Gyrokinetics of thermalisation of turbulent energy in astrophysical plasmas: a fusion-astro synergy success story

←Yohei Kawazura, Michael Barnes→
&
Alex Schekochihin
(Oxford)

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

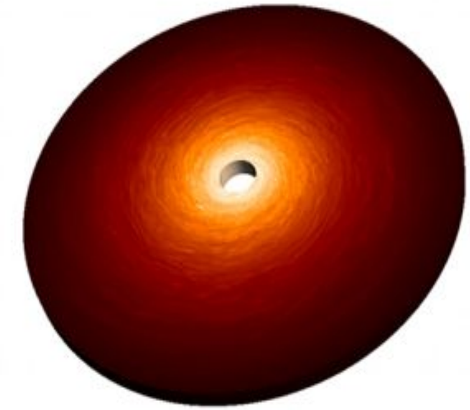
[*PNAS* **116**, 771 (2019) + *JPP* (2019)/arXiv:1812.09792]

News Flash!

From the Even Horizon Telescope press release 10 April 2019: first ever “image” of a black hole (centre of M87 galaxy)

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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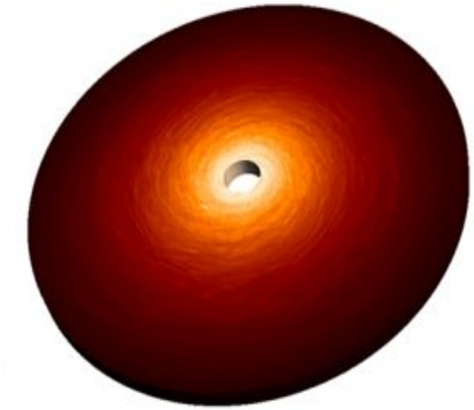

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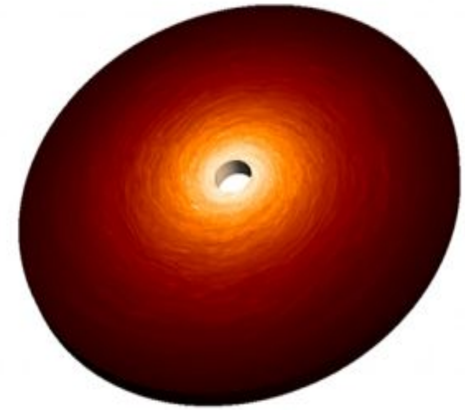

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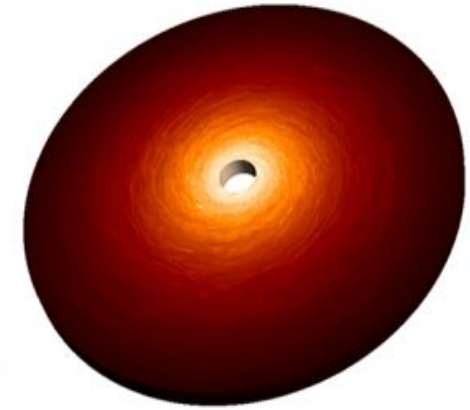

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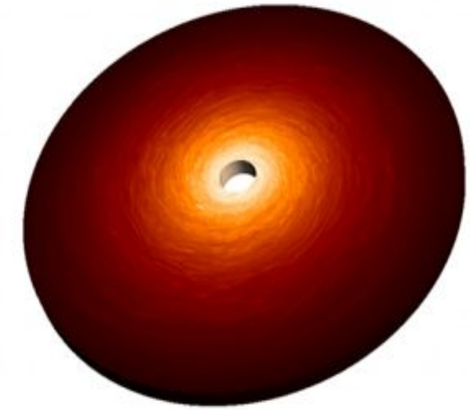

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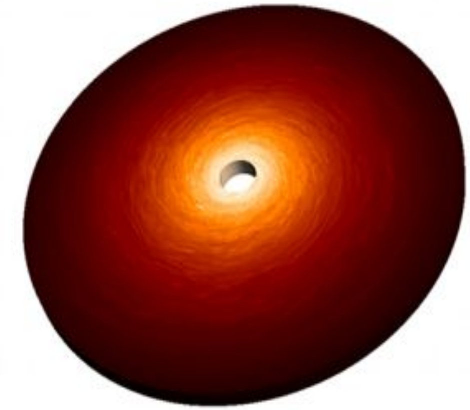

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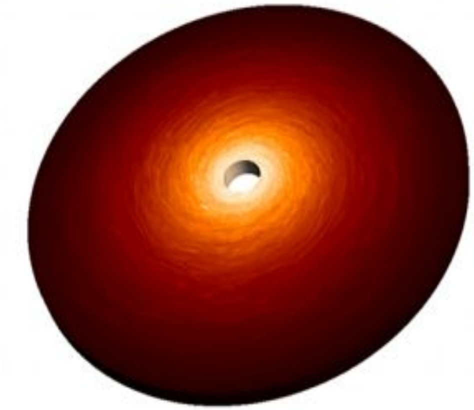

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↳ *Question:* **how is energy injected into turbulence by Keplerian shear partitioned between ions & electrons, as a function of local plasma conditions, viz., β_i and T_i/T_e?**

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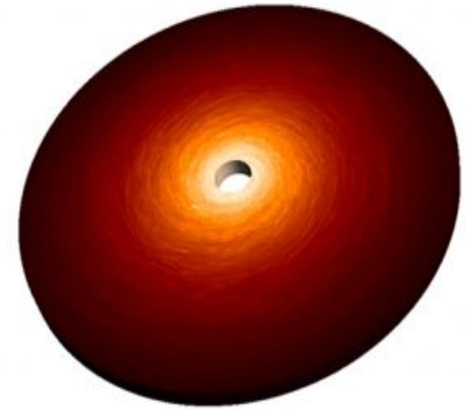

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This question is meaningful in a **weakly collisional plasma**, where Coulomb equilibration between species is slow.

