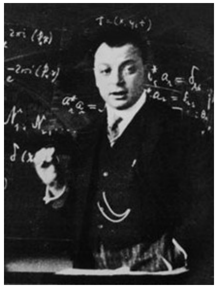


WPI, Vienna 30 July 2018

Ion vs. Electron Heating by Plasma Turbulence

(an accretion-disc problem that opened the "plasmagates")

←Yohei Kawazura, Michael Barnes→

&

Alex Schekochihin

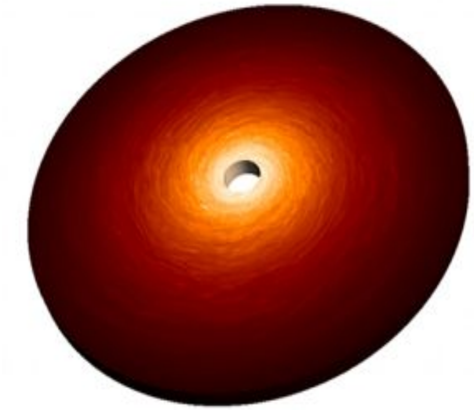
(Oxford)

with thanks to S. Cowley, W. Dorland, E. Quataert (who started this),
G. Howes (who turned it into an astro-useable model),
S. Balbus, F. Parra (who were here to help us),
B. Chandran, M. Kunz, N. Loureiro, A. Mallet, R. Meyrand (who were there to discuss)

[arXiv:1807.07702]

An Astrophysics Problem

Matter in discs **accretes** onto central black hole.



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[Rees, Begelman & Blandford 1982; Narayan & Yi 1995; Quataert & Gruzinov 1999]

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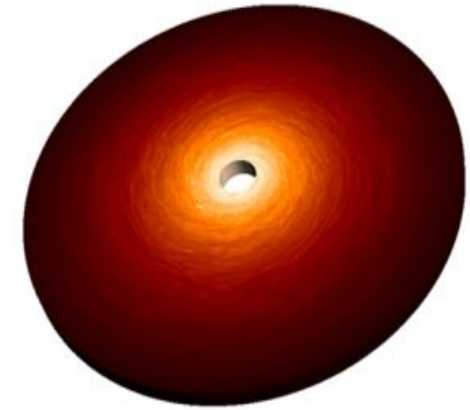

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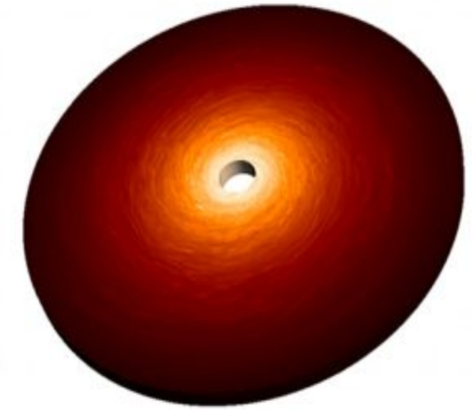

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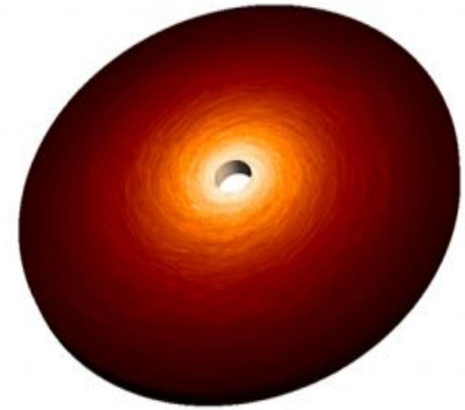

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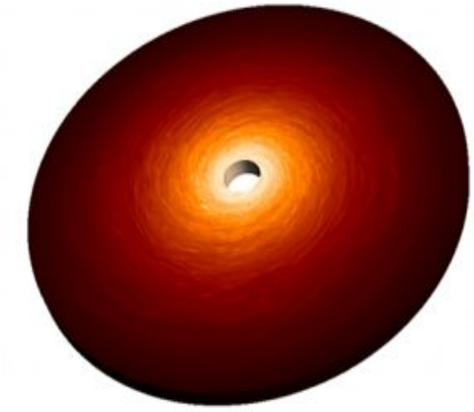

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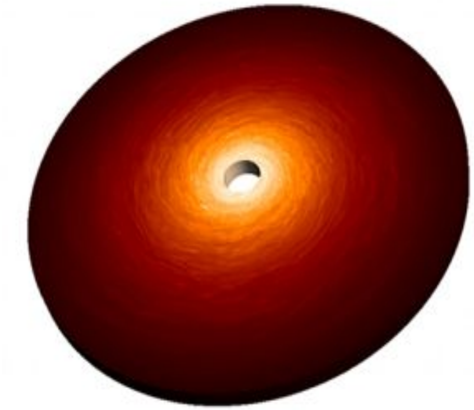

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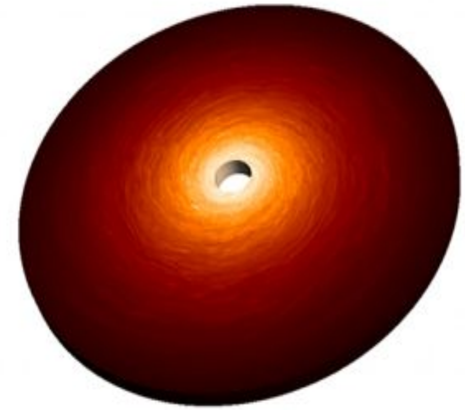

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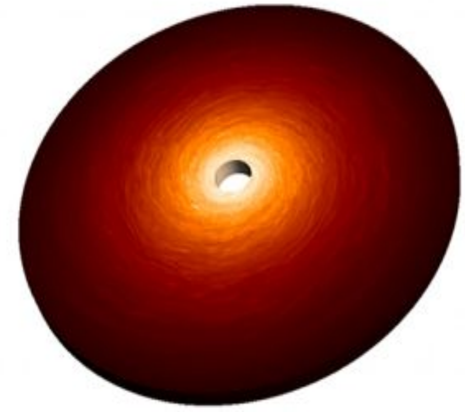

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This question is meaningful in a **weakly collisional plasma**,

where Coulomb equilibration between species is slow.

A Physics Problem

This problem can be cast in **fundamental physics** terms:

A state with different T_i and T_e is out of equilibrium (has free energy).
However, we do not know of any linear instabilities that feed off that.
The only equilibration mechanism we know is collisions: slow!

Is there a nonlinear mechanism for nature to be impatient and push the two species towards equilibrium?

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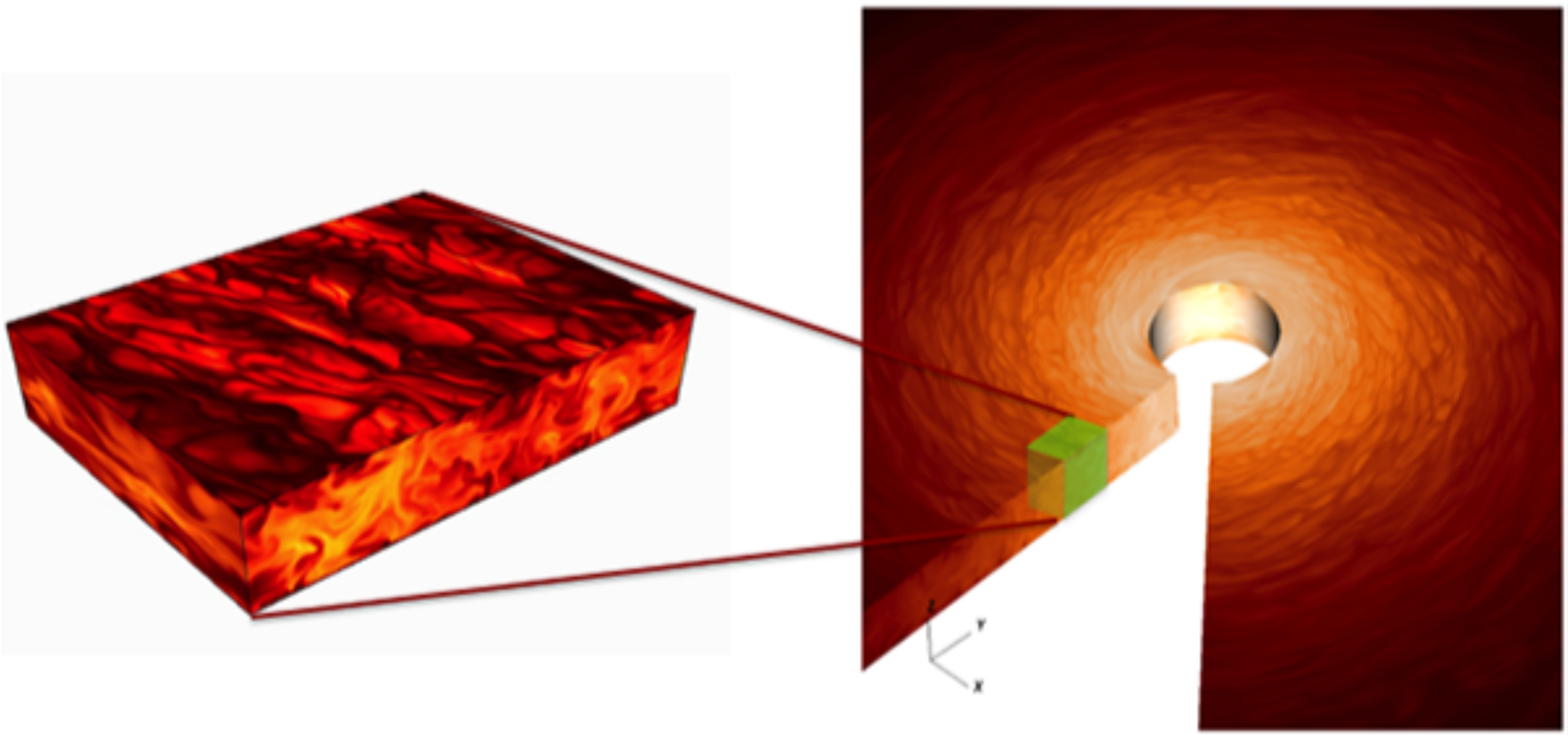
This is a **plasma physics problem**
because in MHD the two species move together.

Global Zoo to Local Universality

General philosophy is that, whatever the global specifics of a particular system, they all happen at MHD scales, where ions and electrons move together, so energy partition between is as yet undecided.

At sufficiently small (but still MHD) scales, turbulence becomes universal, viz., anisotropic ($k_\perp \gg k_\parallel$) MHD turbulence in a strong mean field.

So our problem can be solved in a homogeneous box, into which energy is (artificially) injected at a given rate.



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The compressive cascade is passively advected by the Alfvénic one.

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In the solar wind, observationally, most of the energy is in the Alfvénic cascade; we do not know whether it is so elsewhere in Nature.

In our simulations, we only injected Alfvénic perturbations.

