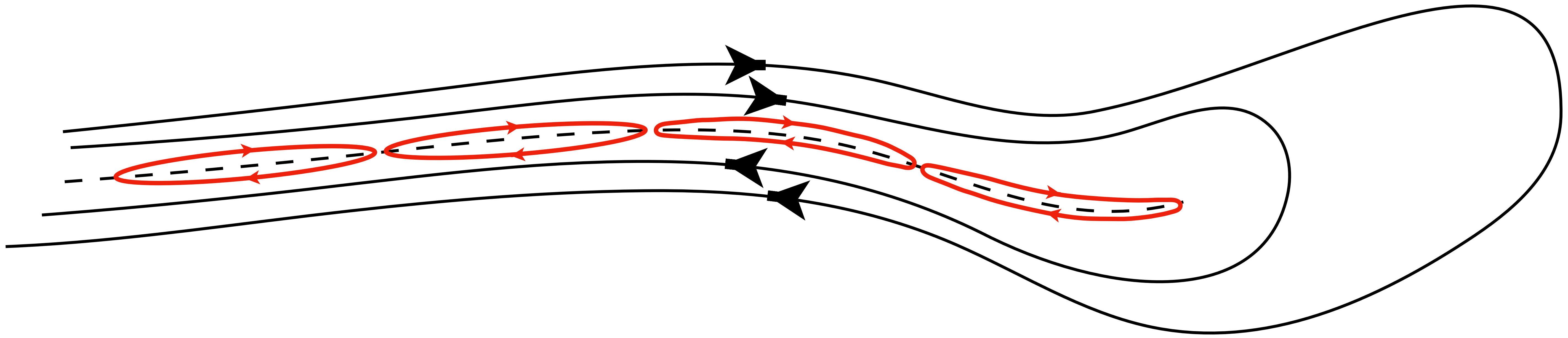
Articles from our group that used Frontera time:

- Tearing instability and current-sheet disruption in the turbulent dynamo
  Galishnikova, Kunz & Schekochihin 2022, Physical Review X
- High-frequency heating of the solar wind triggered by low-frequency turbulence
  Squire *et al.* 2022, Nature Astronomy
- Triggering tearing in a forming current sheet with the mirror instability
  Winarto & Kunz 2022, Journal of Plasma Physics
- Microphysically modified magnetosonic modes in collisionless, high-β plasma
  Majeski, Kunz & Squire 2023, Journal of Plasma Physics
- Electron-ion heating partition in low-β, imbalanced turbulence
  Squire, Meyrand & Kunz, in prep. (submission in Aug 2023)
- Collisionless conduction in a high-β plasma: collision operator for whistler turbulence
  Yerger, Kunz, Bott, Spitkovsky, in prep. (submission in Aug 2023)

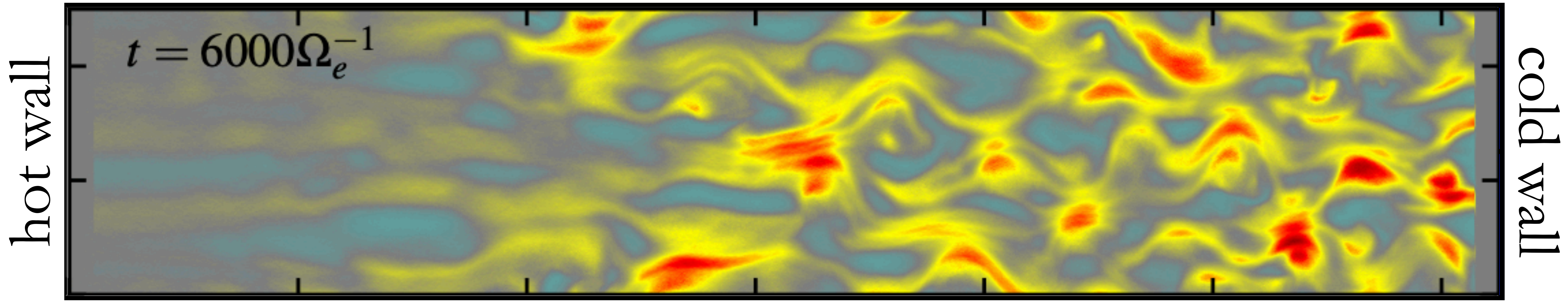


Galishnikova, Kunz & Schekochihin 2022, PRX

Elongated current sheets naturally
produced by the turbulent dynamo
become disrupted by tearing instability
during the nonlinear stage of dynamo,
change geometry and spectrum of field.
Large-scale fields produced.



Microphysically regulated conductive heat transport in collisionless, high-β plasma



heat flux excites **whistler instability**,

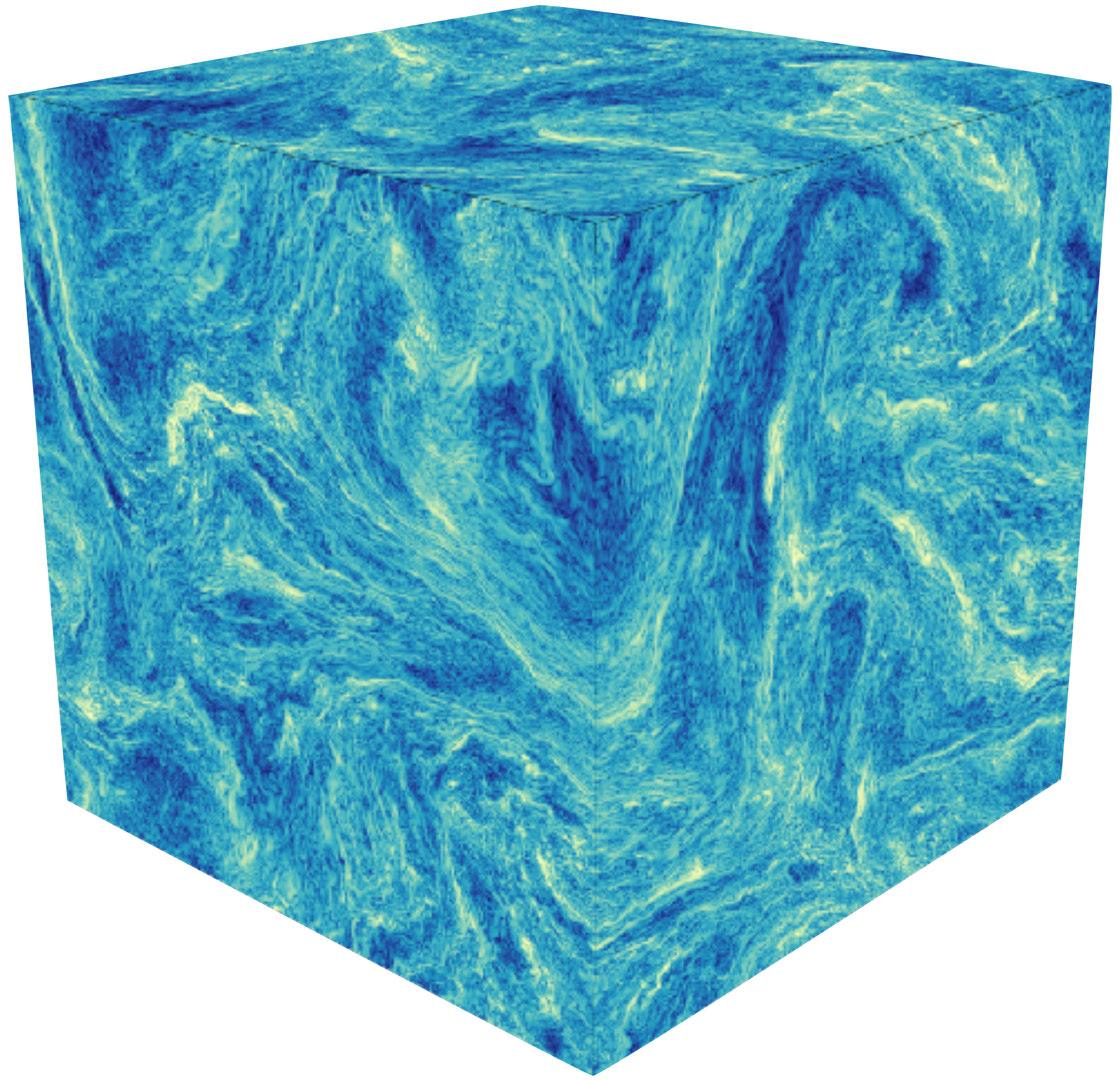
creates bath of scattering magnetic fluctuations,

regulates heat flux through $\nu_\mathrm{e} \sim |v_\mathrm{th,e} \nabla \ln T| \beta_\mathrm{e}$

$$\implies \quad q_{\parallel,\mathrm{e}} \sim \frac{1}{\beta_\mathrm{e}} n T_\mathrm{e} v_\mathrm{th,e}$$