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!

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

Global Zoo to Local Universality

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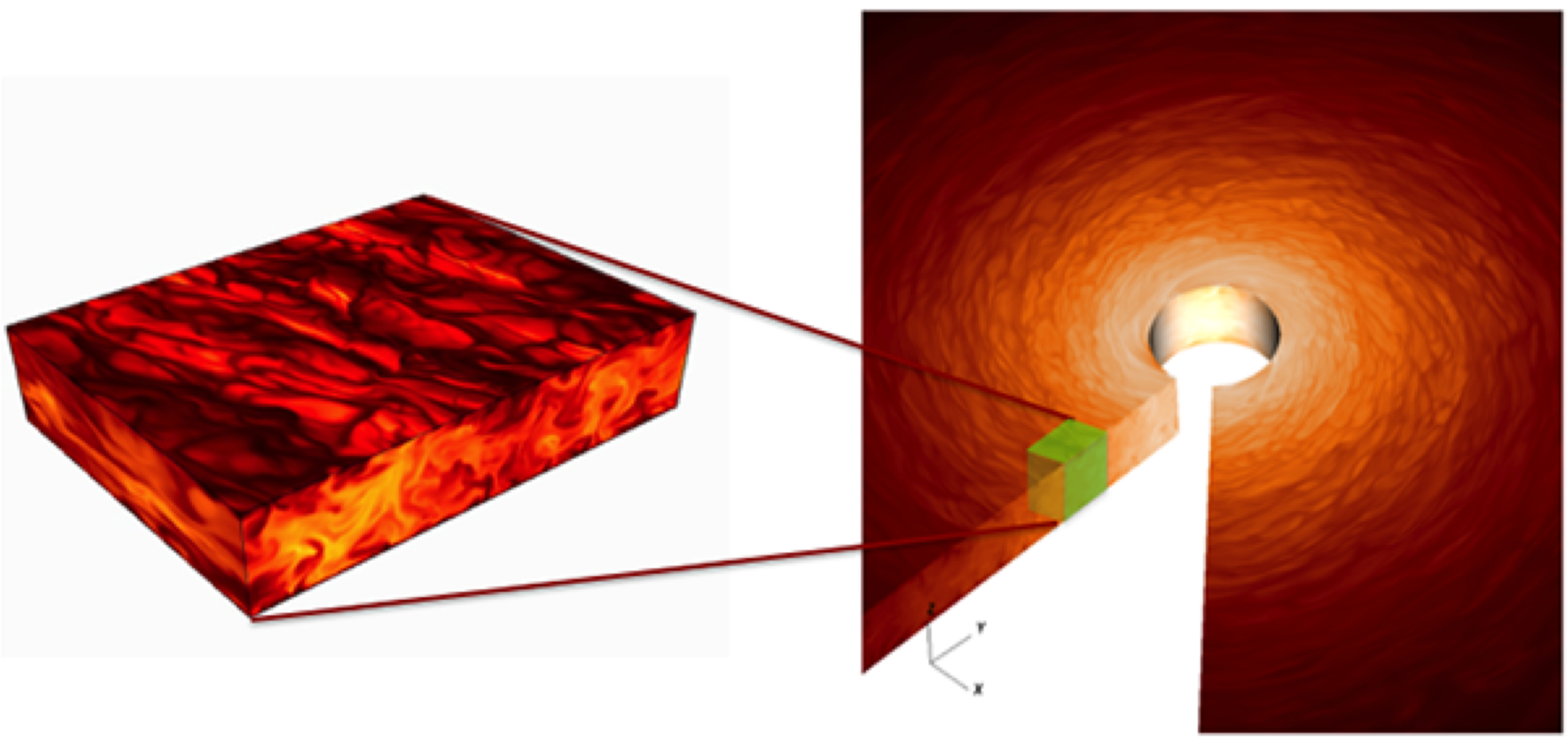
At sufficiently small (but still MHD) scales, turbulence becomes universal, viz., anisotropic ($k_\perp \gg k_\parallel$) MHD turbulence in a strong mean field.

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

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

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

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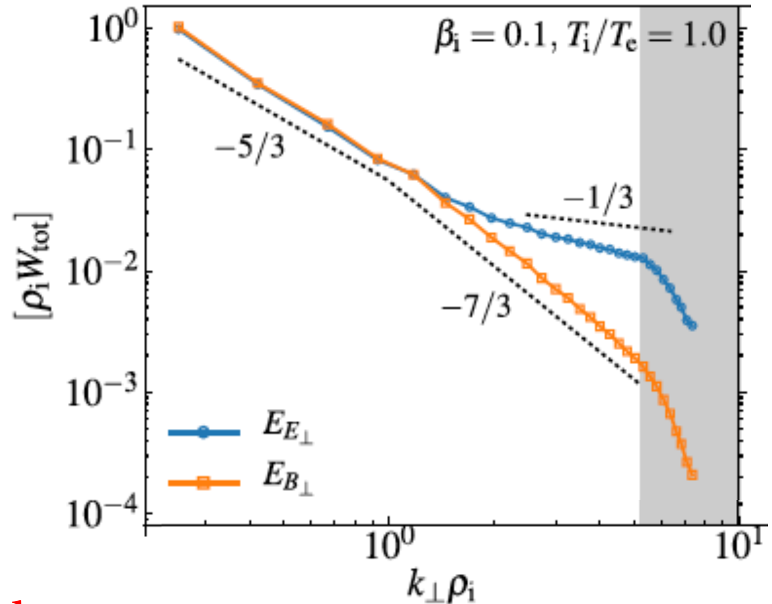