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This changes the nature of turbulence:

from cascade of Alfvén waves ($\omega = k_\parallel v_A,\ E_\perp \sim u_\perp \sim \delta B_\perp$)

+ compressive perturbations

to "kinetic Alfvén waves" (KAW, $\omega \propto k_\parallel v_A k_\perp \rho_i,\ E_\perp \sim k_\perp \delta B_\perp$)

↳ **electron heating** Q_e

+ phase-space cascade of ion entropy (linear & nonlinear phase mixing)

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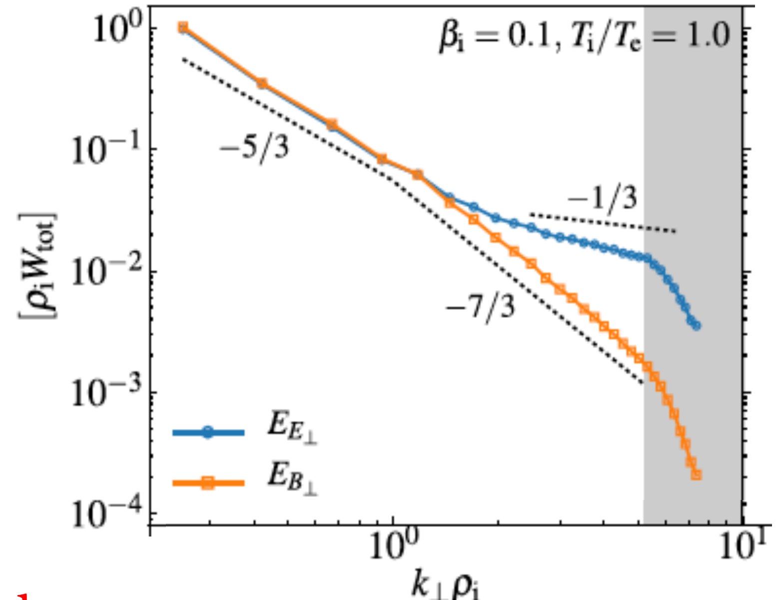

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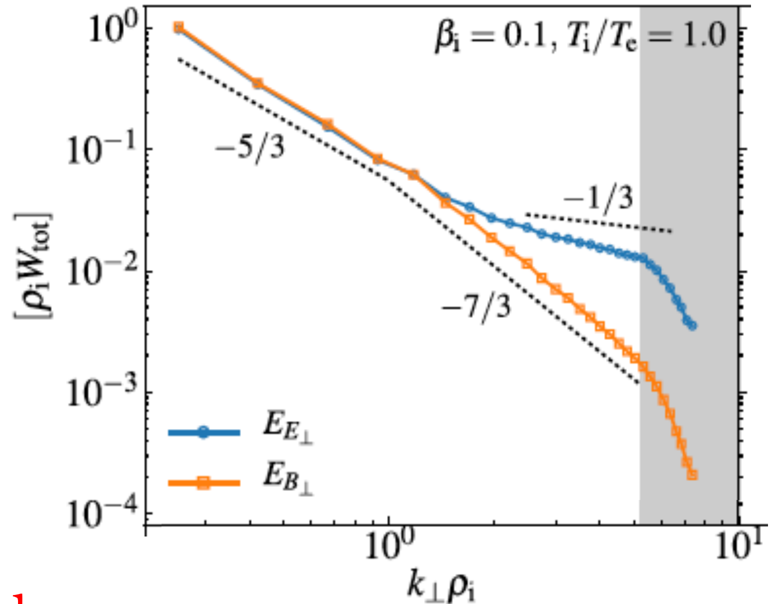

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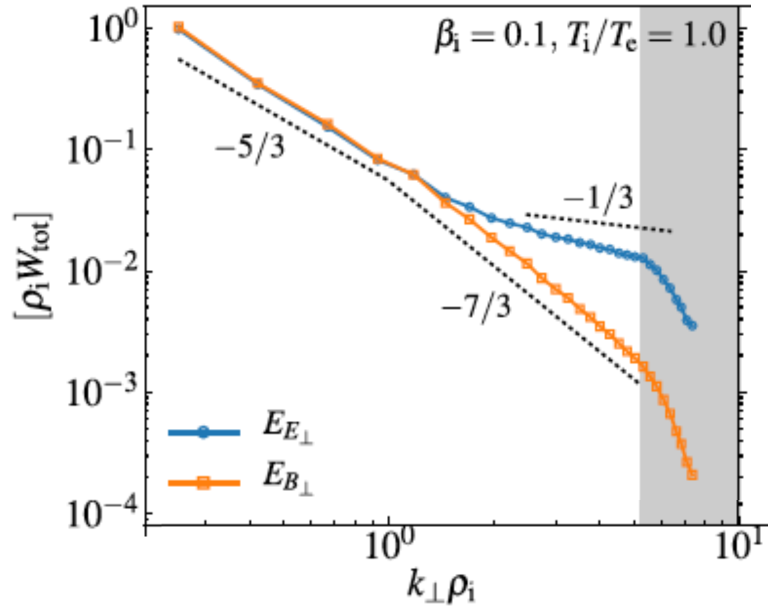
Therefore, all one needs to do is solve for **(gyro)kinetic ions + fluid (isothermal) electrons.**



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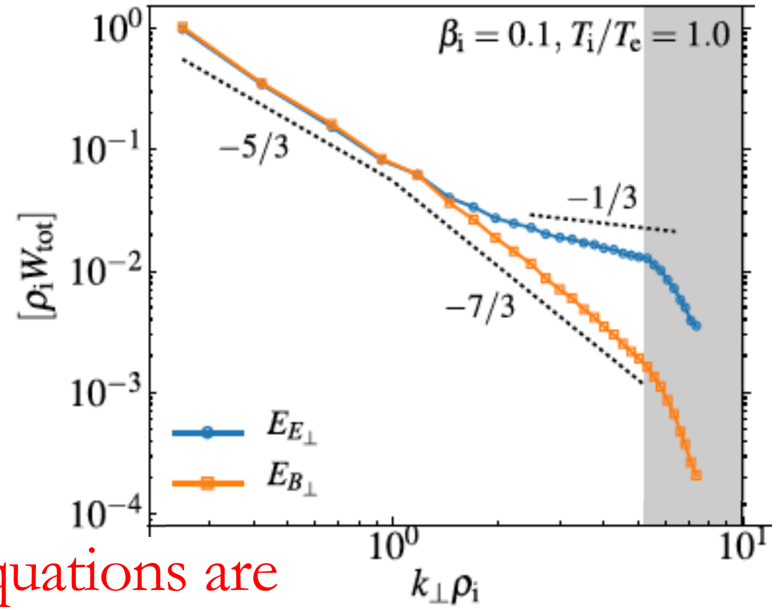


Therefore, all one needs to do is solve for **(gyro)kinetic ions + fluid (isothermal) electrons.** The equations are

$$f = F_0 + \delta f, \quad \delta f = -\varphi(\boldsymbol{r}) F_0 + h(\boldsymbol{R}), \quad \boldsymbol{R} = \boldsymbol{r} + \boldsymbol{\rho}, \quad \boldsymbol{\rho} = \frac{\boldsymbol{v}_\perp \times \hat{\boldsymbol{z}}}{\Omega}$$

$$\frac{\partial h}{\partial t} + v_\parallel \frac{\partial h}{\partial z} + \frac{\rho_i v_{th}}{2}\{\langle\chi\rangle_{\boldsymbol{R}}, h\} = \frac{\partial \langle\chi\rangle_{\boldsymbol{R}}}{\partial t} F_0 + C[h] \quad \langle\chi\rangle_{\boldsymbol{R}} = \hat{J}_0\varphi - 2\hat{v}_\parallel \hat{J}_0 \mathcal{A} + \hat{v}_\perp^2 \hat{J}_1 \frac{\delta B}{B}$$

$$\frac{\partial \mathcal{A}}{\partial t} + \frac{v_{th}}{2}\nabla_\parallel \varphi = \frac{v_{th}}{2}\nabla_\parallel \frac{Z}{\tau}\frac{\delta n}{n} + \eta \nabla_\perp^2 \mathcal{A}, \qquad \varphi = \frac{Ze\phi}{T_i} \qquad \mathcal{A} = \frac{A_\parallel}{\rho_i B_0}$$

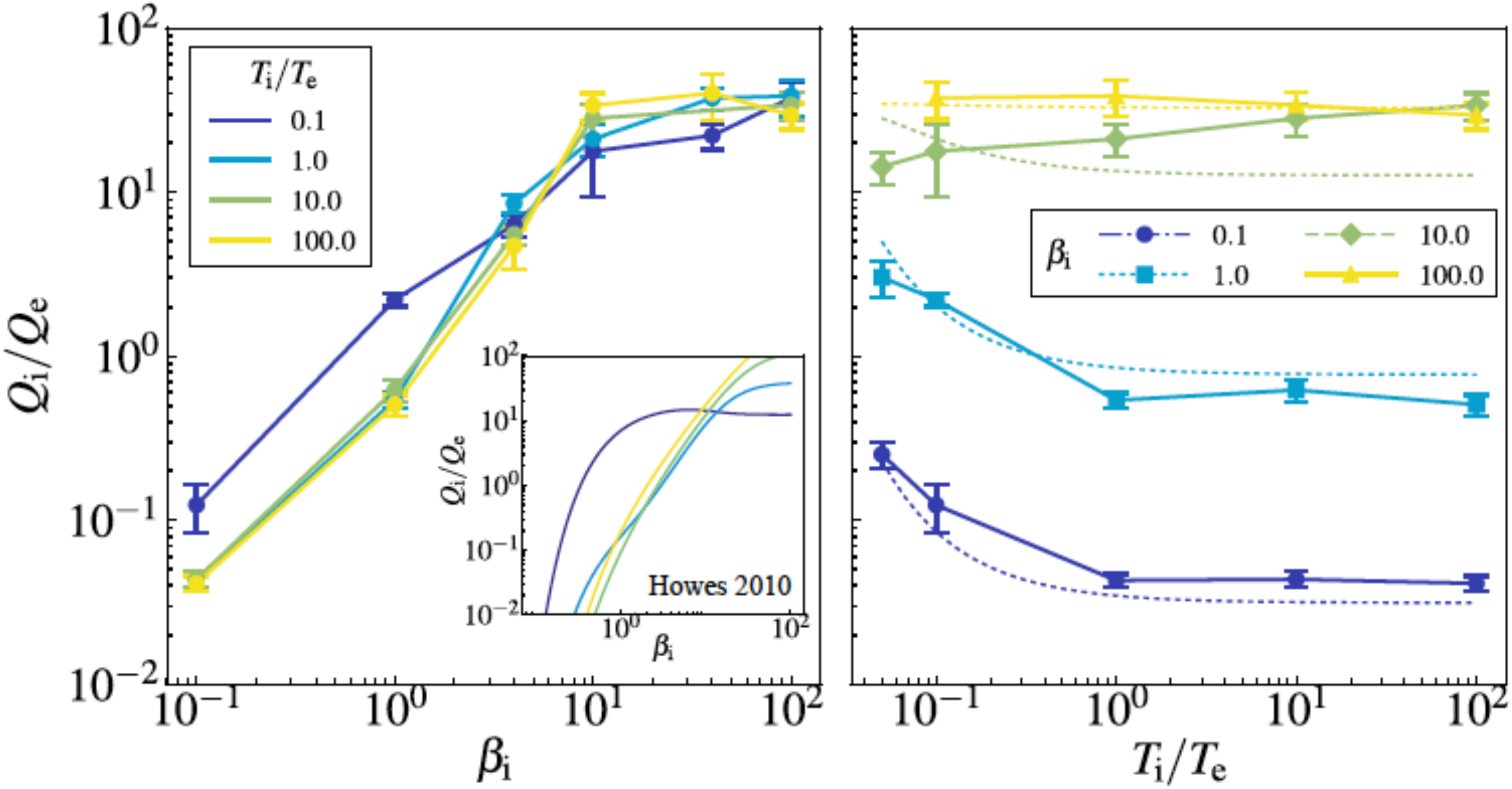
$$\frac{d}{dt}\left(\frac{\delta n}{n} - \frac{\delta B}{B}\right) + \nabla_\parallel u_{\parallel e} = -\frac{\rho_i v_{th}}{2}\left\{\frac{Z}{\tau}\frac{\delta n}{n}, \frac{\delta B}{B}\right\}$$

$$\frac{\delta n}{n} = -\varphi + \overline{\hat{J}_0 h}, \quad \frac{u_{\parallel e}}{v_{th}} = \frac{1}{\beta_i}\hat{\nabla}_\perp^2 \mathcal{A} + \overline{\hat{v}_\parallel \hat{J}_0 h} + \mathcal{J}_{ext}, \quad \frac{2}{\beta_i}\frac{\delta B}{B} = \left(1 + \frac{Z}{\tau}\right)\varphi - \frac{Z}{\tau}\overline{\hat{J}_0 h} - \overline{\hat{v}_\perp^2 \hat{J}_1 h}$$

New code: Kawazura & Barnes 2018, *JCP* **360**, 57

[AAS et al. 2009, *ApJS* **182**, 310]