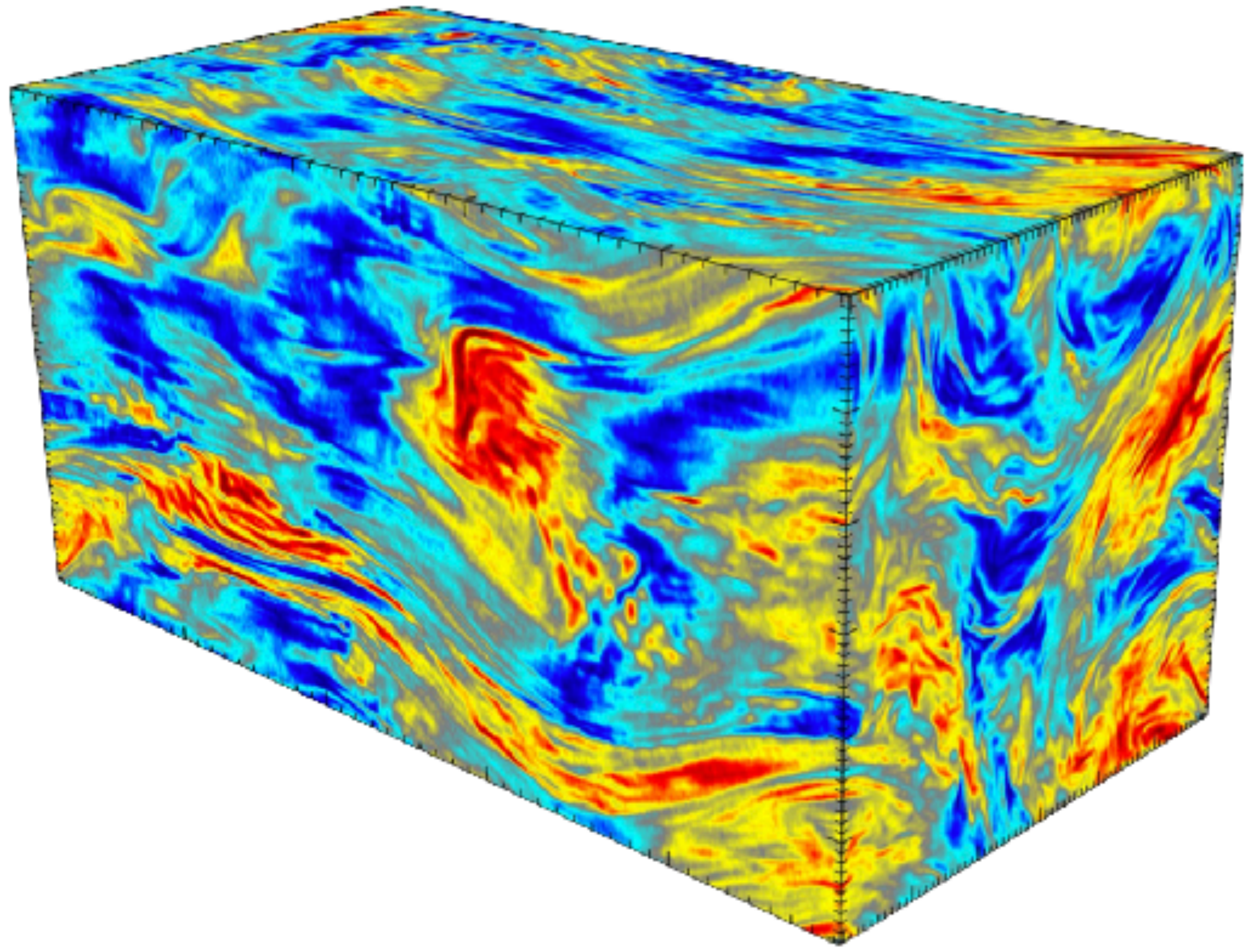
Yerger et al. (2023, in prep) verifies this result up to $L_T = 2000\rho_e$, then uses a several methods to obtain an **effective collision operator** for whistler-e$^-$ interactions

turbulent plasma dynamo

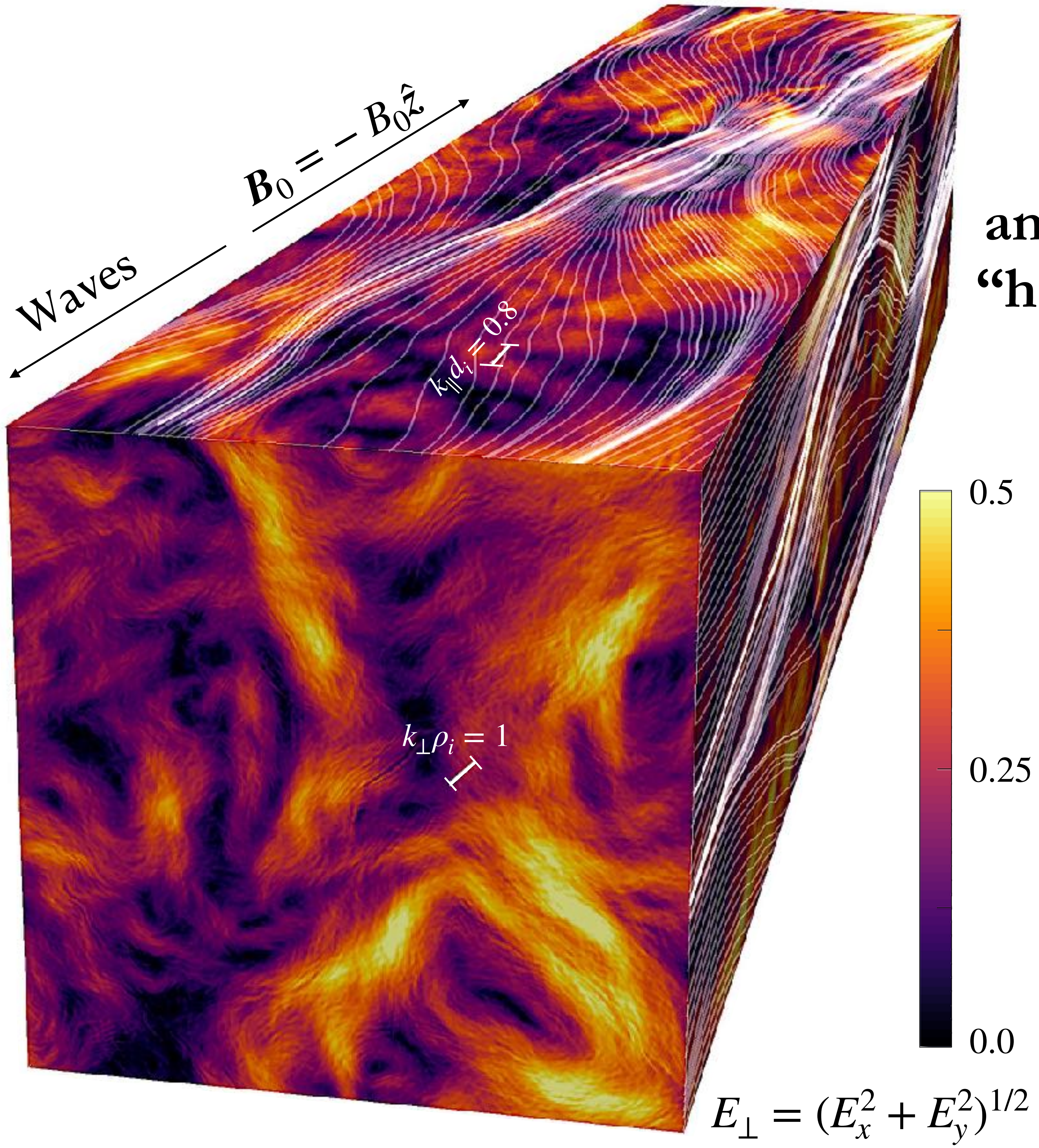


St-Onge & Kunz 2018

kinetic Alfvénic turbulence at high β



imbalanced solar-wind turbulence and ion heating: “helicity barrier”