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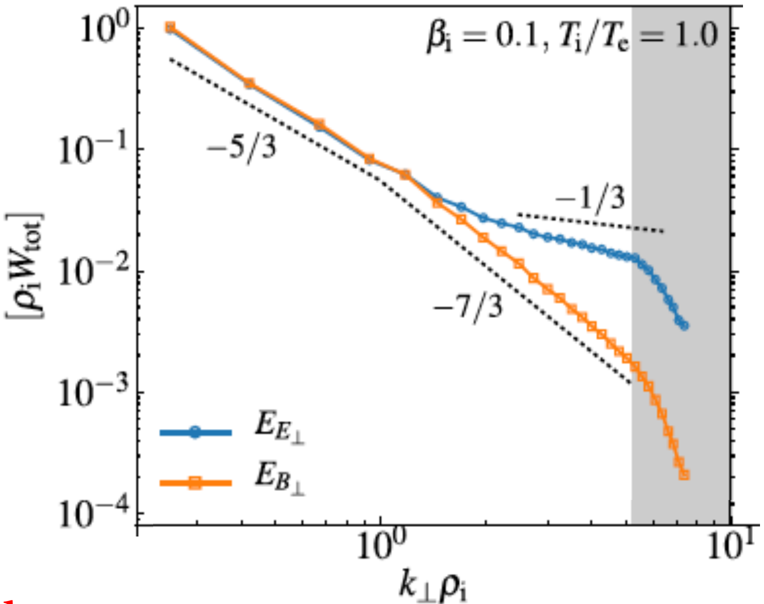

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Fusion Tools to Astro Problems

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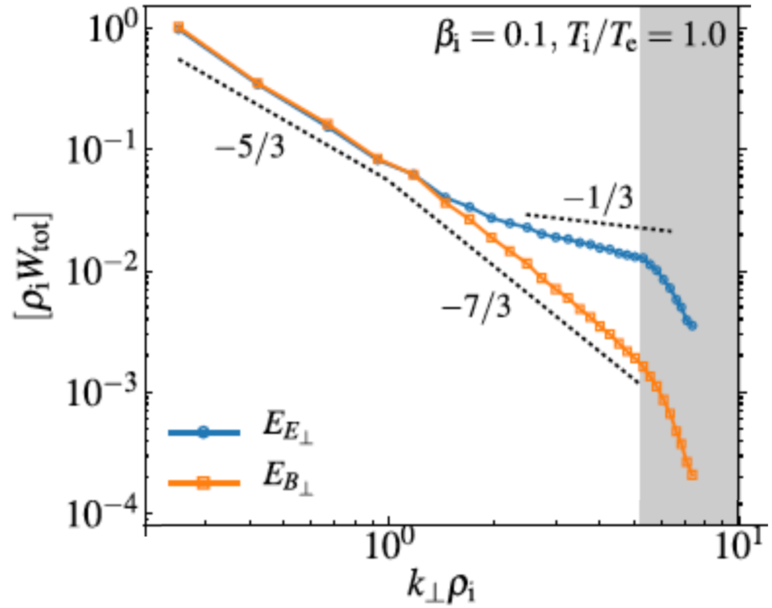

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The project they started has led to massive progress in theory, modelling & understanding of both extragalactic plasmas and (especially) turbulence in the Solar Wind

(even though brute-force GK numerical solution of the original heating problem turned out to be much more challenging than anticipated).

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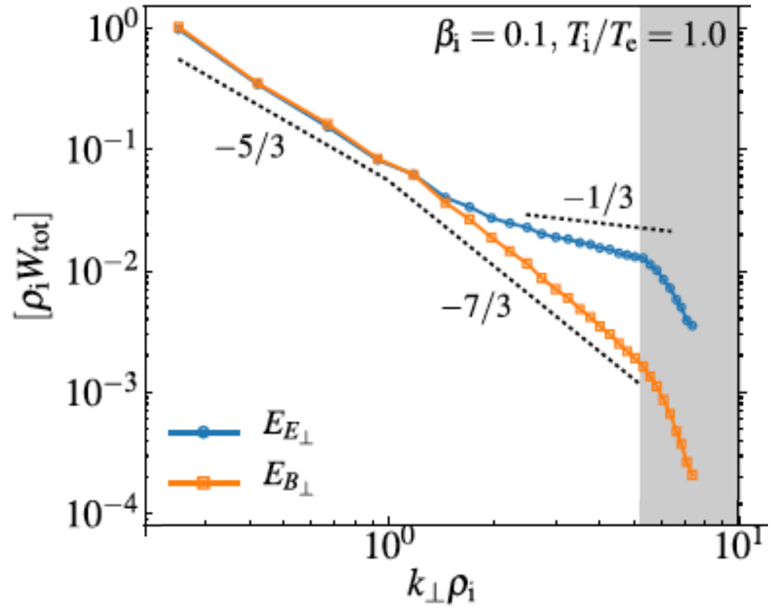