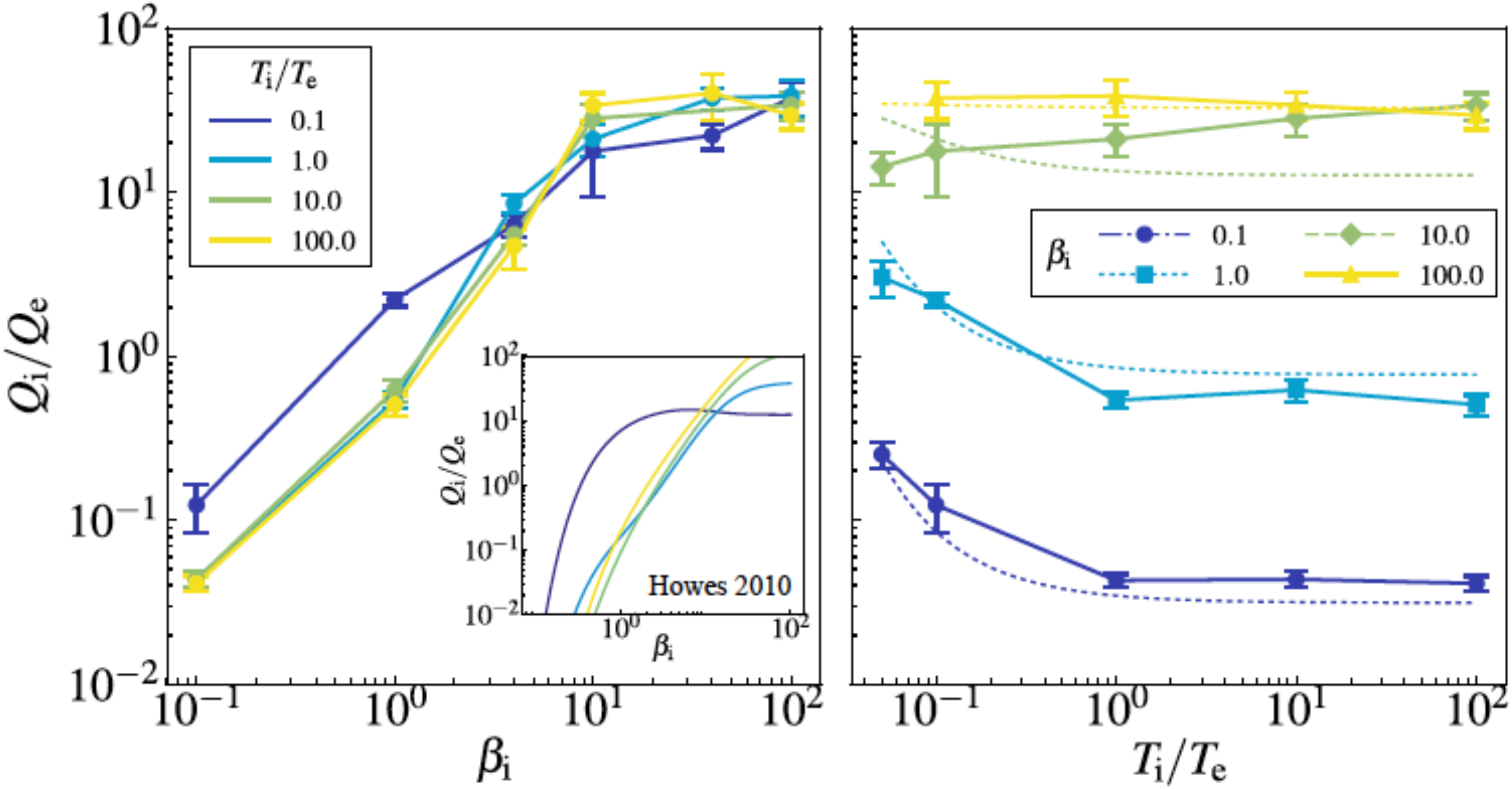
Result ©*Yohei Kawazura 2018*



previous, full-GK calculations by Howes et al. 2008, 2011; Told et al. 2015, Bañon Navarro et al. 2016 could only afford to do one point: $\beta_i = 1$, $T_i/T_e = 1$

[Kawazura et al. 2018, arXiv:1807.07702]

Result ©Yohei Kawazura 2018



Turbulence is indifferent to species inequality (except perhaps a little at $T_i \ll T_e$ and $\beta_i \lesssim 1$)

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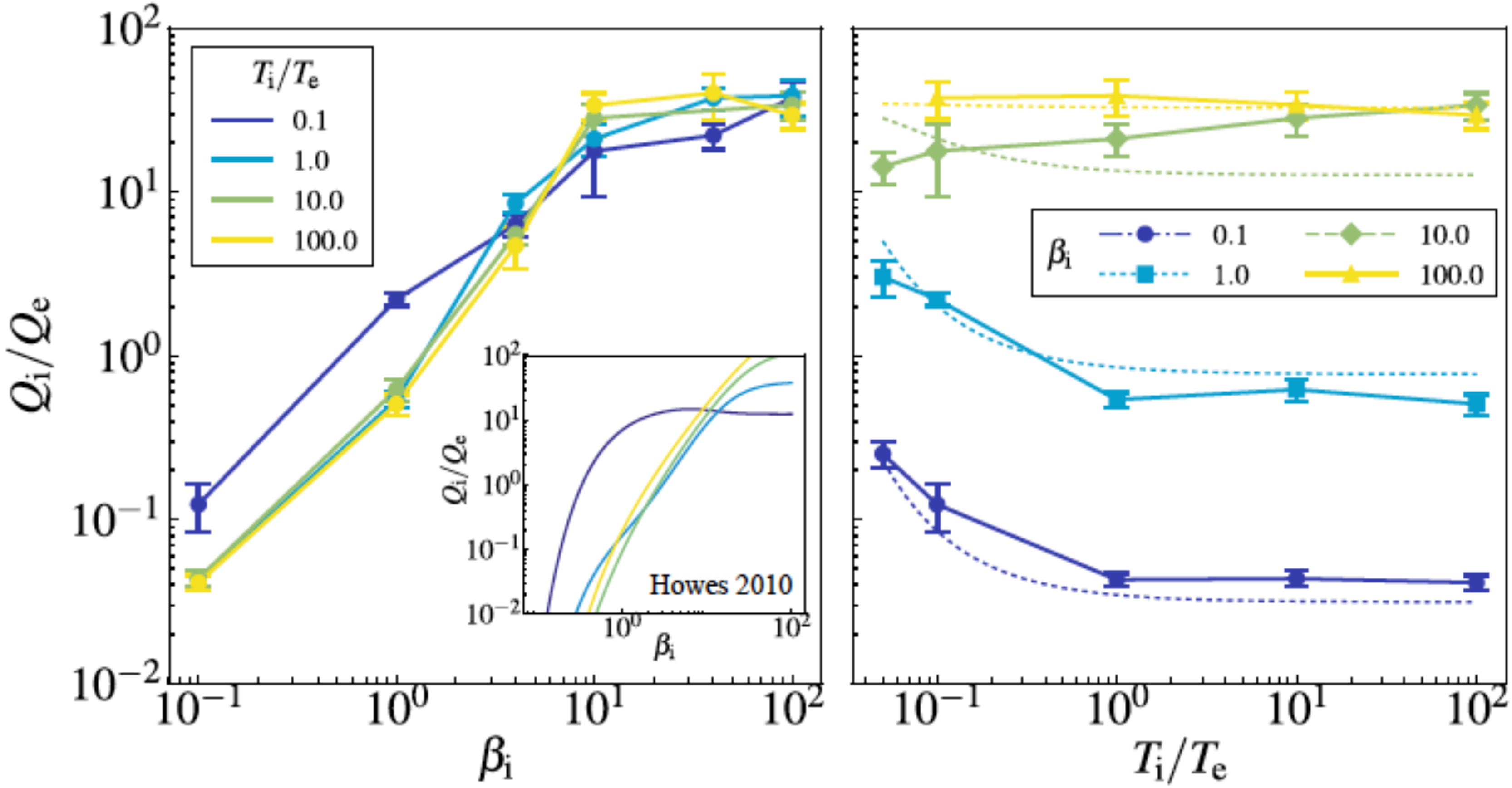

Disequilibration of species:
at high β_i, ions get hotter
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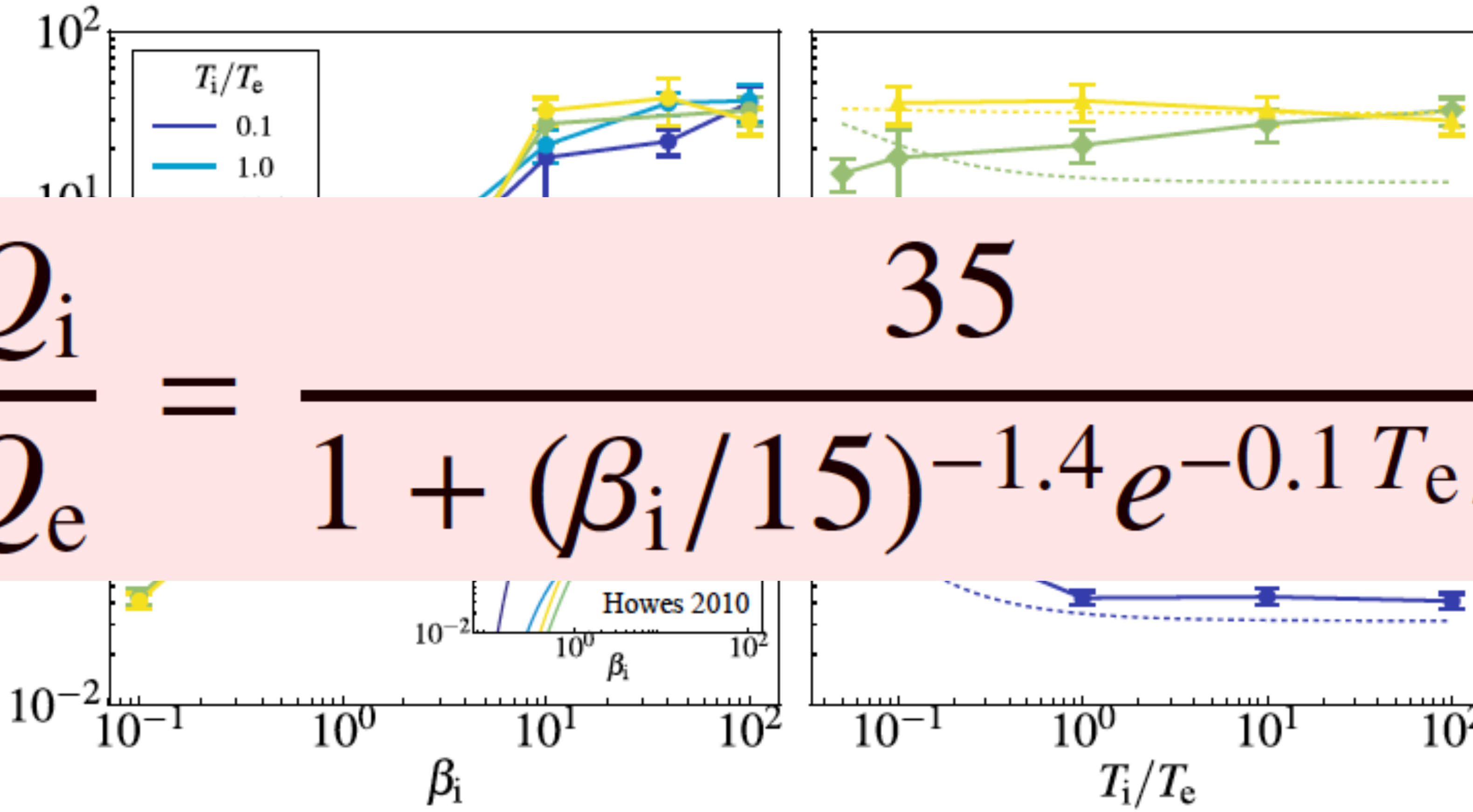
Prescription for Modellers