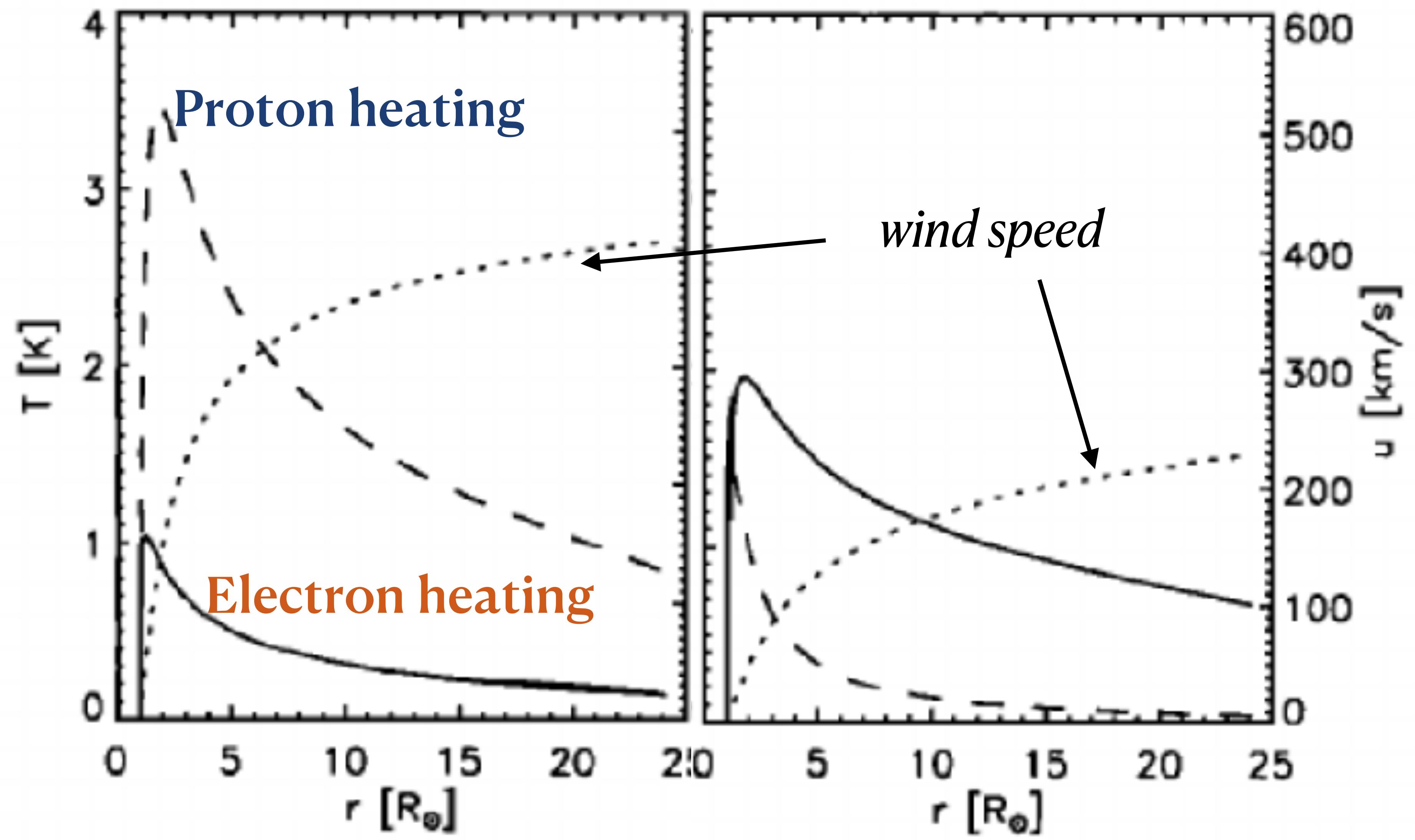


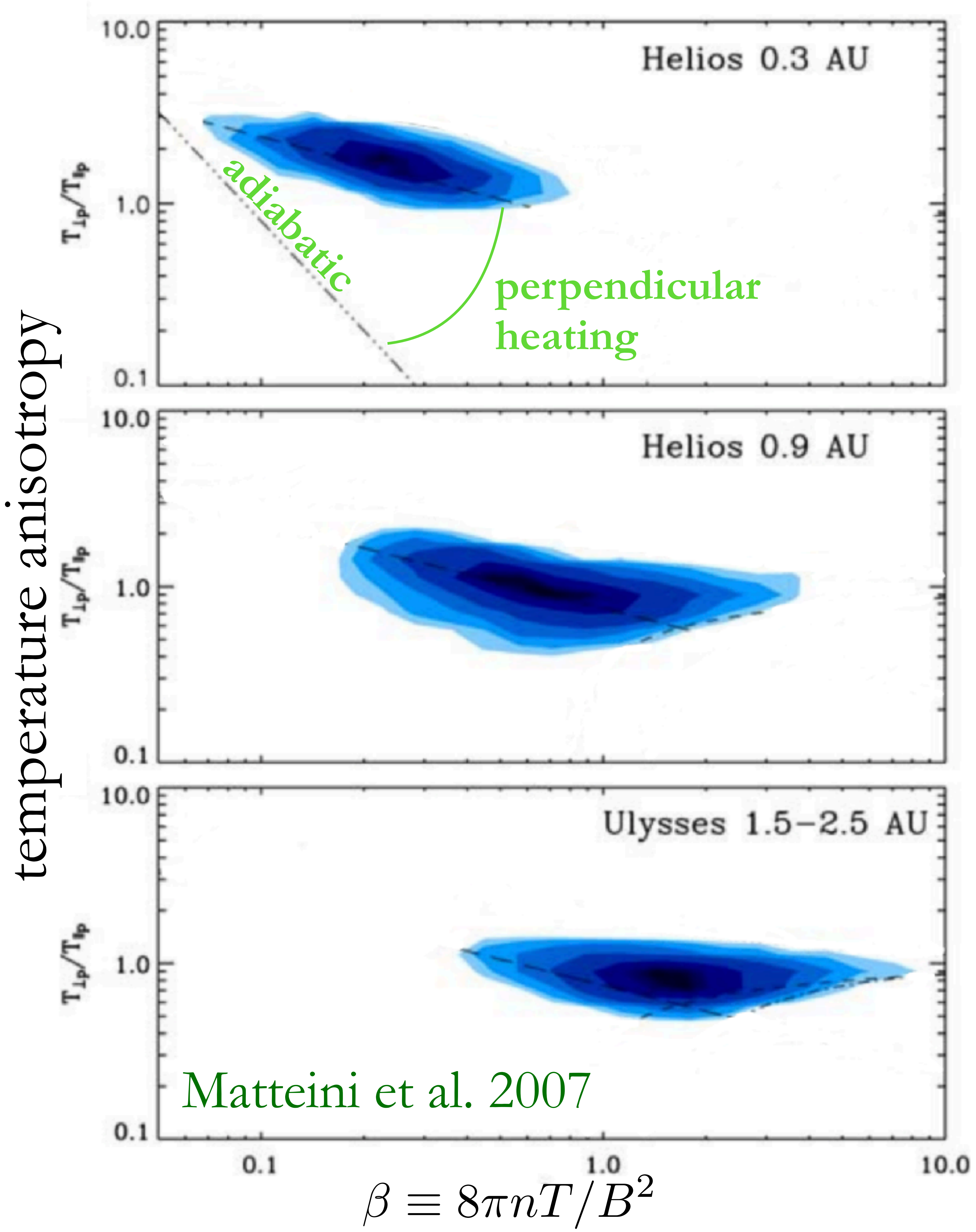
Squire, Meyrand, Kunz, Arzamasskiy, Schekochihin & Quataert 2022

Fast solar wind heating observations

- Ions heated dominantly over electrons
- Heated more in the perpendicular direction
- Heating spatially extended out to several solar radii

e.g. Hansteen & Leer 1995





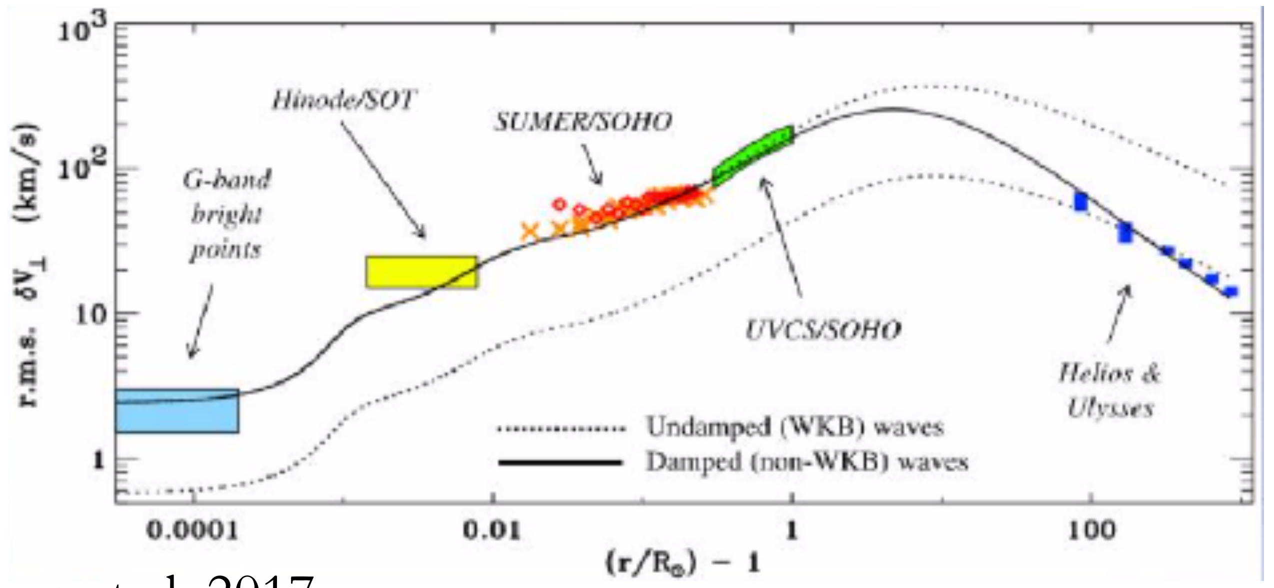
Matteini et al. 2007

Mechanism must dominantly heat ions perpendicularly

Alfvénic turbulence

+ Converts magnetic to thermal energy
+ Observed (Belcher & Davis etc.) and sufficient power to heat corona and solar wind (e.g., De Pontieu+ 2007, Tomczyk+ 2007)

- Balanced, low amplitude, low beta turbulence dominantly heats electrons
- Ion Landau damping at higher beta heats in parallel direction