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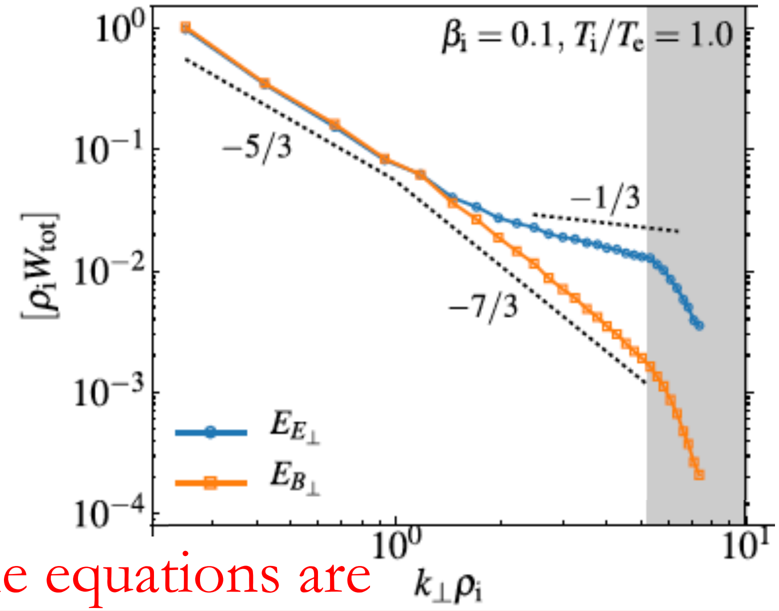


$$f = F_0 + \delta f, \quad \delta f = -\varphi(\boldsymbol{r})F_0 + h(\boldsymbol{R}), \quad \boldsymbol{R} = \boldsymbol{r} + \boldsymbol{\rho}, \quad \boldsymbol{\rho} = \frac{\boldsymbol{v}_\perp \times \hat{\boldsymbol{z}}}{\Omega}$$

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

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

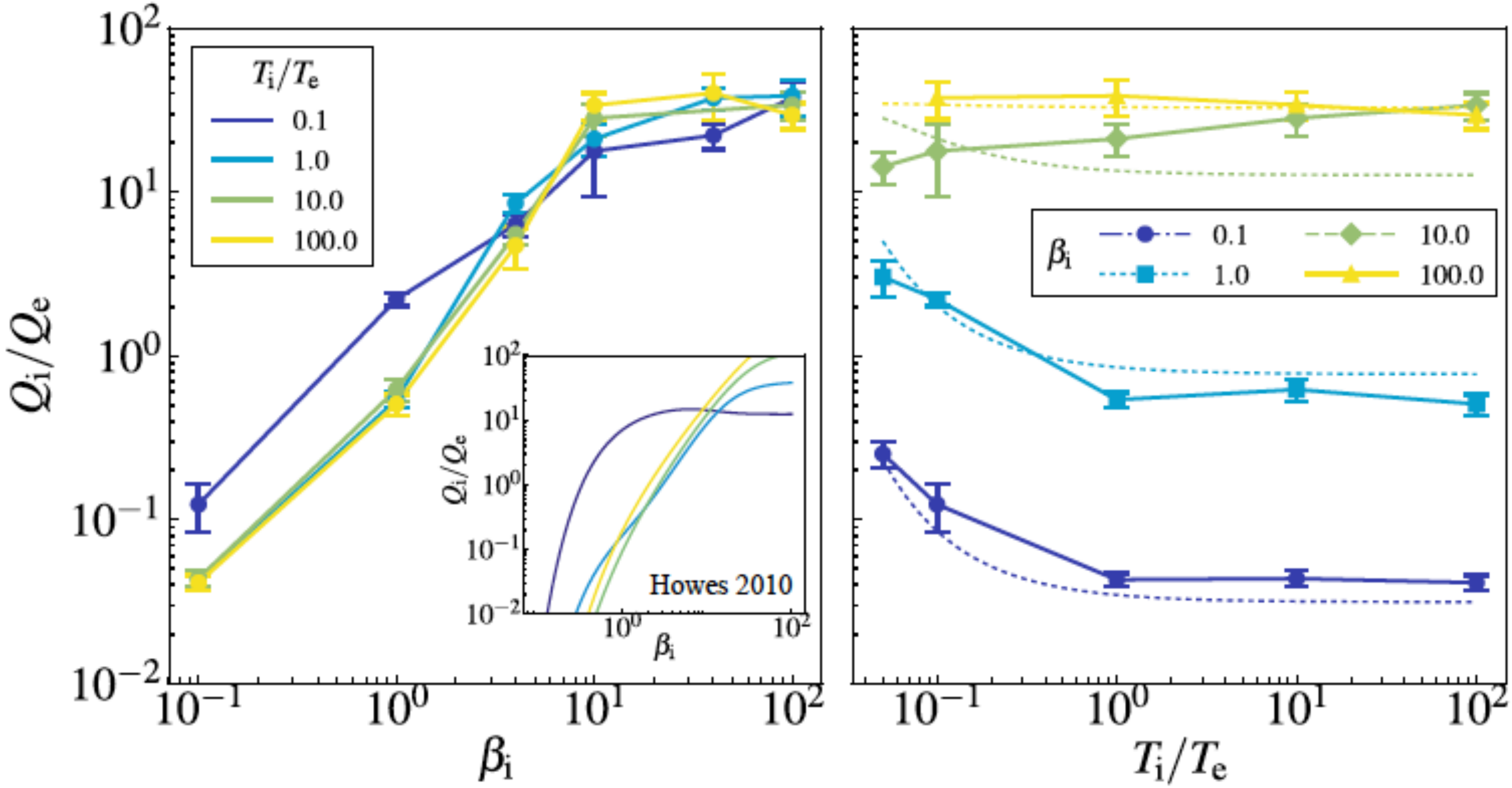
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\delta n}{n} - \frac{\delta B}{B}\right) + \nabla_\parallel u_{\parallel e} = -\frac{\rho_i v_{\rm th}}{2}\left\{\frac{Z}{\tau}\frac{\delta n}{n}, \frac{\delta B}{B}\right\}$$