$$\frac{Q_i}{Q_e} = \frac{35}{1 + (\beta_i/15)^{-1.4} e^{-0.1\, T_e/T_i}}$$

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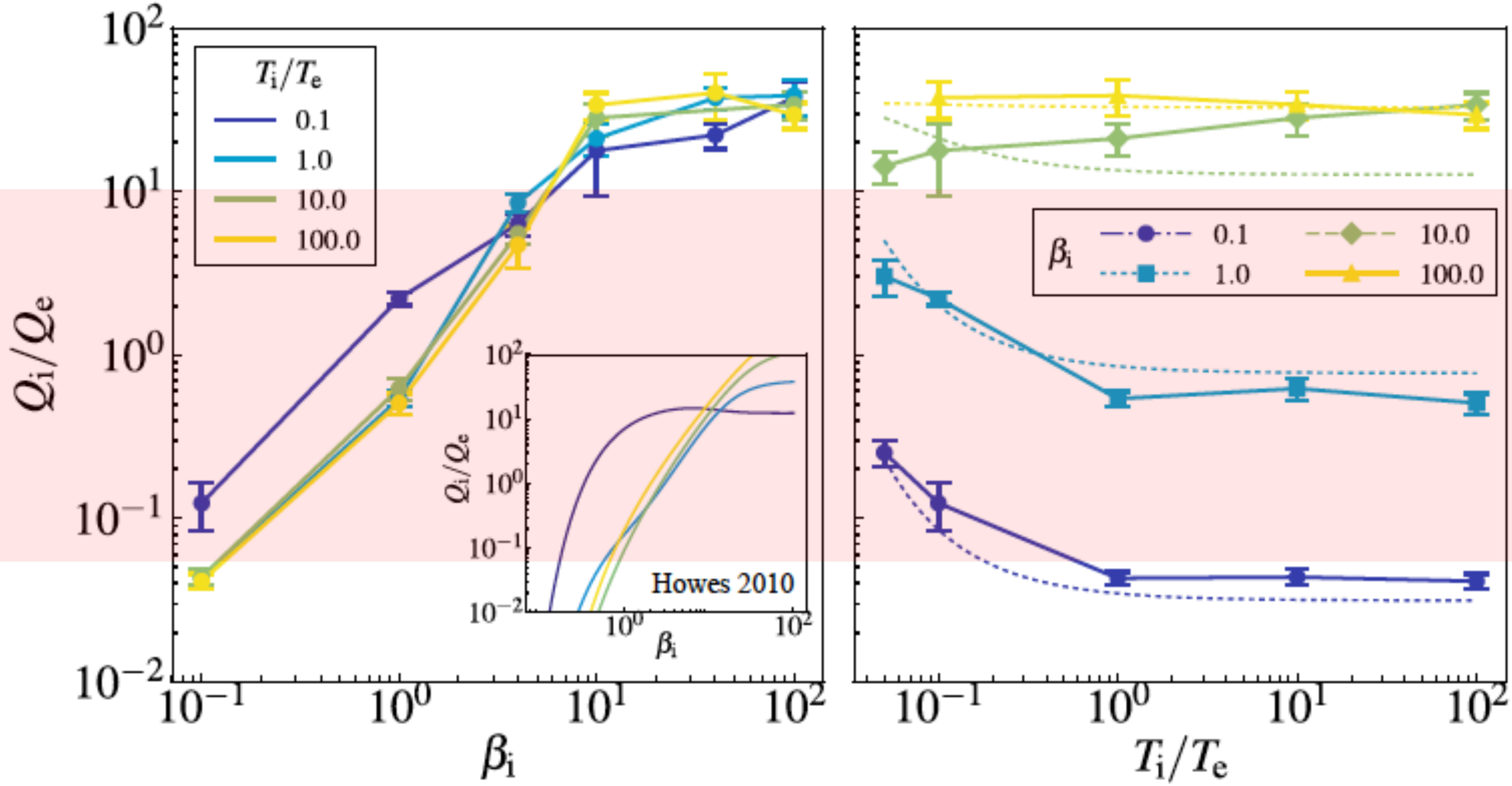

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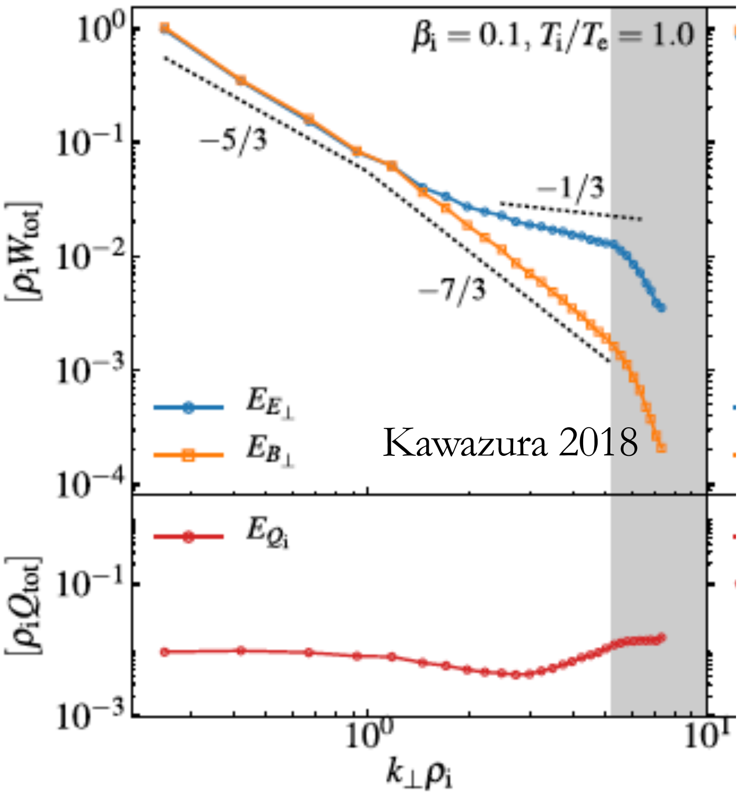
Low Beta



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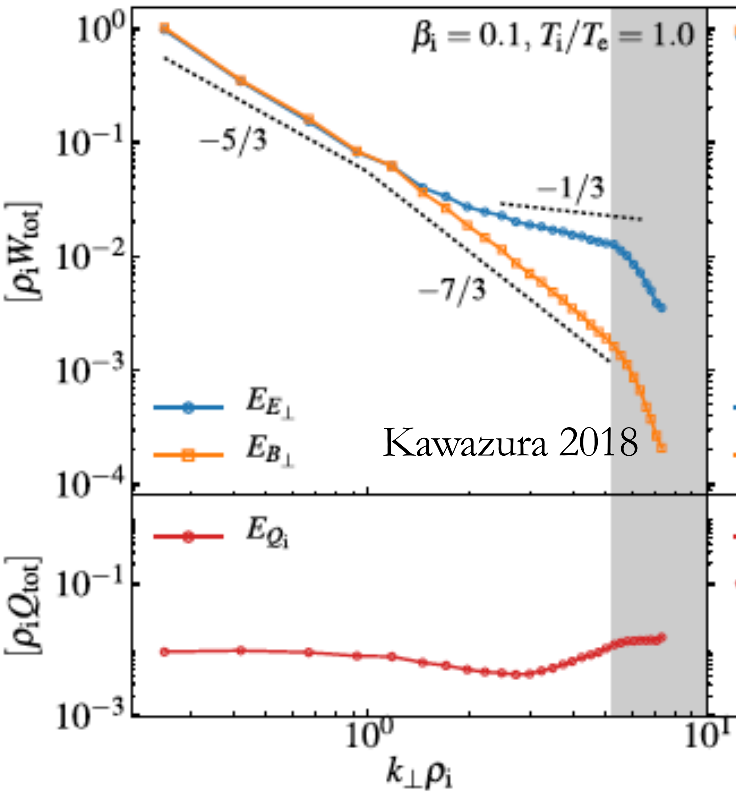

One can prove analytically that $Q_i/Q_e \to 0$ as $\beta_i \to 0$ because ions are slower than Alfvén waves: $v_{thi} = v_A\, \beta_i^{1/2} \ll v_A$

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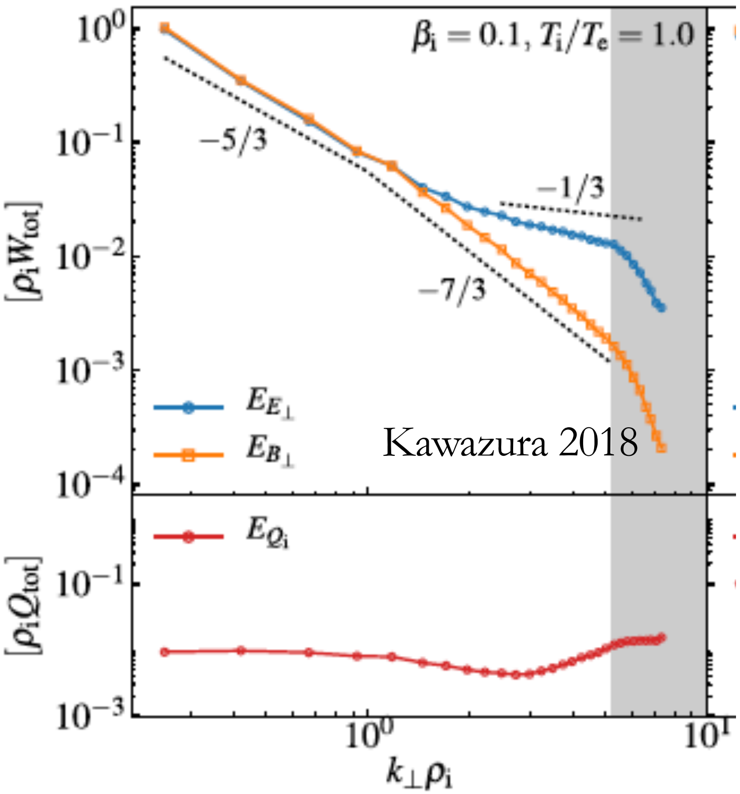

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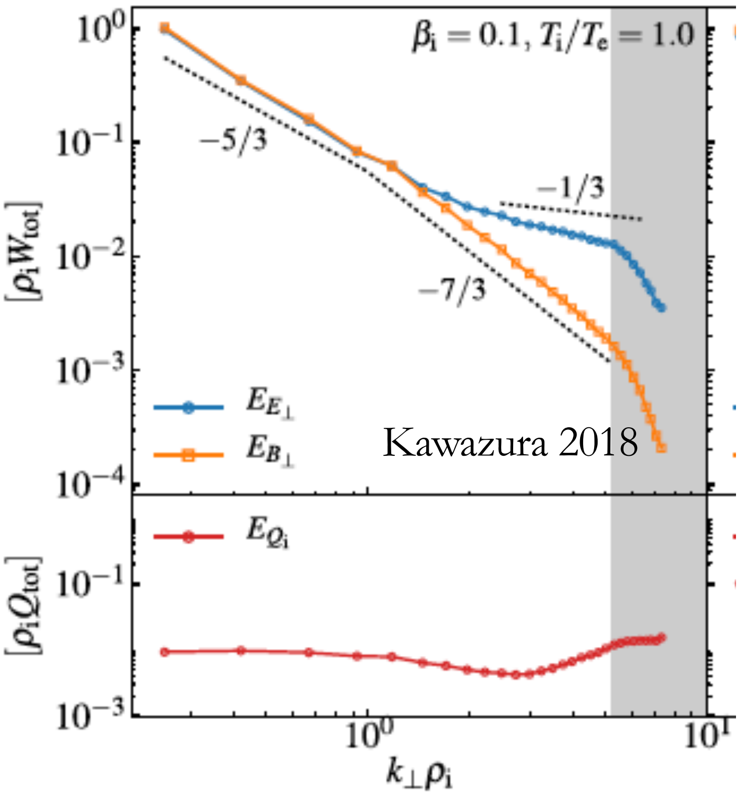