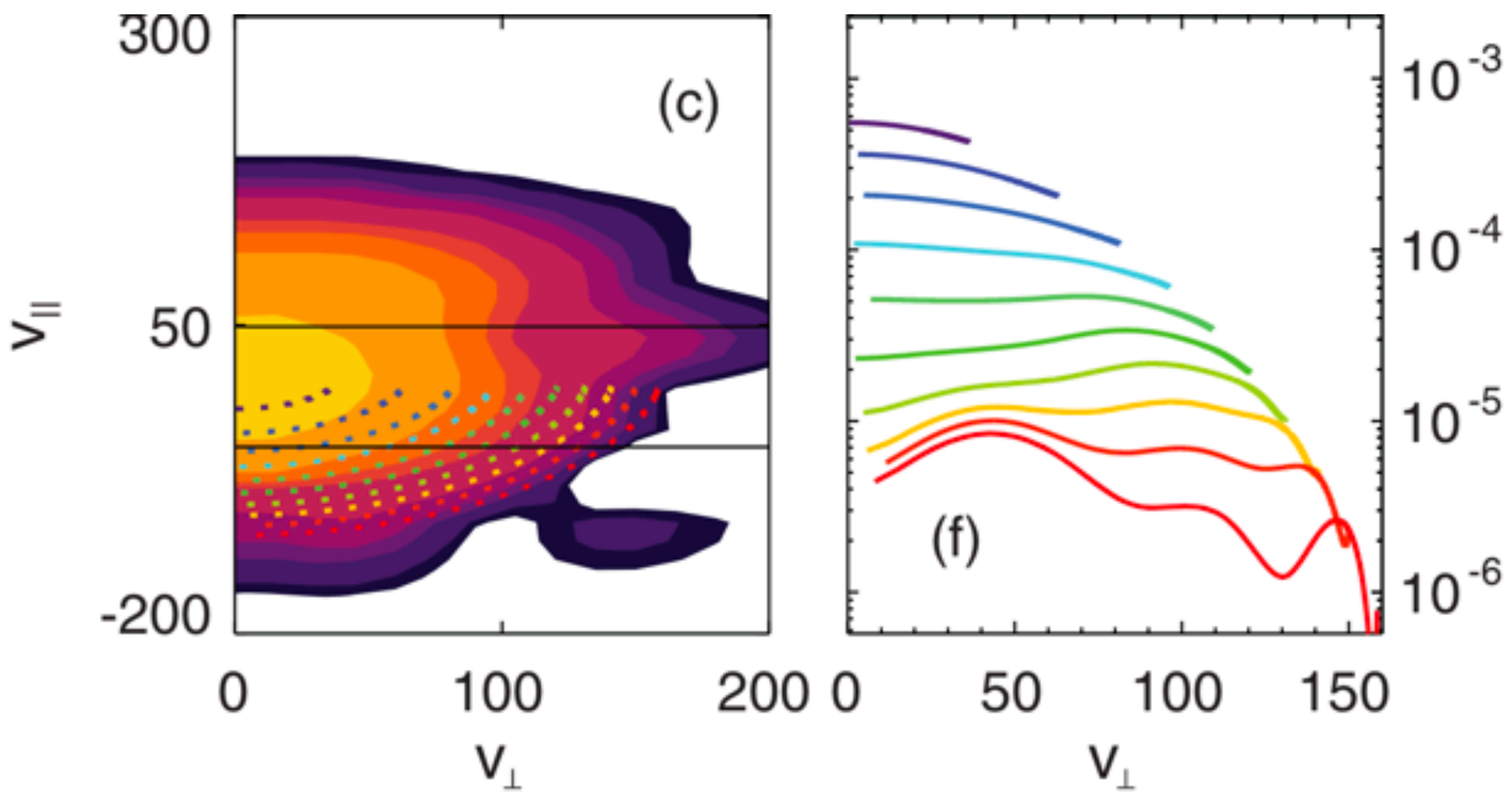


Cranmer et al. 2017

ICW heating

+ Heats perpendicularly
+ ICWs are observed in solar wind

- Source of ICWs? Propagation of ICWs to large radii mostly ruled out (Hollweg 2000)

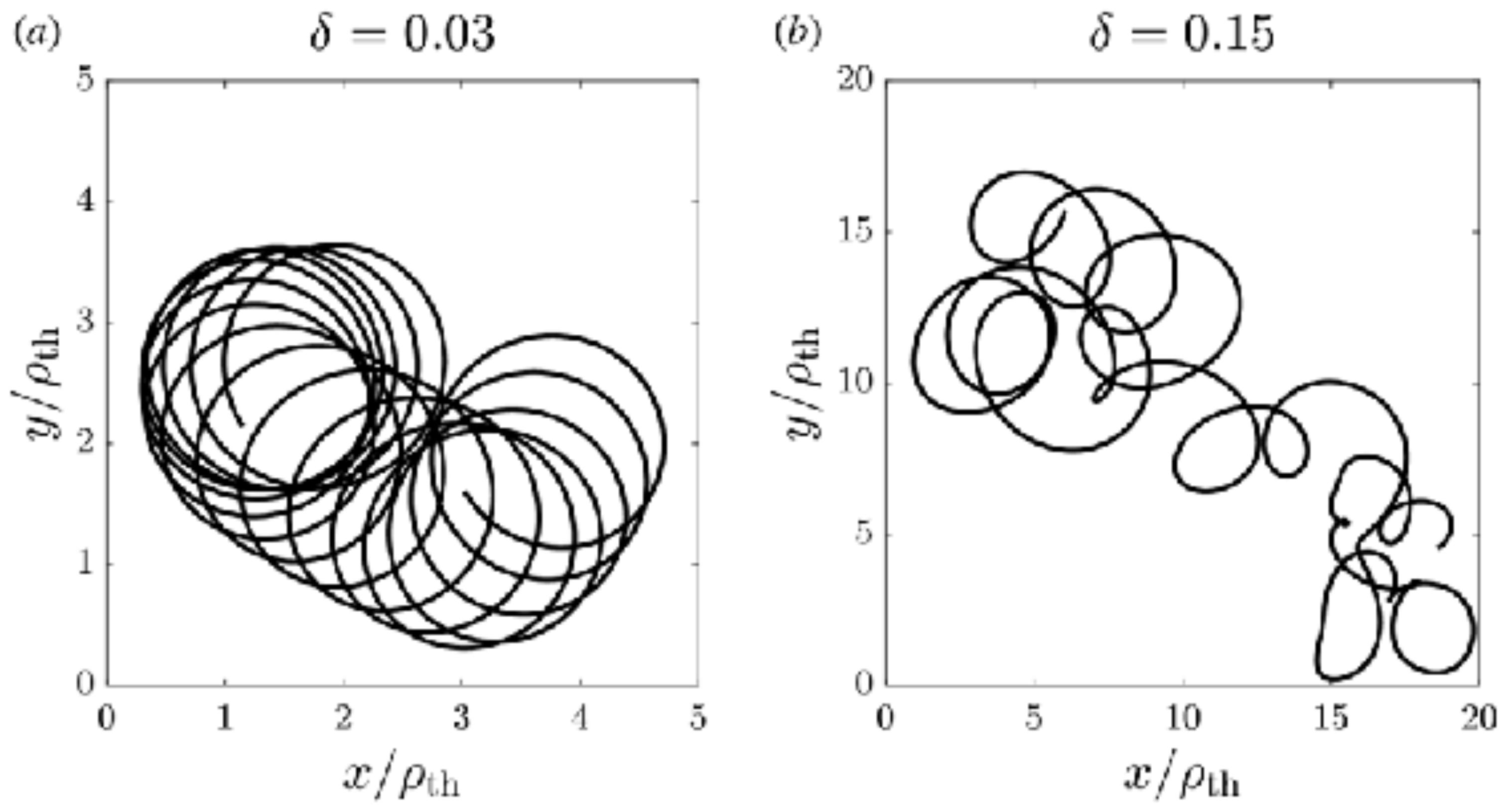


Bowen et al. 2022

Stochastic heating

+ Heats perpendicularly
+ Heats at lower frequencies, at larger amplitudes in magnetic spectra

- Requires sufficient fluctuation amplitude above a critical value

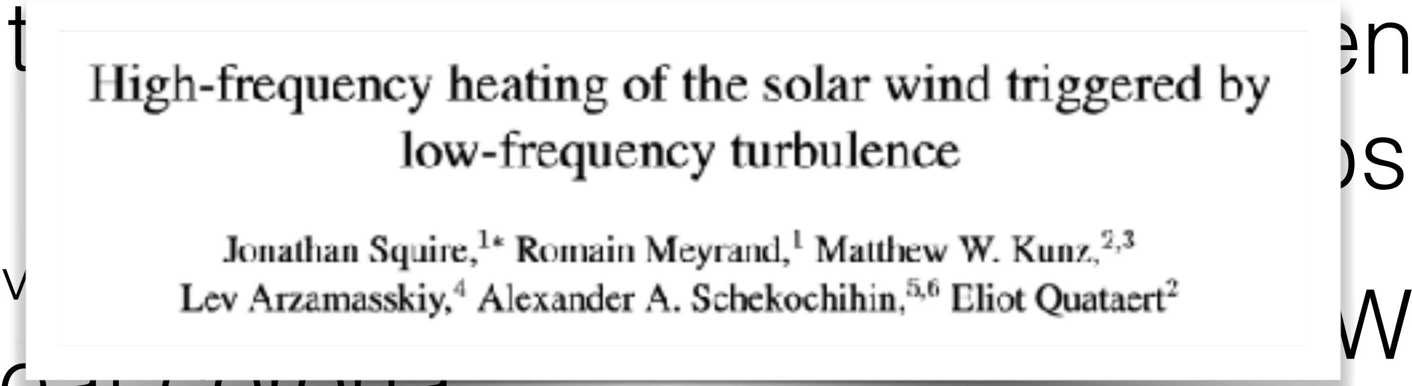


Hoppock et al. 2018

Mechanism must dominantly heat ions perpendicularly

Alfvénic turbulence

Compatible! (2022)


High-frequency heating of the solar wind triggered by low-frequency turbulence

Jonathan Squire,[1*] Romain Meyrand,[1] Matthew W. Kunz,[2,3] Lev Arzamasskiy,[4] Alexander A. Schekochihin,[5,6] Eliot Quataert[2]