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

AstroGK/YoheiGK: Kawazura & Barnes 2018, *JCP* **360**, 57

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

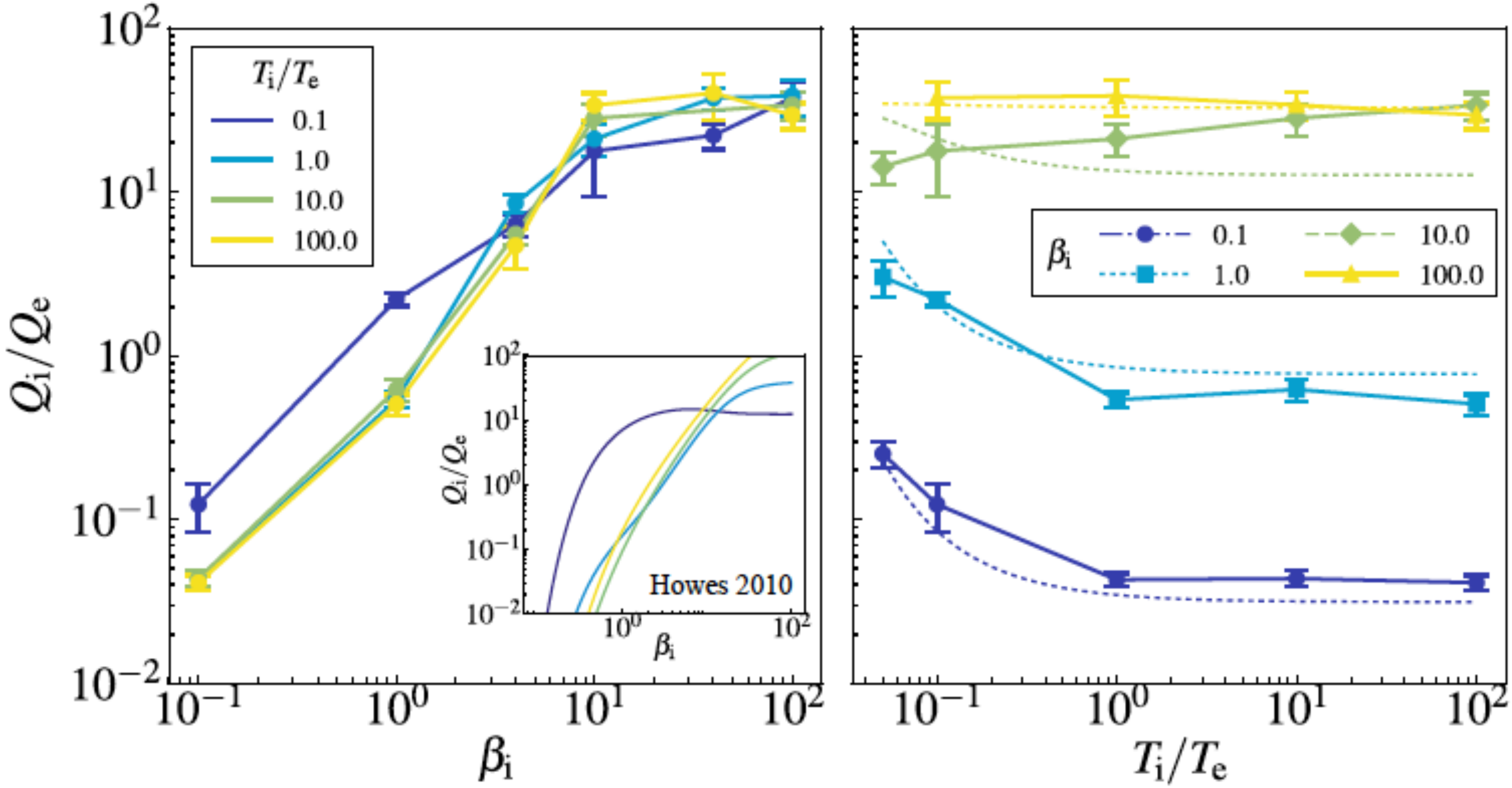
Result ©*Yohei Kawazura 2019*



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: $\beta_i = 1$, $T_i/T_e = 1$
(although TenBarge et al. 2013 did scope out beyond that, in published & unpublished work)

[Kawazura et al. 2019, PNAS 116, 771]