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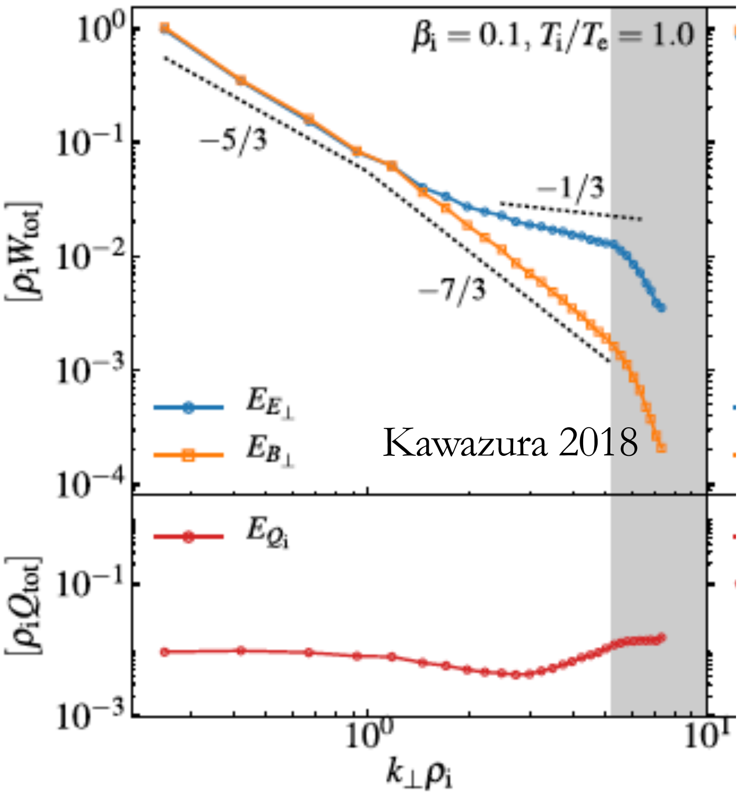

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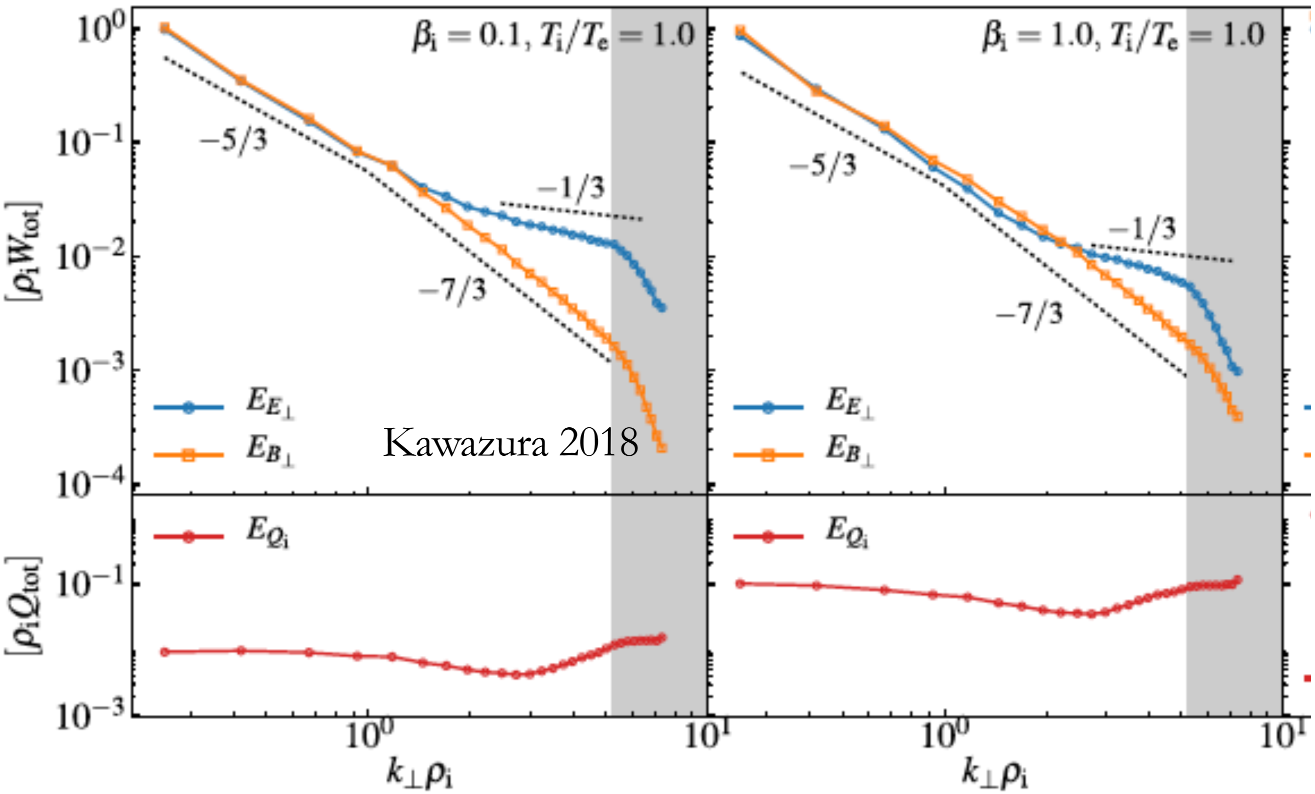
CAVEATS:

- GK does not have **stochastic ion heating** [Chandran 2010]
- We might not be resolving **multiscale reconnection heating** [cf. Rowan, Sironi, Narayan 2017]

Beta = 1



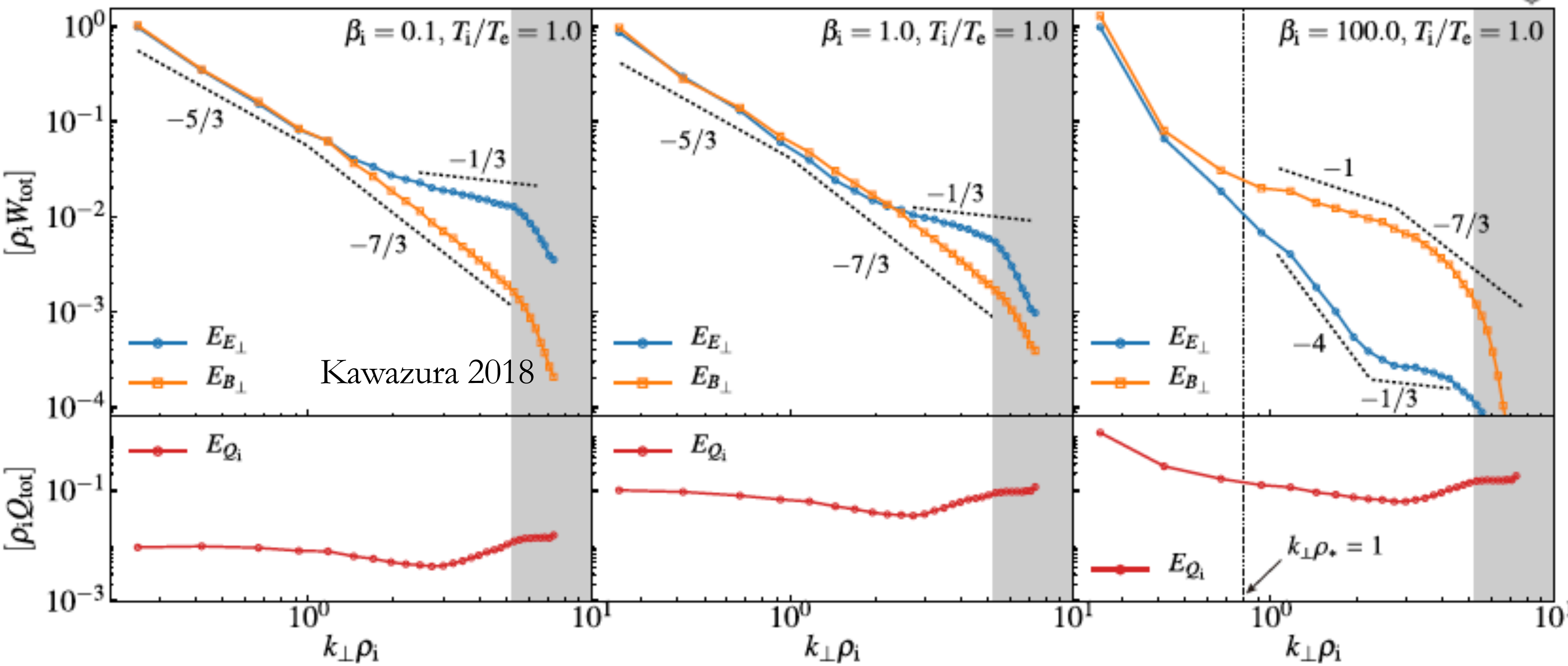
***Qi/Qe* ≅ 0.5**

[same result found by Told et al. 2015 in full two-species GK]

Non-asymptotic case: a bit of this, a bit of that…

[Kawazura et al. 2018, arXiv:1807.07702]

High Beta



[Kawazura et al. 2018, arXiv:1807.07702]

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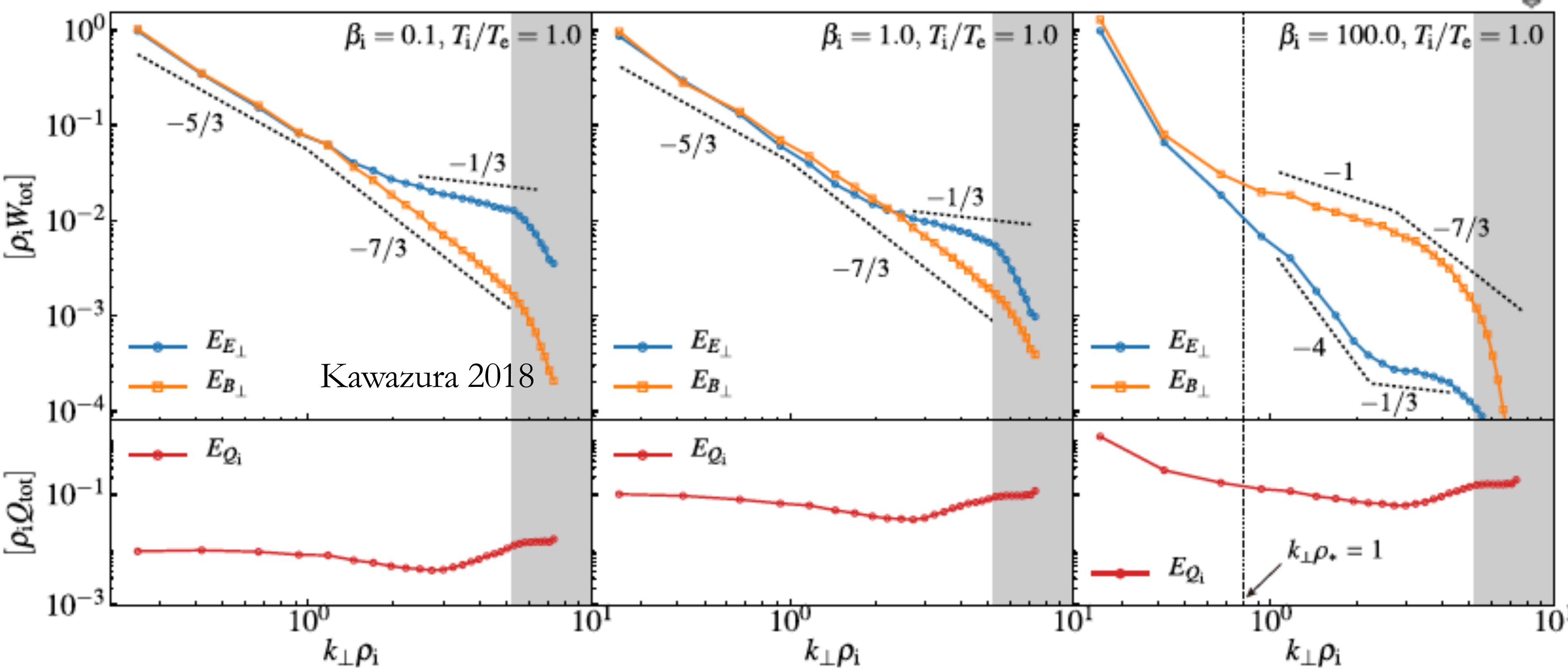
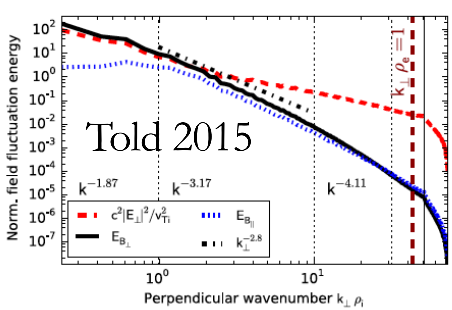
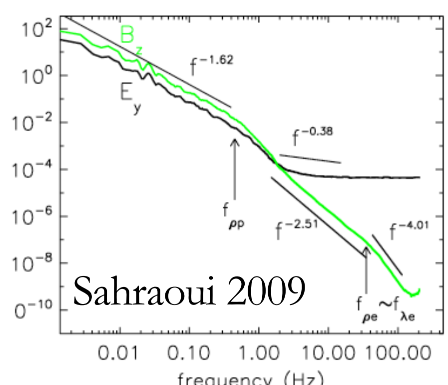