- \+ Converts magnetic t energy
- \+ Observed (Belcher & Dav sufficient power to heat corona and solar wind (e.g., De Pontieu+ 2007, Tomczyk+ 2007)
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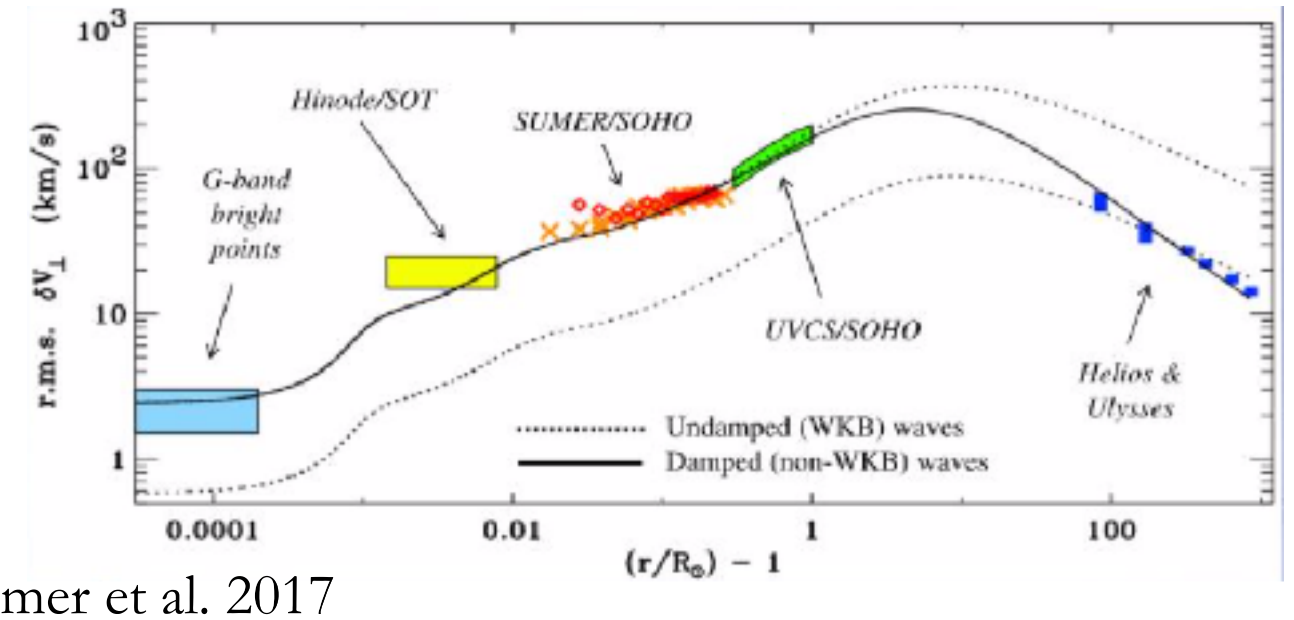
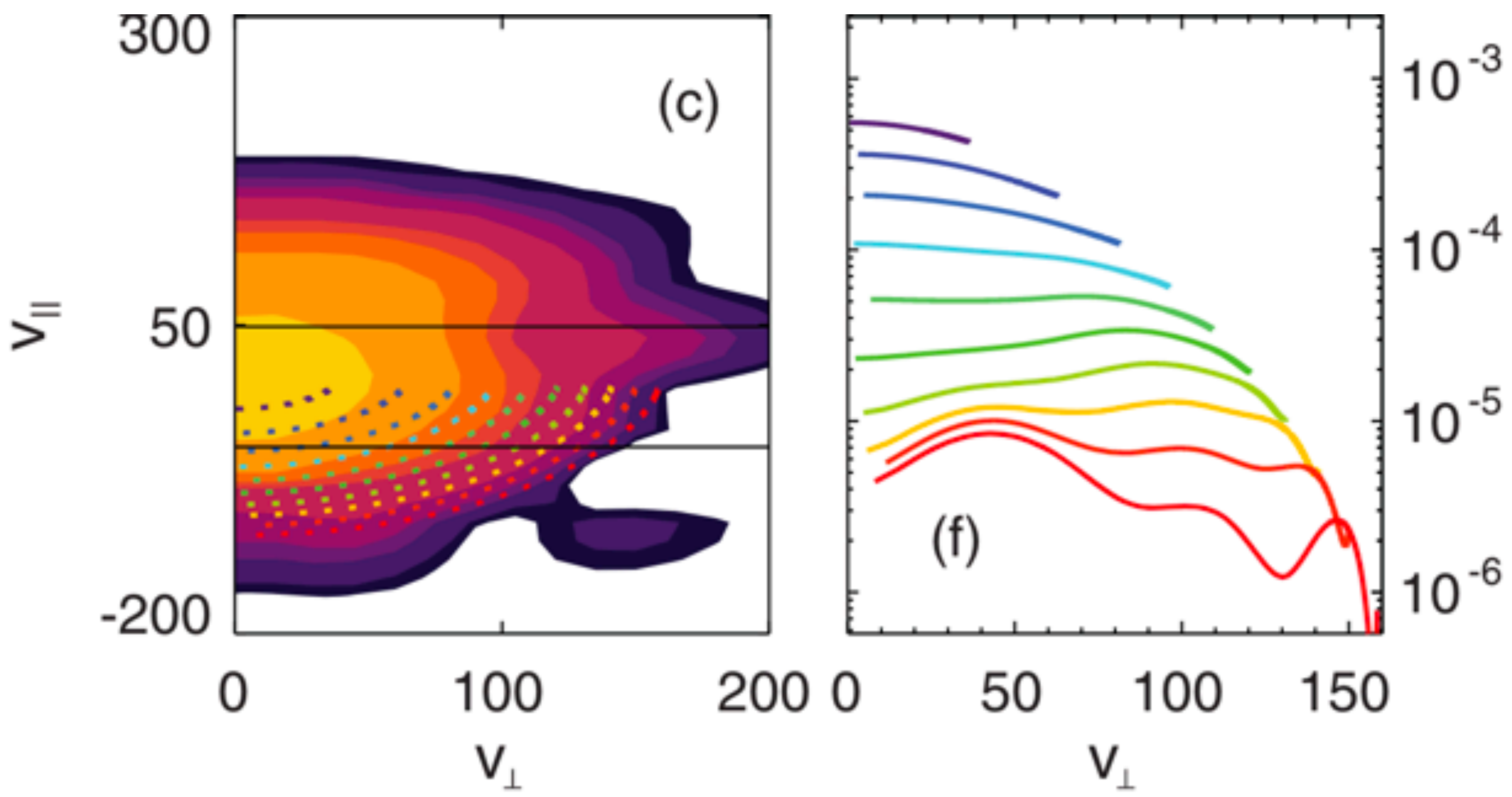


Cranmer et al. 2017

ICW heating

endicularly
served in solar wind

Ws? Propagation of ICWs to large radii mostly ruled out (Hollweg 2000)



Bowen et al. 2022

Stochastic heating

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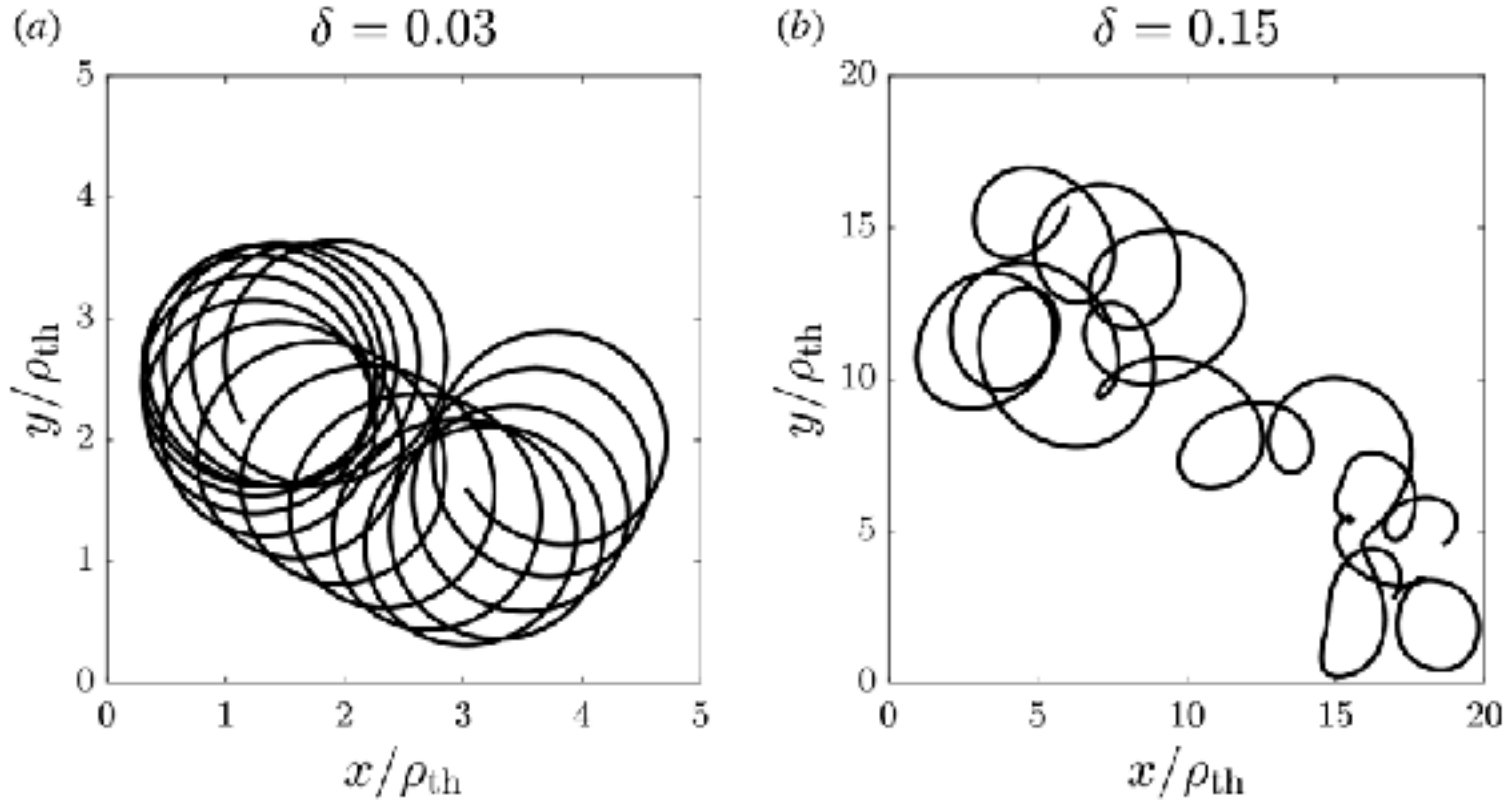