Result ©*Yohei Kawazura 2019*



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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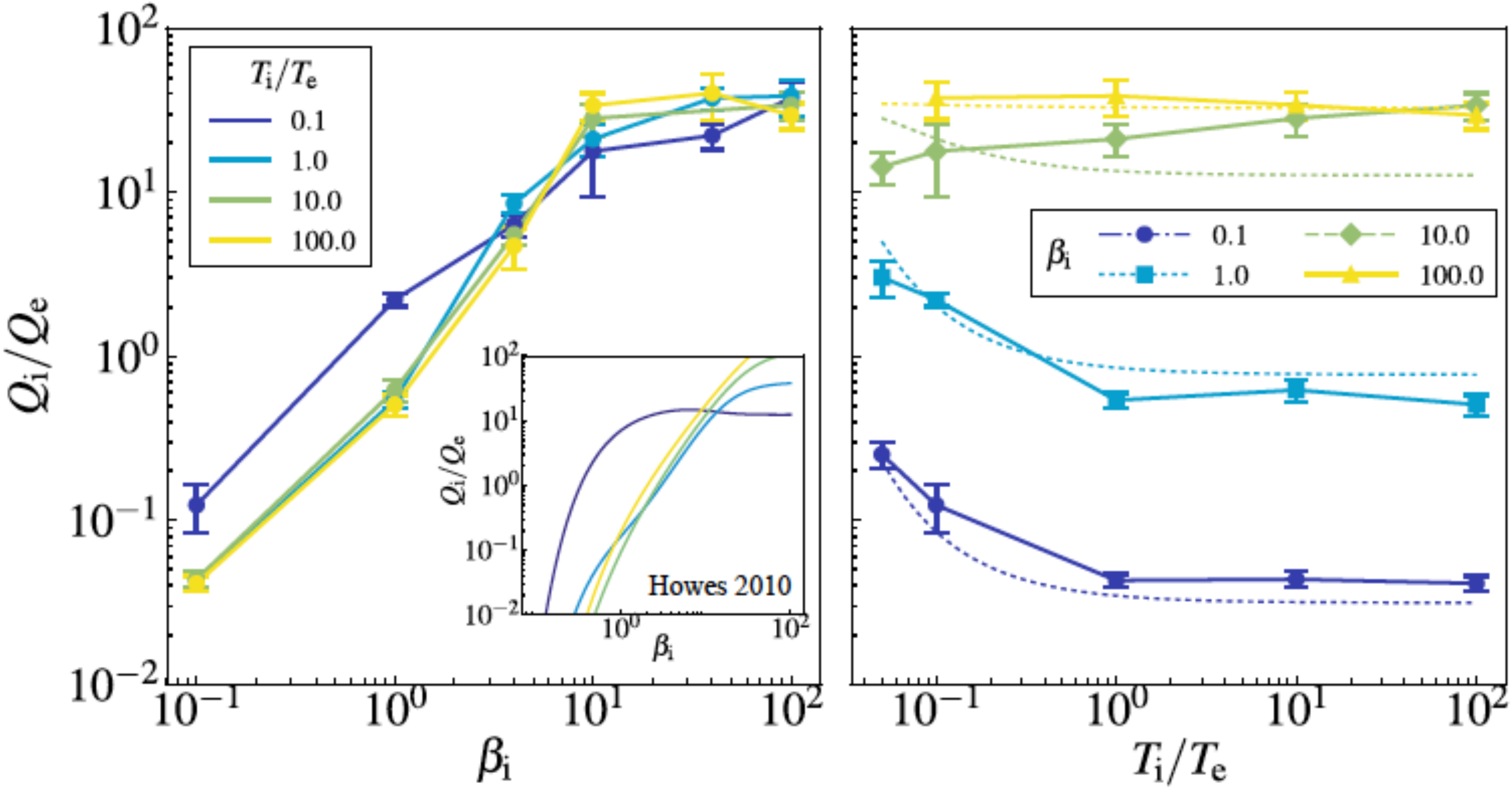

Disequilibration of species:
at high β_i, ions get hotter
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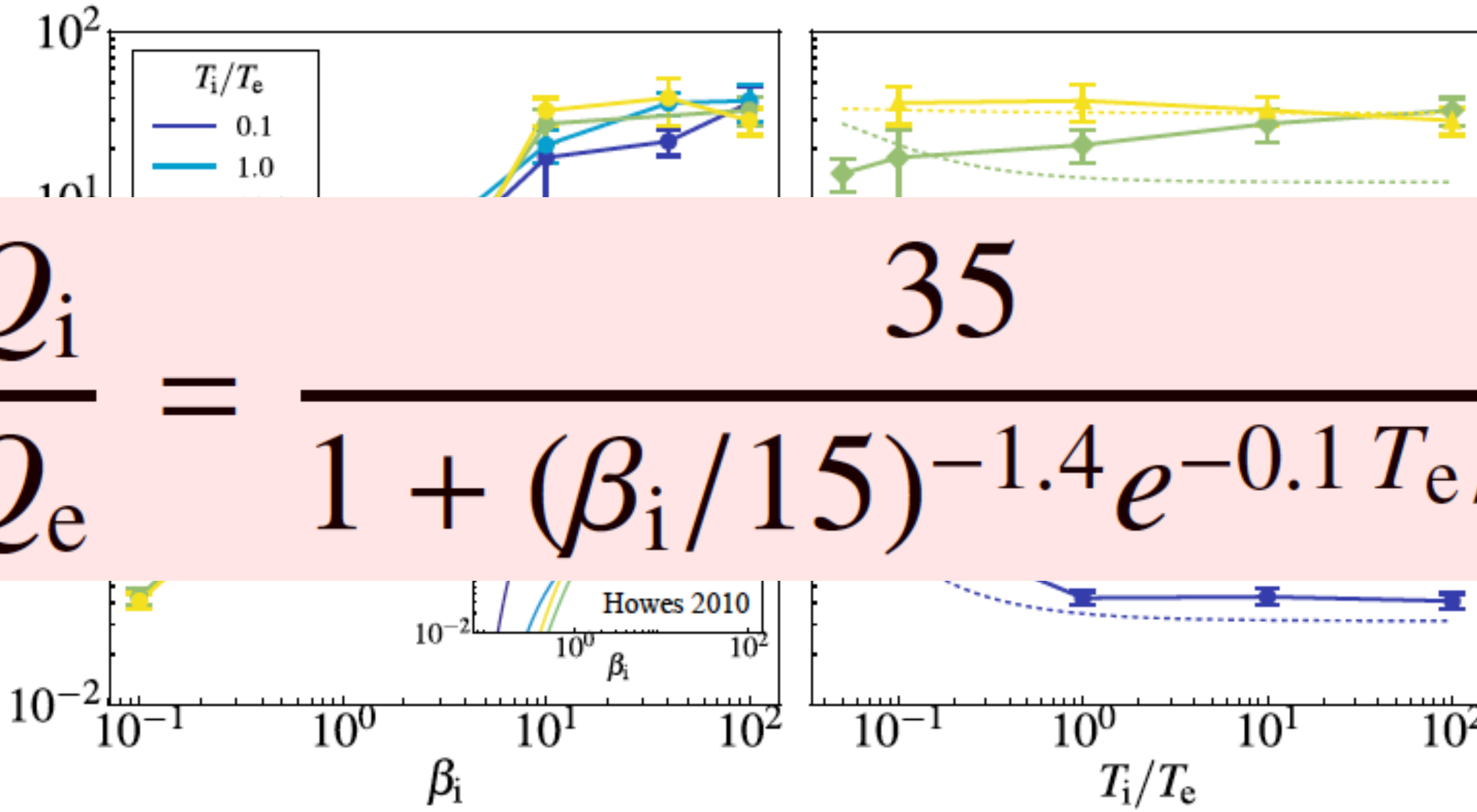
Prescription for Modellers