These are familiar from simulations and solar wind…





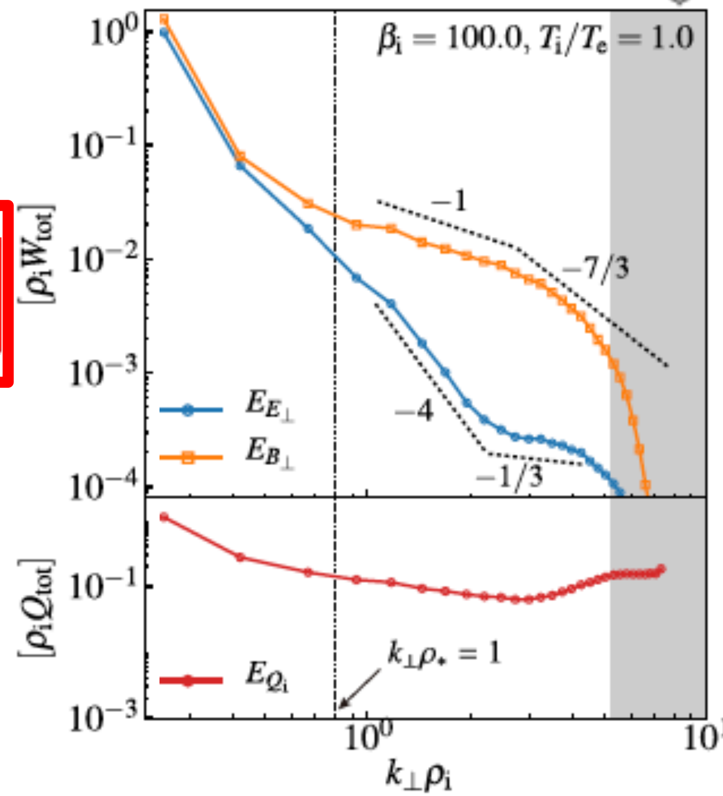
↑

…but this is a **new regime!**

High Beta

Alfvén waves at high β_i are heavily damped and stop propagating around $k_\perp \rho_* = 1,\ \rho_* \sim \rho_i \beta_i^{-1/4}$:

$$\omega = |k_\parallel| v_A \left[\pm\sqrt{1-(k_\perp \rho_*)^4} - i(k_\perp \rho_*)^2 \right]$$



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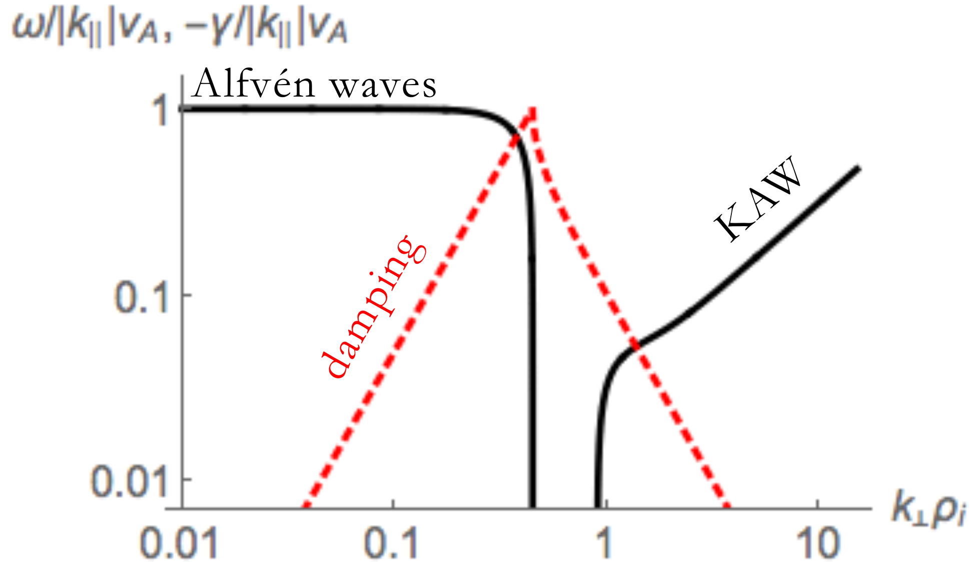

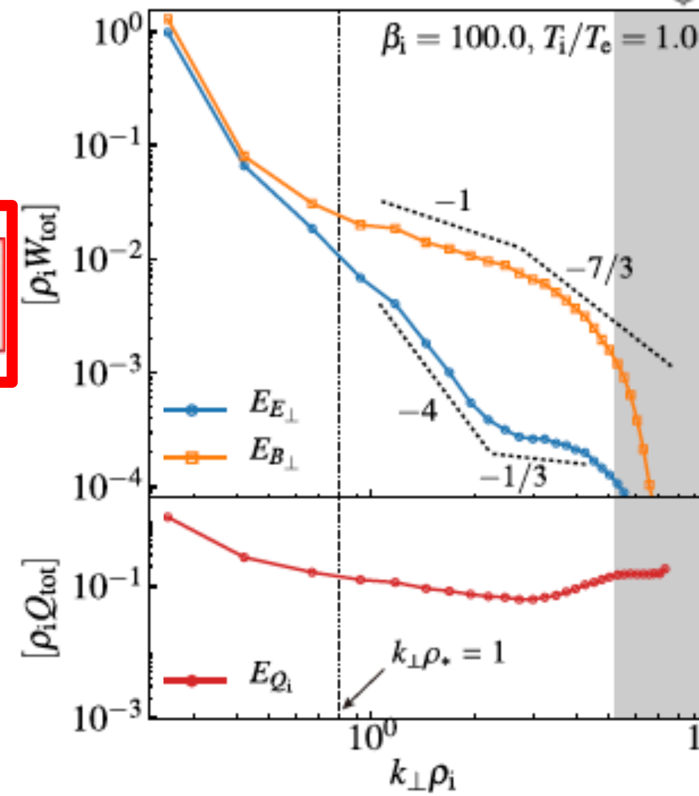

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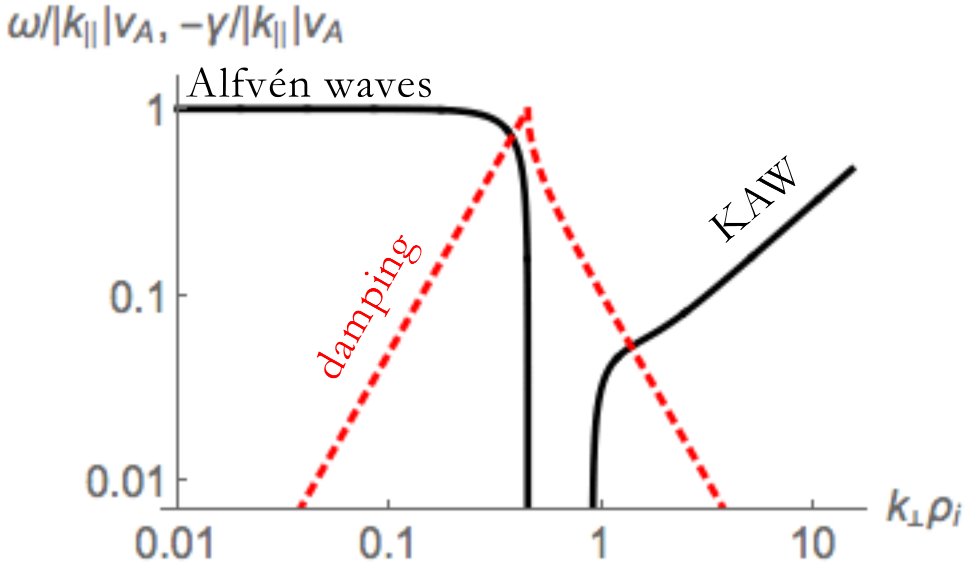

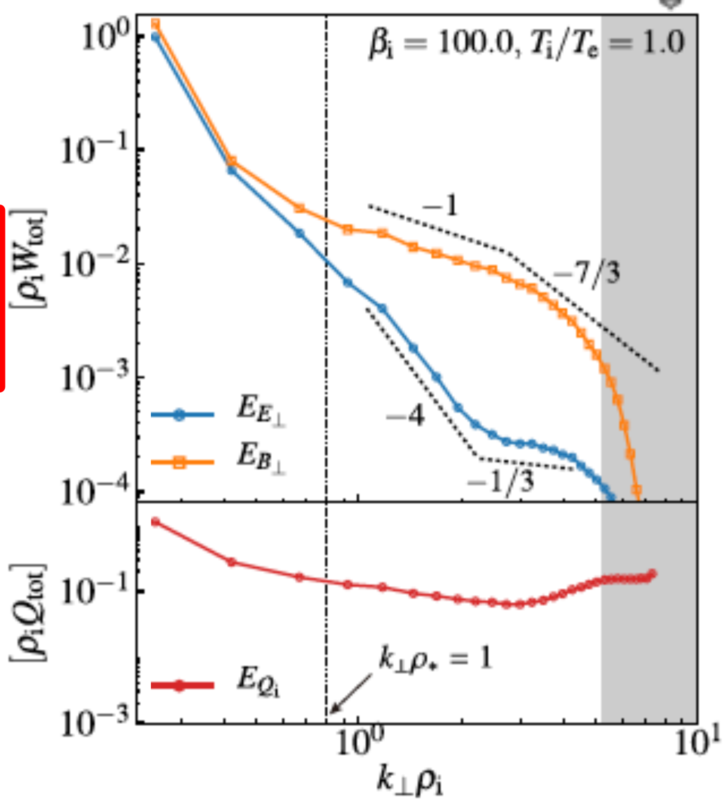

At $k_\perp \rho_* \gg 1$, like an overdamped oscillator:
magnetic fields (displacements) **not damped**
velocities heavily damped

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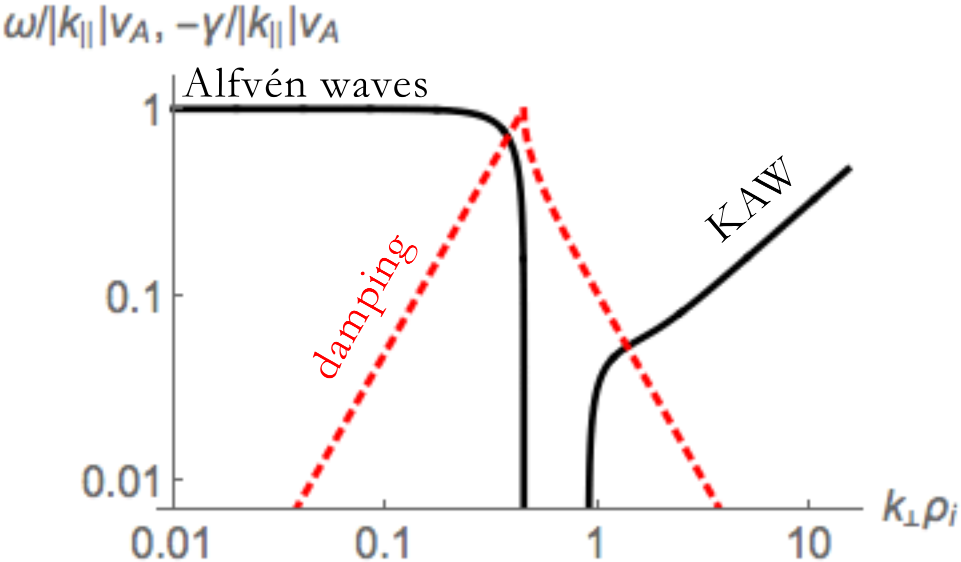