Hoppock et al. 2018

Helicity barrier blocks electron heating in imbalanced turbulence…

if cross-helicity is not zero

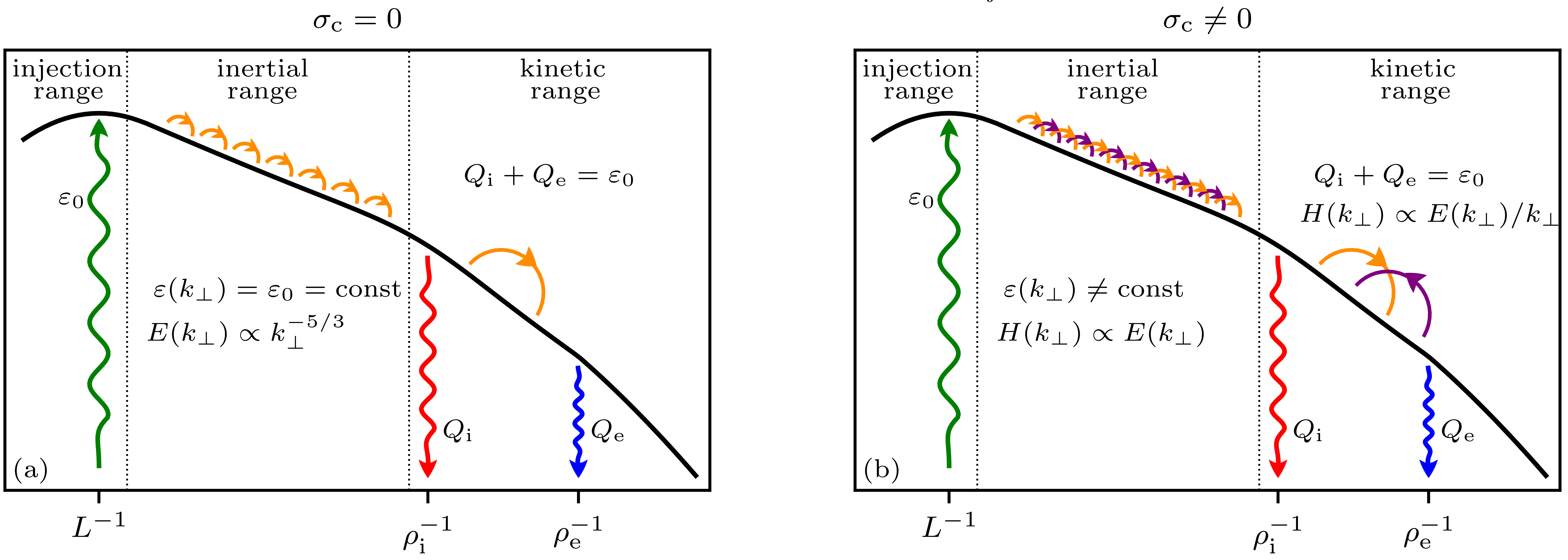
$$\boldsymbol{z}^{\pm} \equiv \boldsymbol{u} \pm \boldsymbol{B}/\sqrt{4\pi\rho}$$

$$H(k_\perp) = E(k_\perp)/v_{\rm ph}(k_\perp)$$

$$\ell \gg \rho_{\rm i} \qquad \int {\rm d}^3\boldsymbol{x} \left(\frac{|\boldsymbol{z}^+|^2}{2} - \frac{|\boldsymbol{z}^-|^2}{2} \right) \propto \int {\rm d}^3\boldsymbol{x}\, (\boldsymbol{u}_\perp \cdot \boldsymbol{B}_\perp) = {\rm const}$$

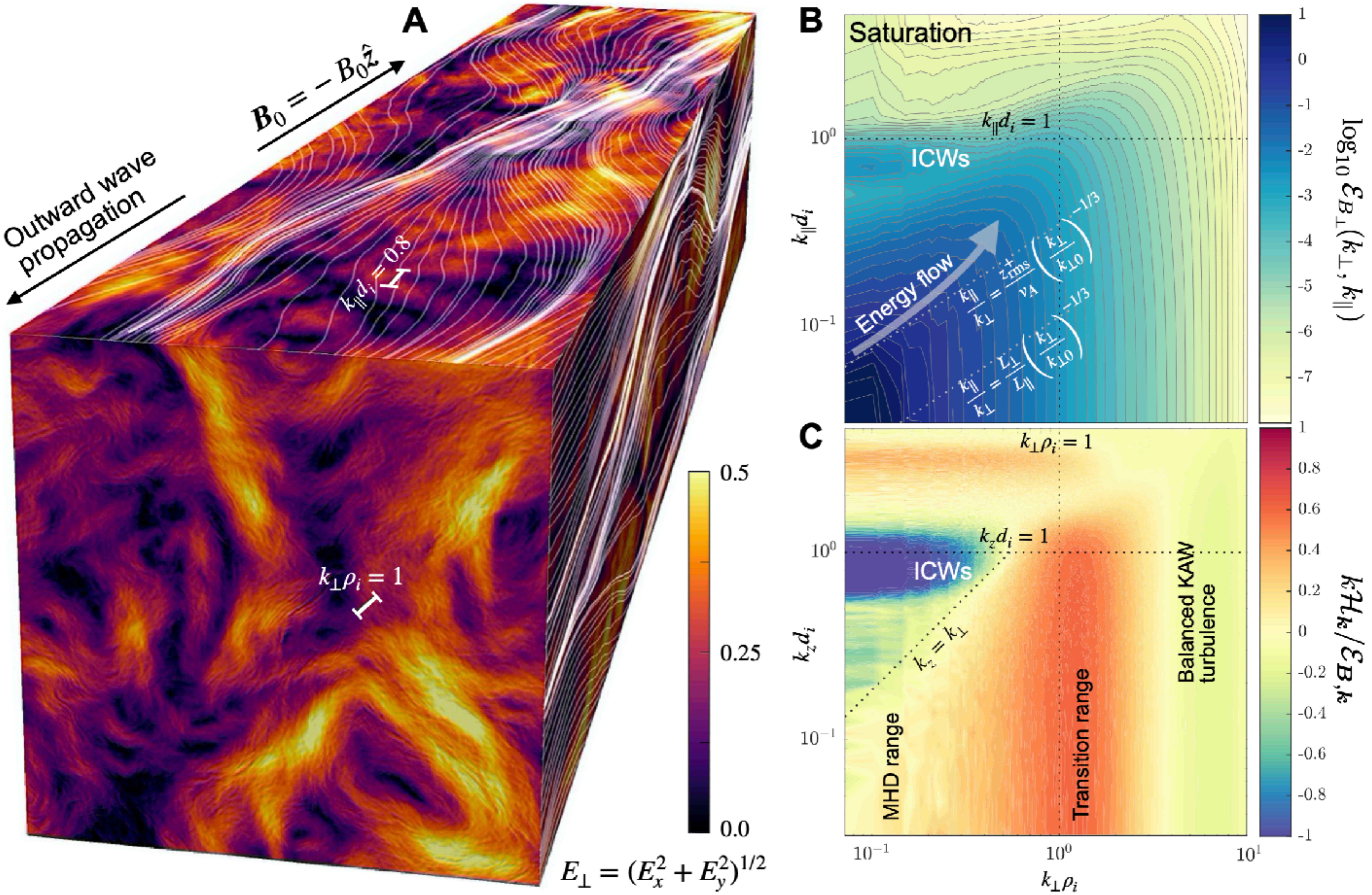
$$\int {\rm d}^3\boldsymbol{x} \left(\frac{\rho \boldsymbol{u}^2}{2} + \frac{\boldsymbol{B}^2}{8\pi} \right) = {\rm const} \quad \text{(energy flux conserved during cascade)}$$

$$\ell \ll \rho_{\rm i} \qquad \int {\rm d}^3\boldsymbol{x}\, \delta B_\parallel A_\parallel = {\rm const}$$