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

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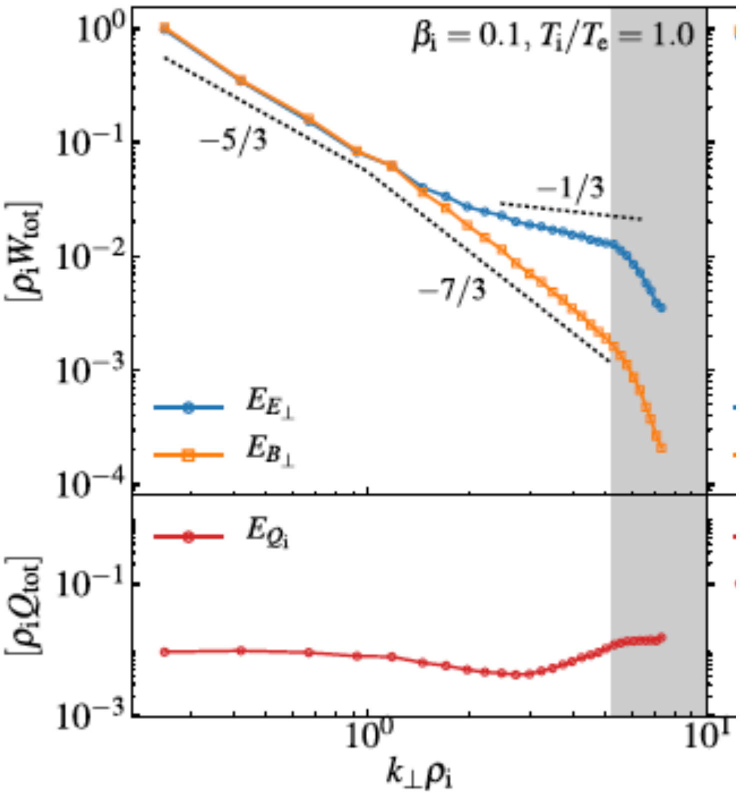

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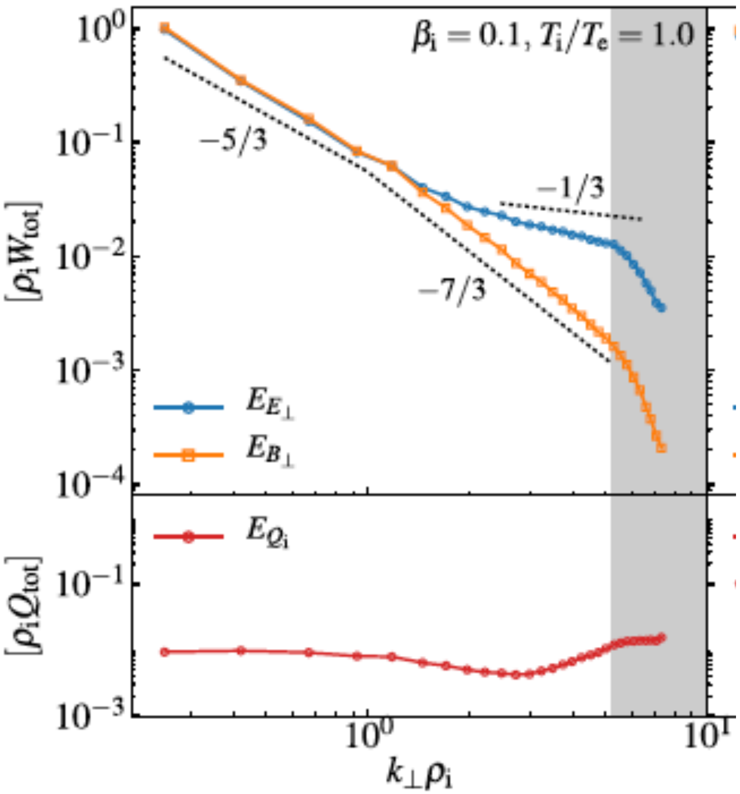

One can <u>prove analytically</u> that $\boldsymbol{Q_i/Q_e} \rightarrow \mathbf{0}$ as $\beta_i \rightarrow 0$ because ions are slower than Alfvén waves: $v_{thi} = v_A \beta_i^{1/2} \ll v_A$

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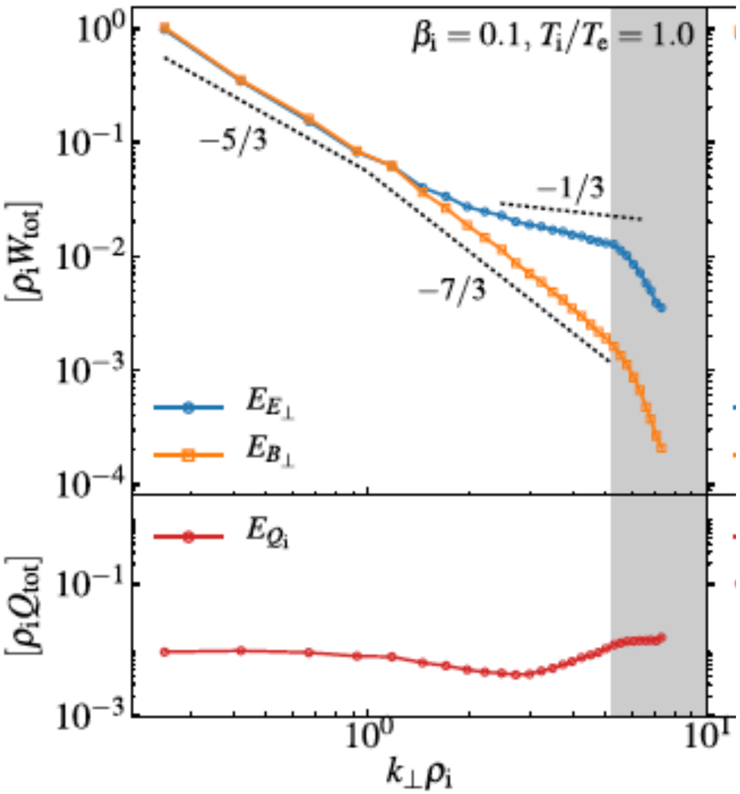