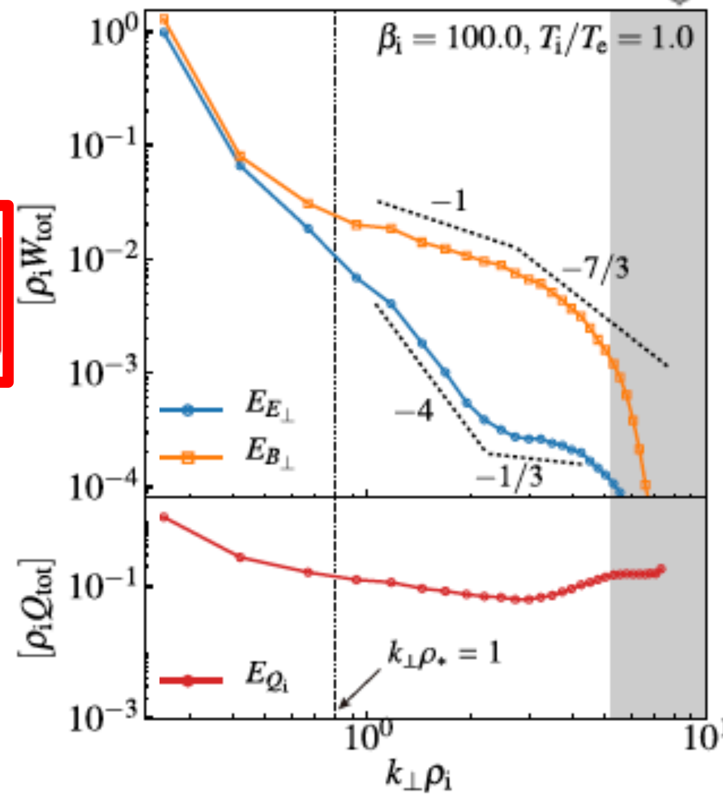

Magnetic-only cascade (fields advected by ρ_*-scale motions)

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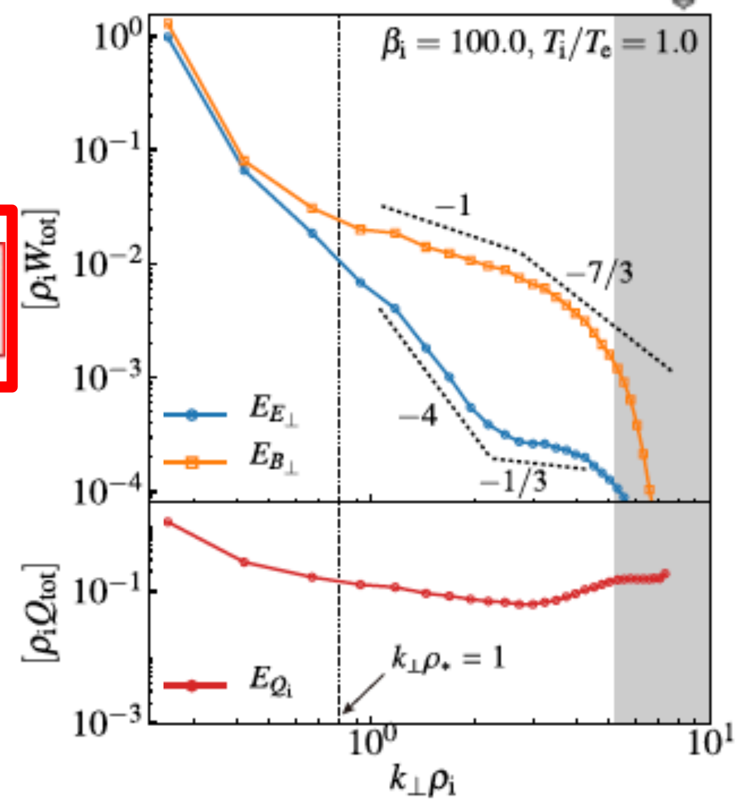

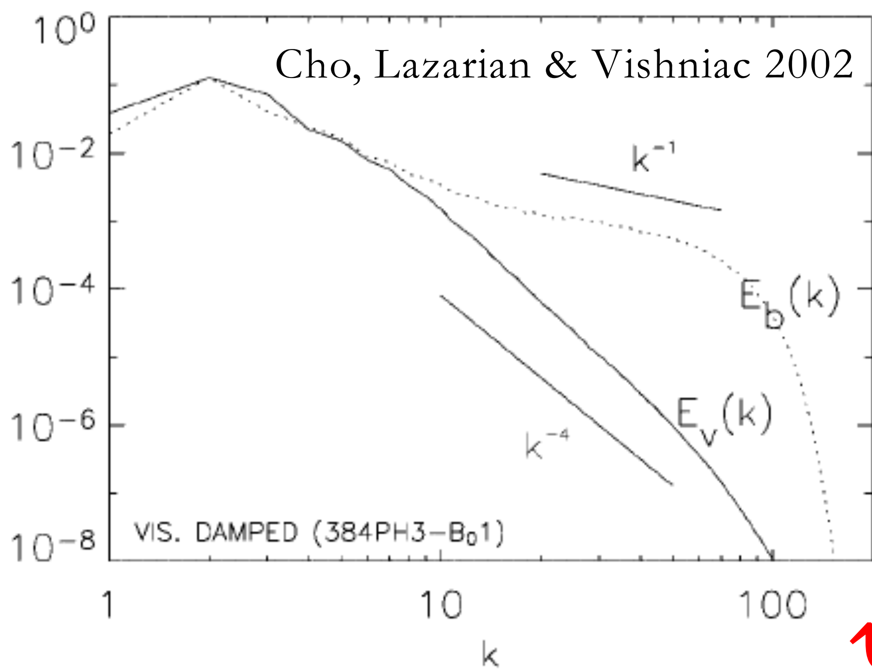

Magnetic-only cascade (fields advected by ρ_*-scale motions)

Reminiscent of high-Pm MHD turbulence at subviscous scales

[Kawazura et al. 2018, arXiv:1807.07702]

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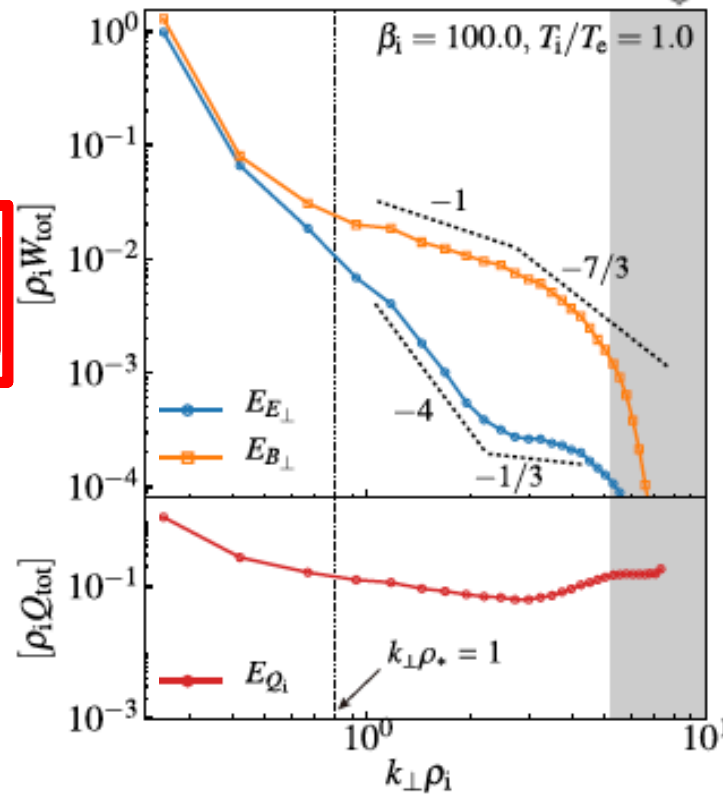
Since $\mathrm{Im}\,\omega \sim |k_\parallel| v_A \sim \tau_{\mathrm{nlin}}^{-1}$ at $k_\perp \rho_* \sim 1$, **an order-unity fraction of cascaded energy is converted into ion heat**



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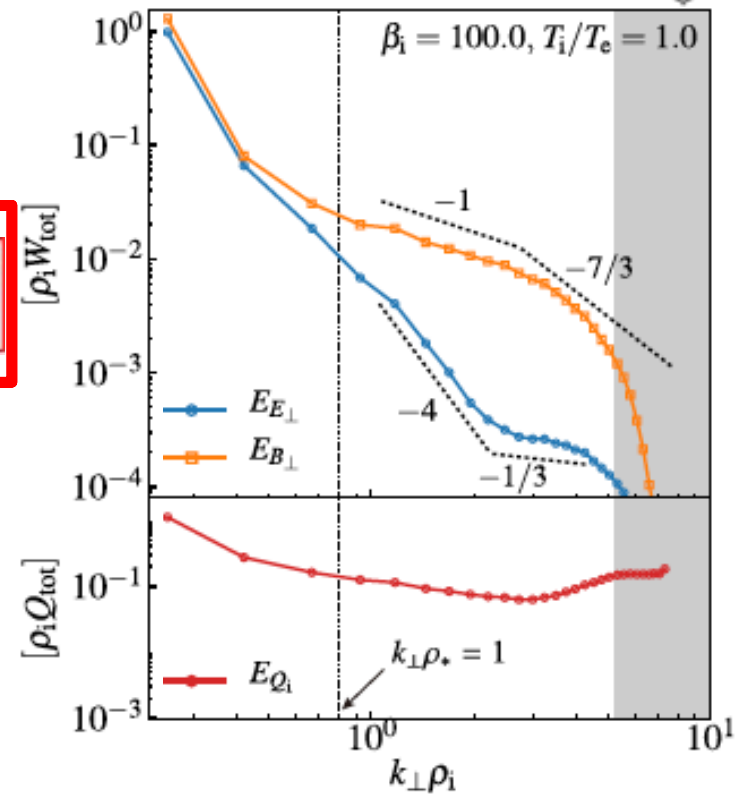
What fraction is what numerics tell us, viz., ***$Q_i/Q_e \sim 30$***



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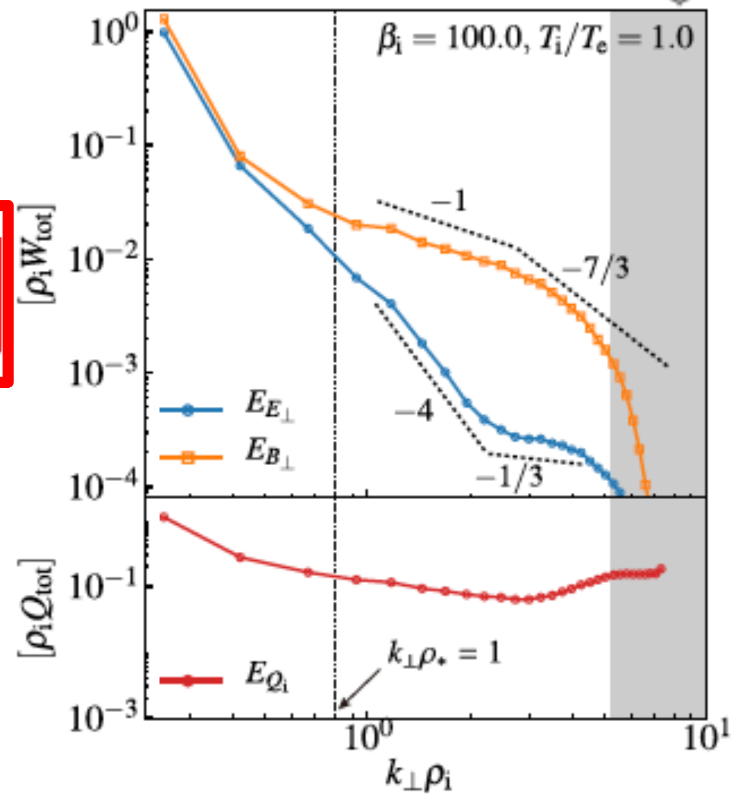

Magnetic-only cascade (fields advected by ρ_*-scale motions)