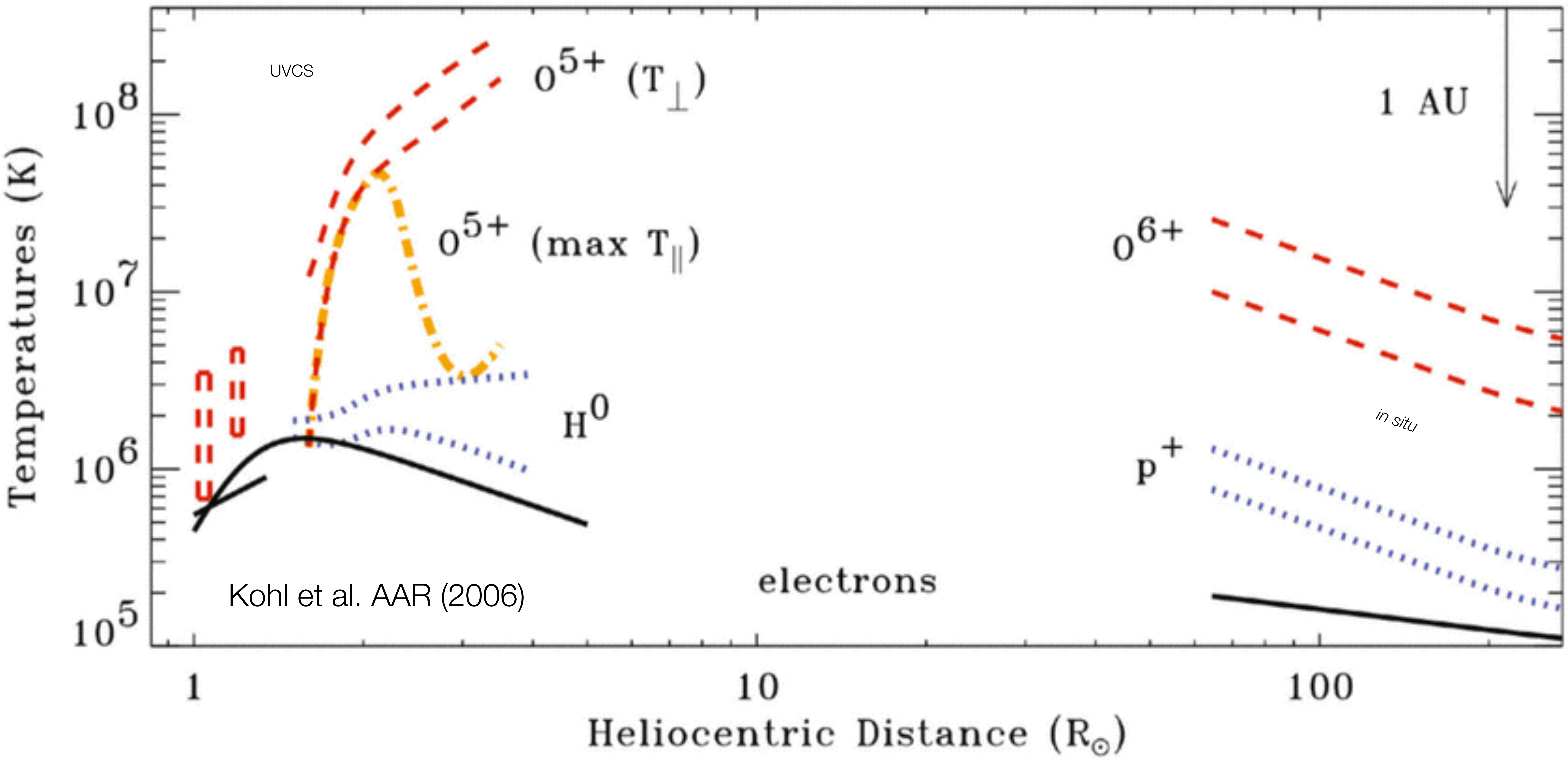


…and can lead to ICW heating of ions

Pegasus++ hybrid-kinetic imbalanced turbulence simulations on Frontera (Squire, Meyrand, Kunz, Arzamasskiy, Schekochihin & Quataert 2022)



Minor ions are heated even more strongly than protons



Kohl et al. AAR (2006)

How much are minor ions heated in balanced vs. imbalanced turbulence? Heated by ICWs? Stochastically heated?

Minor ions in Pegasus++

Hybrid-kinetics lets us drop electron scales (less computationally expensive than full kinetic PIC)

$$\frac{\partial f_{\mathrm{i}}}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla} f_{\mathrm{i}} + \boxed{\frac{Ze}{m_{\mathrm{i}}}}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}\times\boldsymbol{B}\right)\cdot\frac{\partial f_{\mathrm{i}}}{\partial \boldsymbol{v}} = \left(\frac{\partial f_{\mathrm{i}}}{\partial t}\right)_{\mathrm{coll}}$$

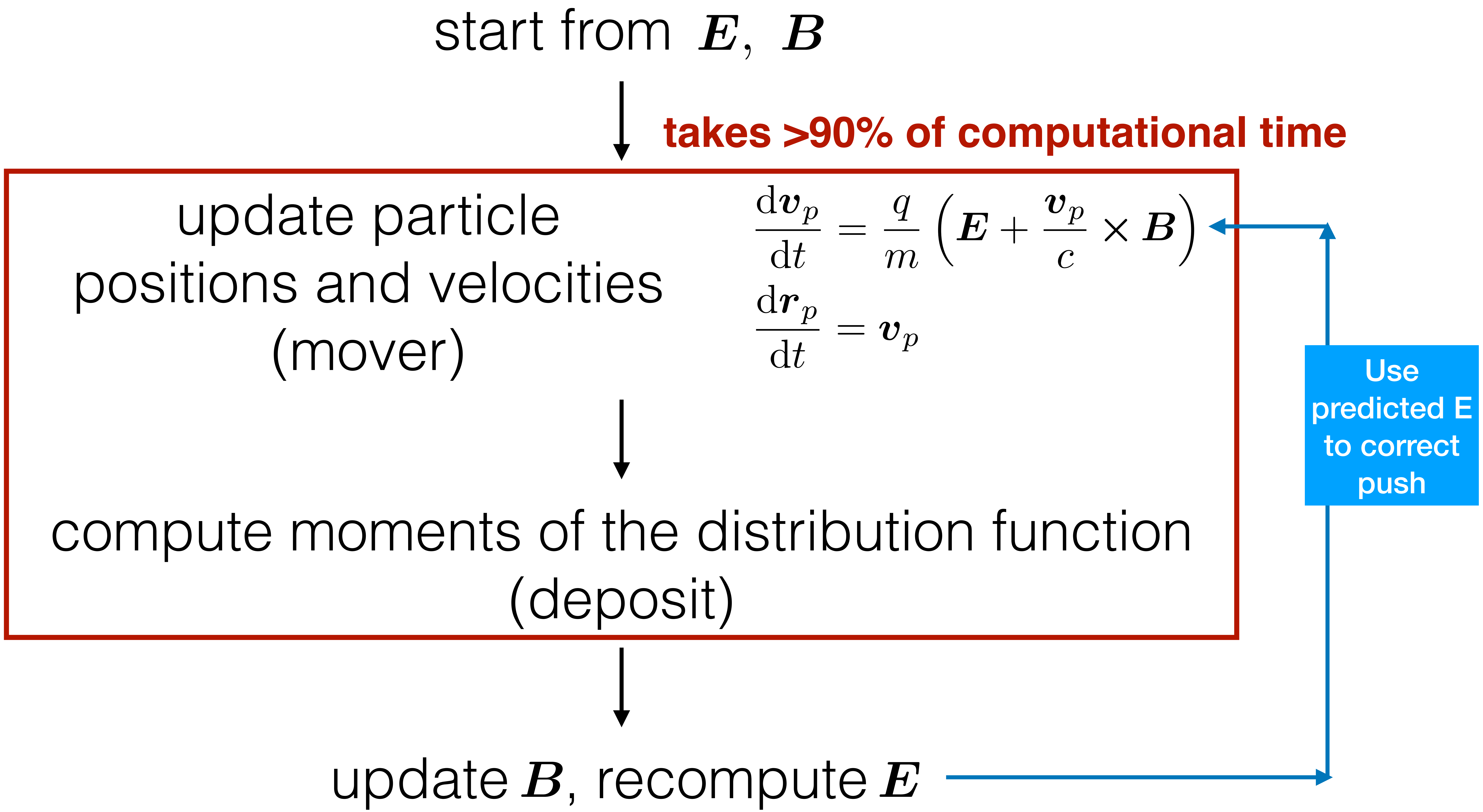
$$\boldsymbol{E} = -\frac{1}{en_{\mathrm{e}}}\boldsymbol{\nabla} p_{\mathrm{e}} - \frac{1}{c}\boldsymbol{u}_{\mathrm{e}}\times\boldsymbol{B} + \eta\boldsymbol{j}$$

$$\boxed{= \sum_i q_i n_i} \qquad = \boxed{\frac{\sum_i q_i n_i \boldsymbol{u}_i - \boldsymbol{j}}{\sum_i q_i n_i}}$$

Hybrid-kinetic equations with minor ions

- Minor ions stored in separate particle list (modular from main code)
- Can treat actively/passively

Simplified version of the original loop



start from $\boldsymbol{E}, \ \boldsymbol{B}$

takes >90% of computational time

update particle positions and velocities (mover)

$$\frac{\mathrm{d}\boldsymbol{v}_p}{\mathrm{d}t} = \frac{q}{m}\left(\boldsymbol{E} + \frac{\boldsymbol{v}_p}{c} \times \boldsymbol{B}\right)$$

$$\frac{\mathrm{d}\boldsymbol{r}_p}{\mathrm{d}t} = \boldsymbol{v}_p$$

compute moments of the distribution function (deposit)

update $\boldsymbol{B}$, recompute $\boldsymbol{E}$

Use predicted E to correct push

E is a quasi-neutrality constraint: hybrid-kinetics is implicit!