What fraction is what numerics tell us, viz.,
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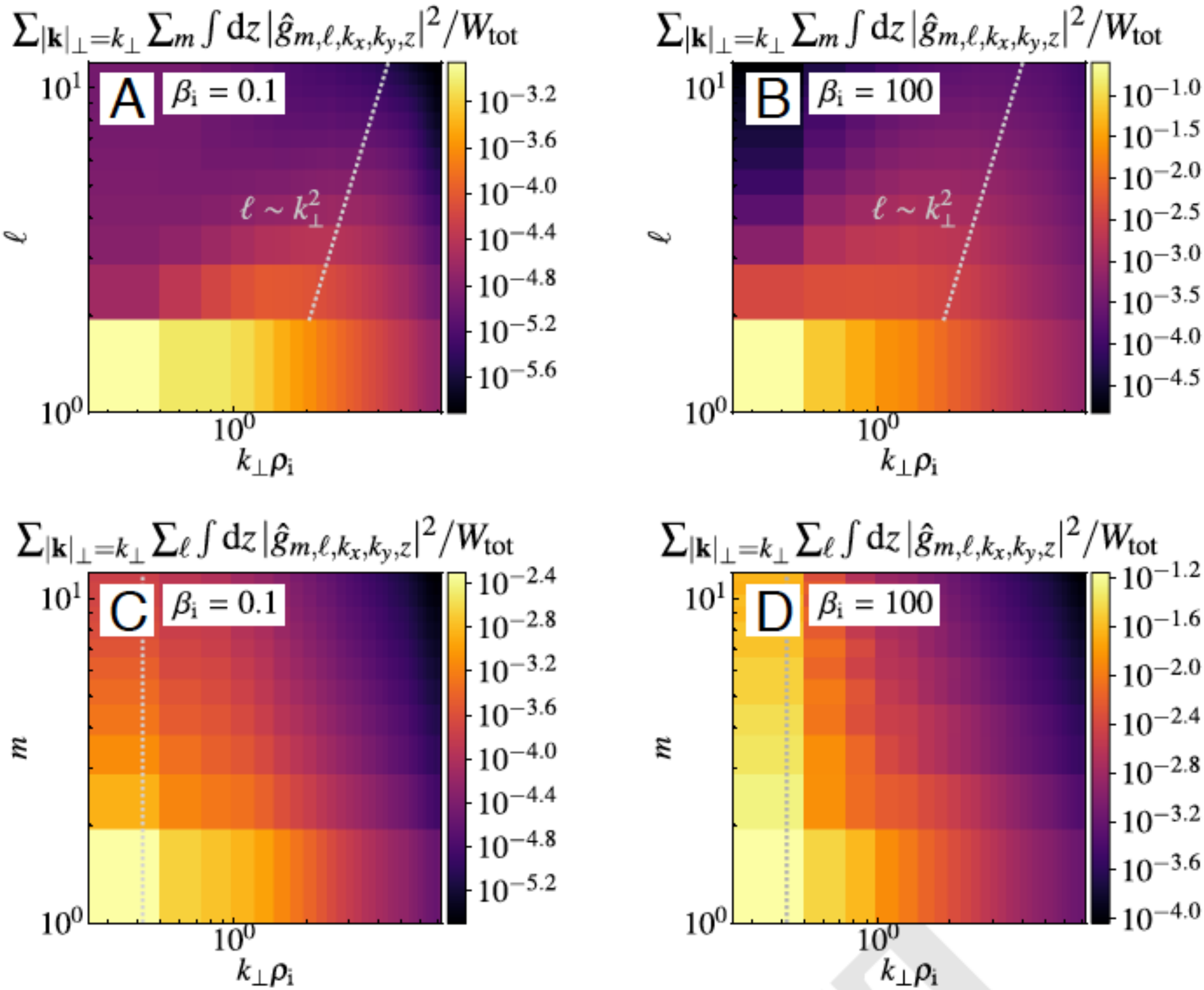
Why this, exactly, and why it saturates is to do with

- how efficient Landau damping is in a turbulent environment [cf. AAS et al. 2016, *JPP* **82**, 905820212: echo effect]
- how efficiently energy is channeled from magnetic to KAW cascade

Phase-Space Cascades

Laguerre (dual to $v_\perp$)

Hermite (dual to $v_\parallel$)



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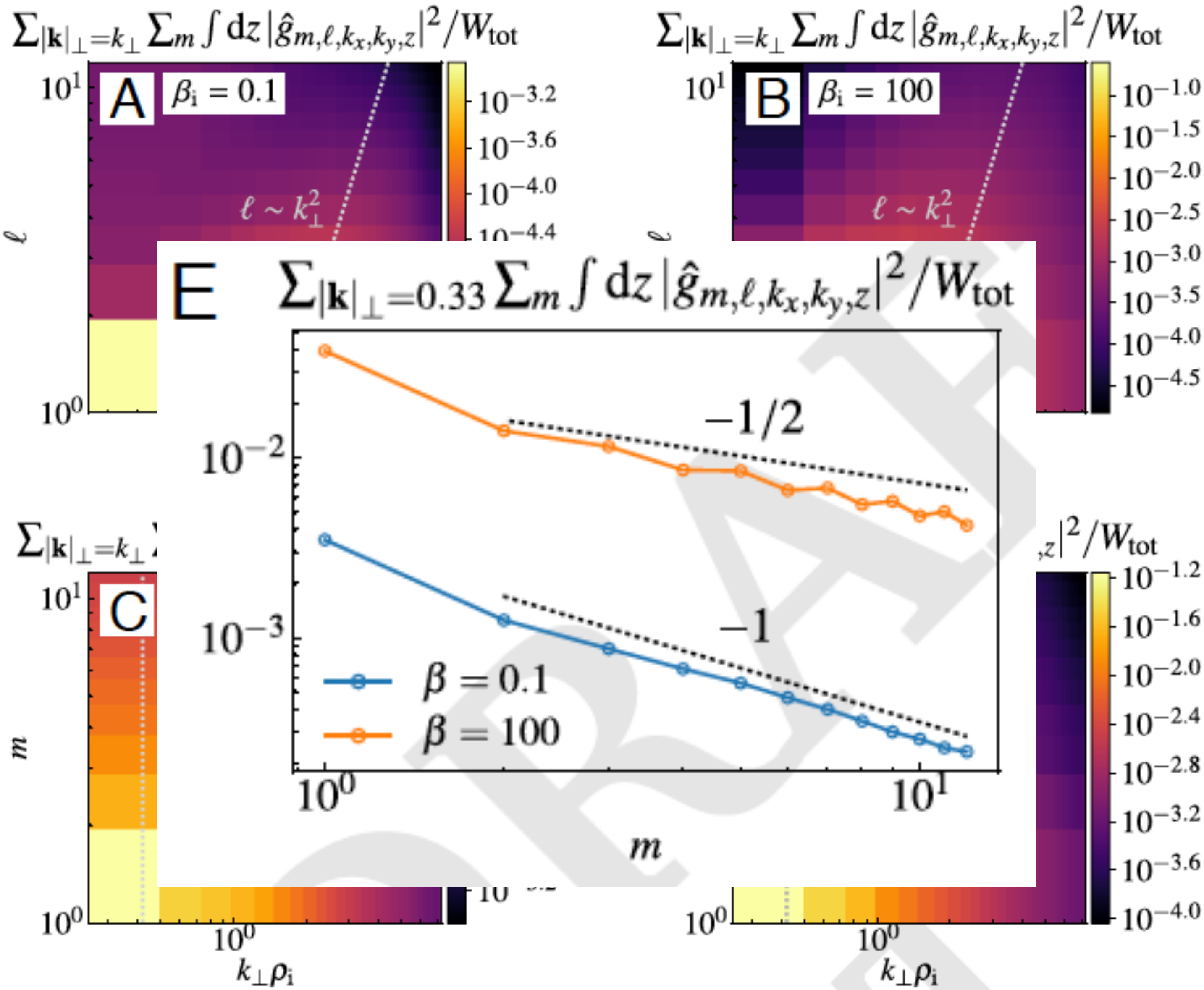

[Kawazura et al. 2018,
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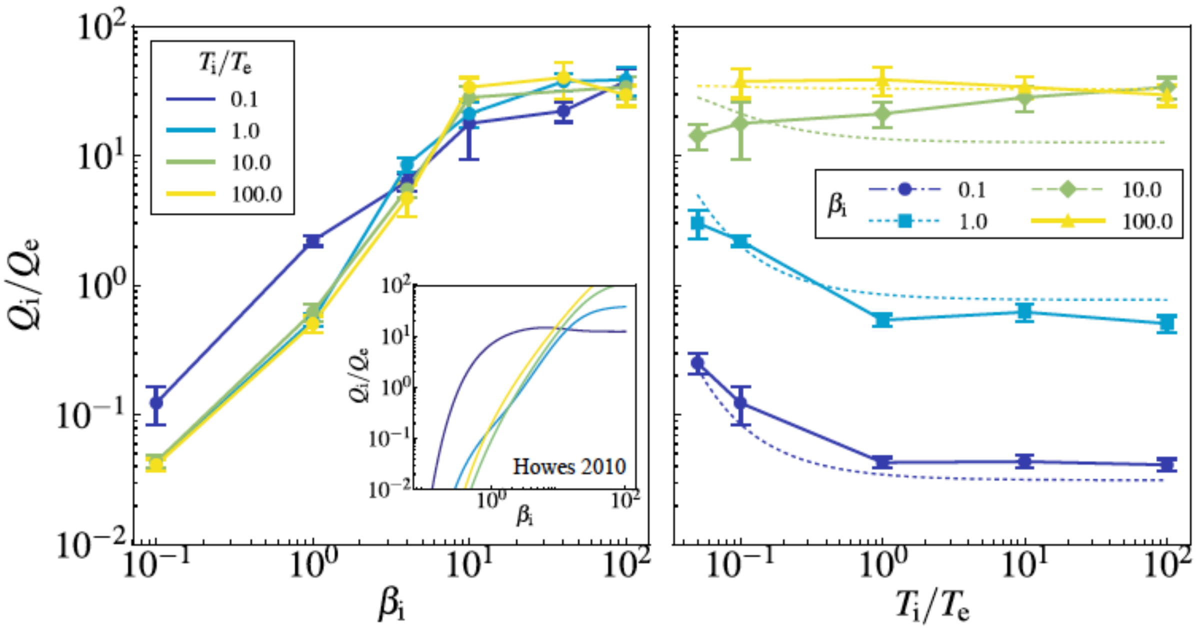
Conclusions

- At **low beta**, i-e energy partition happens at MHD (outer) scale:
  Q_i/Q_e = **compressive/Alfvénic**
- At **high beta**, i-e energy partition happens just above ion Larmor scale; for an Alfvénic cascade, $Q_i/Q_e \to 30$

There is a **new regime of turbulence**, resembling high-Pm MHD



$$\frac{Q_i}{Q_e} = \frac{35}{1+(\beta_i/15)^{-1.4} e^{-0.1\, T_e/T_i}}$$

[Kawazura et al. 2018, arXiv:1807.07702]

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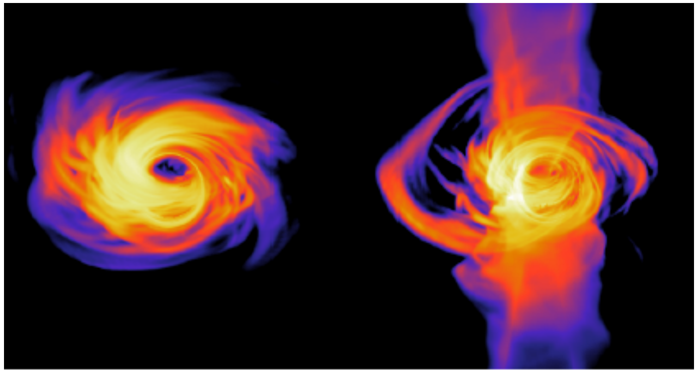
  There is a **new regime of turbulence**, resembling high-Pm MHD
- **Astrophysically**, this amount of ion heating is not dominant enough to explain low luminosity of Sgr A* without assuming low accretion enabled by significant outflows;
  within that, the very low electron heating at low beta turns out to be crucial for **the jet showing up in emission**



more Q_e **less Q_e**

from Chael, Rowan, Narayan et al. arXiv:1804.06416

[Kawazura et al. 2018, arXiv:1807.07702]

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  within that, the very low electron heating at low beta turns out to be crucial for **the jet showing up in emission**
- A take-away for those interested in fundamental plasma physics:

  turbulence is indifferent to species inequality

  (heating is independent of T_i/T_e)

  and indeed promotes **disequilibration of species**

  (hotter ions at high β_i and hotter electrons at low β_i)

[Kawazura et al. 2018, arXiv:1807.07702]