Pegasus++ loop with minor ions

start from $\boldsymbol{E},\ \boldsymbol{B}$

↓

takes >90% of computational time

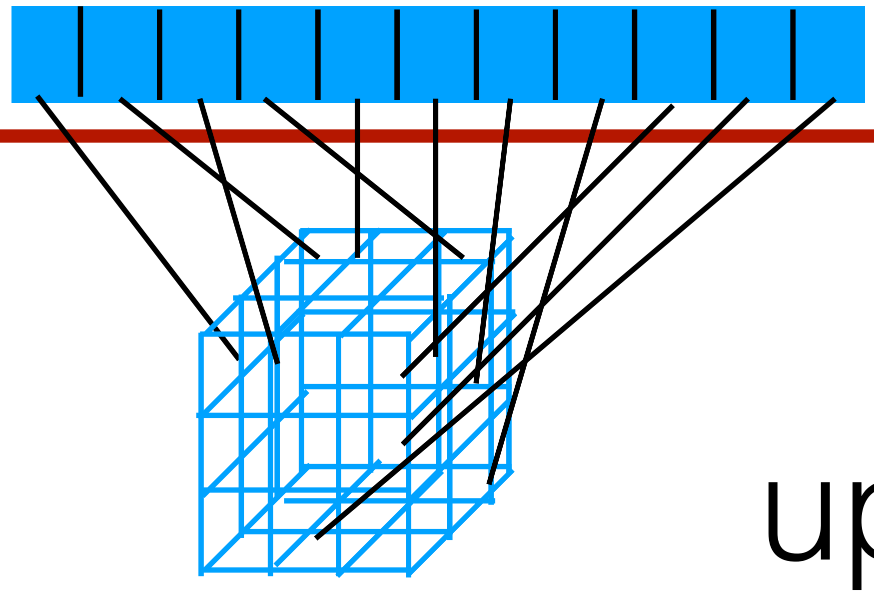
update particle positions and velocities (separate movers)

$$\frac{\mathrm{d}\boldsymbol{v}_p}{\mathrm{d}t} = \frac{q}{m}\left(\boldsymbol{E} + \frac{\boldsymbol{v}_p}{c} \times \boldsymbol{B}\right) \qquad \frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = \frac{q_i}{m_i}\left(\boldsymbol{E} + \frac{\boldsymbol{v}_i}{c} \times \boldsymbol{B}\right)$$

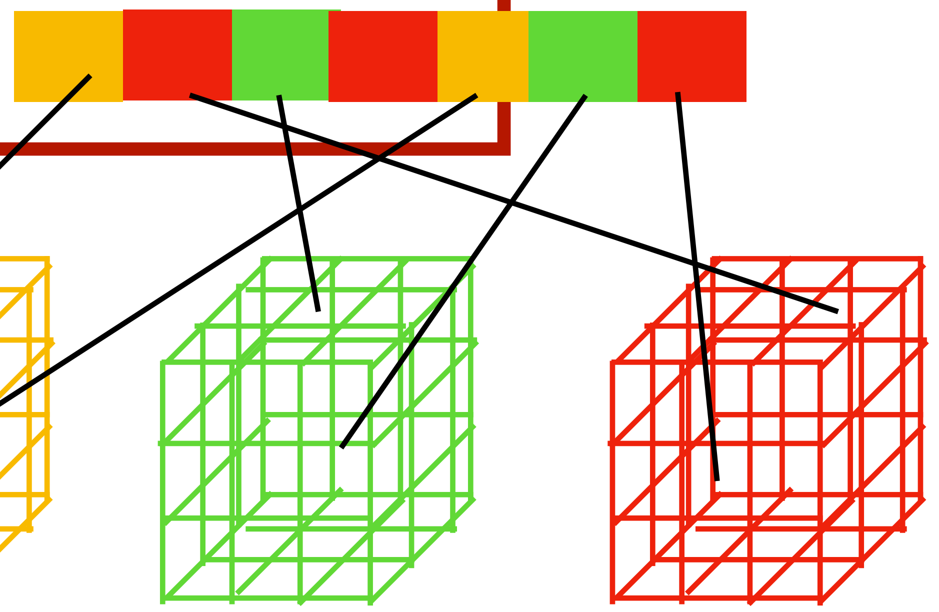
$$\frac{\mathrm{d}\boldsymbol{r}_p}{\mathrm{d}t} = \boldsymbol{v}_p \qquad \frac{\mathrm{d}\boldsymbol{r}_i}{\mathrm{d}t} = \boldsymbol{v}_i$$

↓

compute moments of the distribution function



(separate deposits)



↓

update $\boldsymbol{B}$, recompute $\boldsymbol{E}$

Example of a Pegasus++ minor ion test

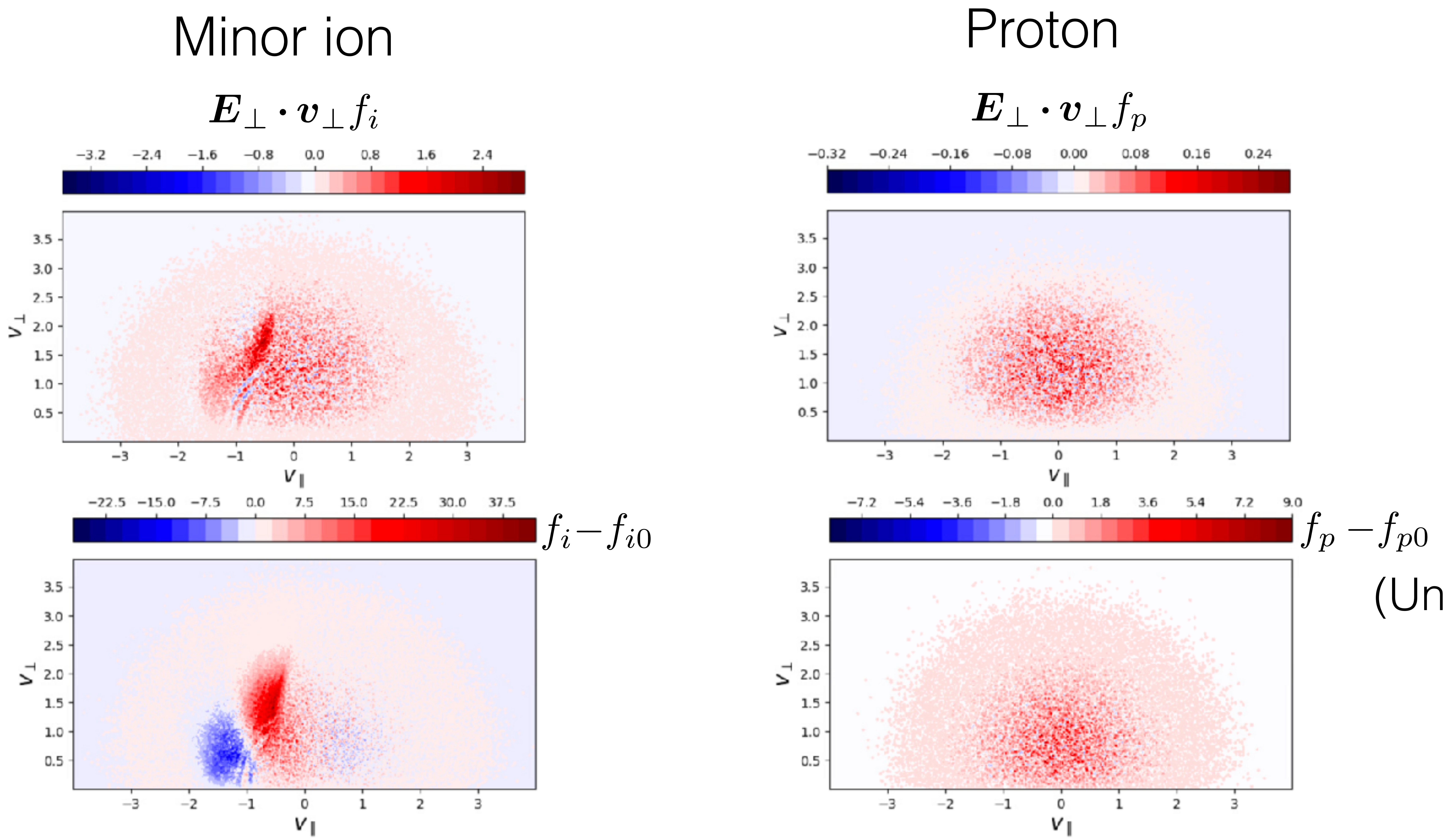
1D ion cyclotron wave test - observed heating of resonant minor ion species

$$\frac{q_i}{q_p} = 1$$

$$\frac{m_i}{m_p} = 4$$

$$\frac{n_i}{n_p} = 0.03$$

$$\frac{T_i}{T_p} = 36$$



(Unnormalized)

$$\beta_p = 1$$

$$k_\parallel = \frac{2\pi}{100}$$

Upcoming frontera runs

- Minor ion imbalanced turbulence runs
    - Study the impact of imbalance and beta on the helicity barrier and associated heating of different solar-wind ions
- High-beta turbulence run with compressive driving (Stephen Majeski)
- Dynamo run to test the idea of an explosive phase of plasma dynamo (Muni Zhou)