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It is also possible to prove analytically that, **while all energy in the Alfvénic cascade will go into electrons,**
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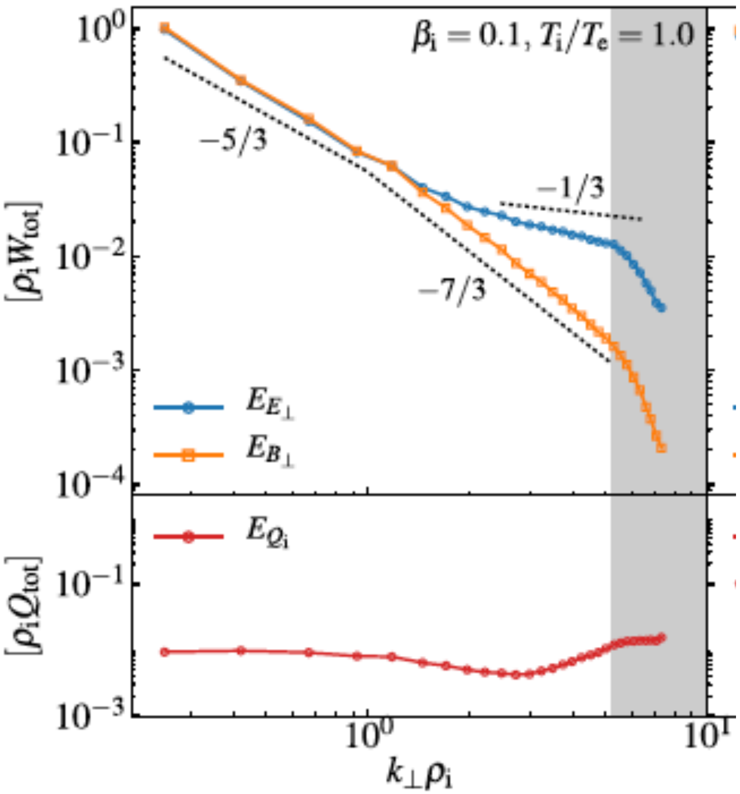

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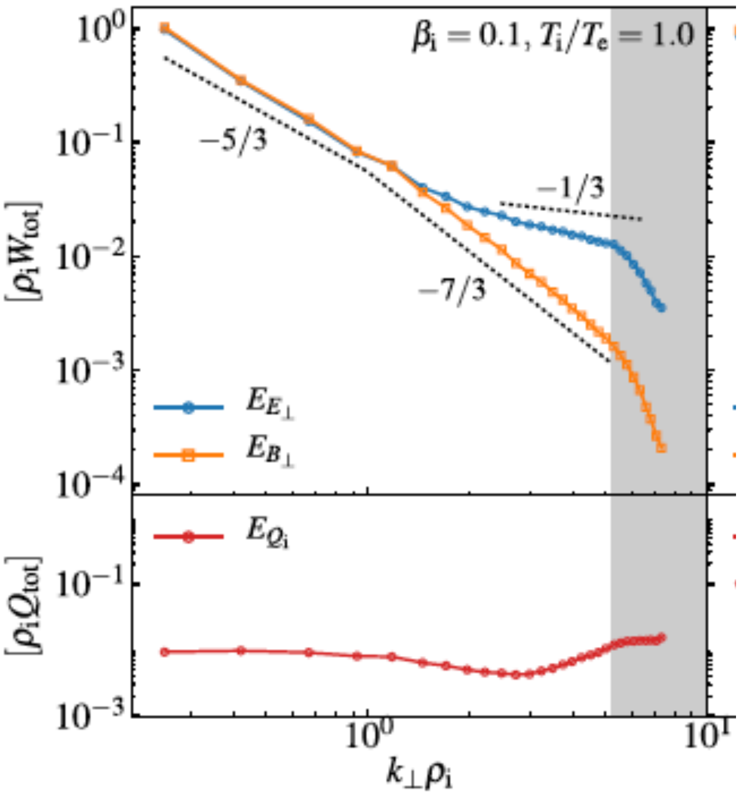
It is also possible to <u>prove analytically</u> that, **while all energy in the Alfvénic cascade will go into electrons, all energy in the compressive cascade will go into ions**

↳ **In low-beta GK plasmas, energy partition is decided at the outer (MHD) scale!**

[Kawazura et al. 2019, PNAS 116, 771]

[AAS et al. 2019, JPP/arXiv:1812.09792]

Low Beta



One can <u>prove analytically</u> that $\boldsymbol{Q_i/Q_e \to 0}$ as $\beta_i \to 0$ because ions are slower than Alfvén waves: $v_{\mathrm{th}i} = v_A \beta_i^{1/2} \ll v_A$

It is also possible to <u>prove analytically</u> that, **while all energy in the Alfvénic cascade will go into electrons, all energy in the compressive cascade will go into ions**

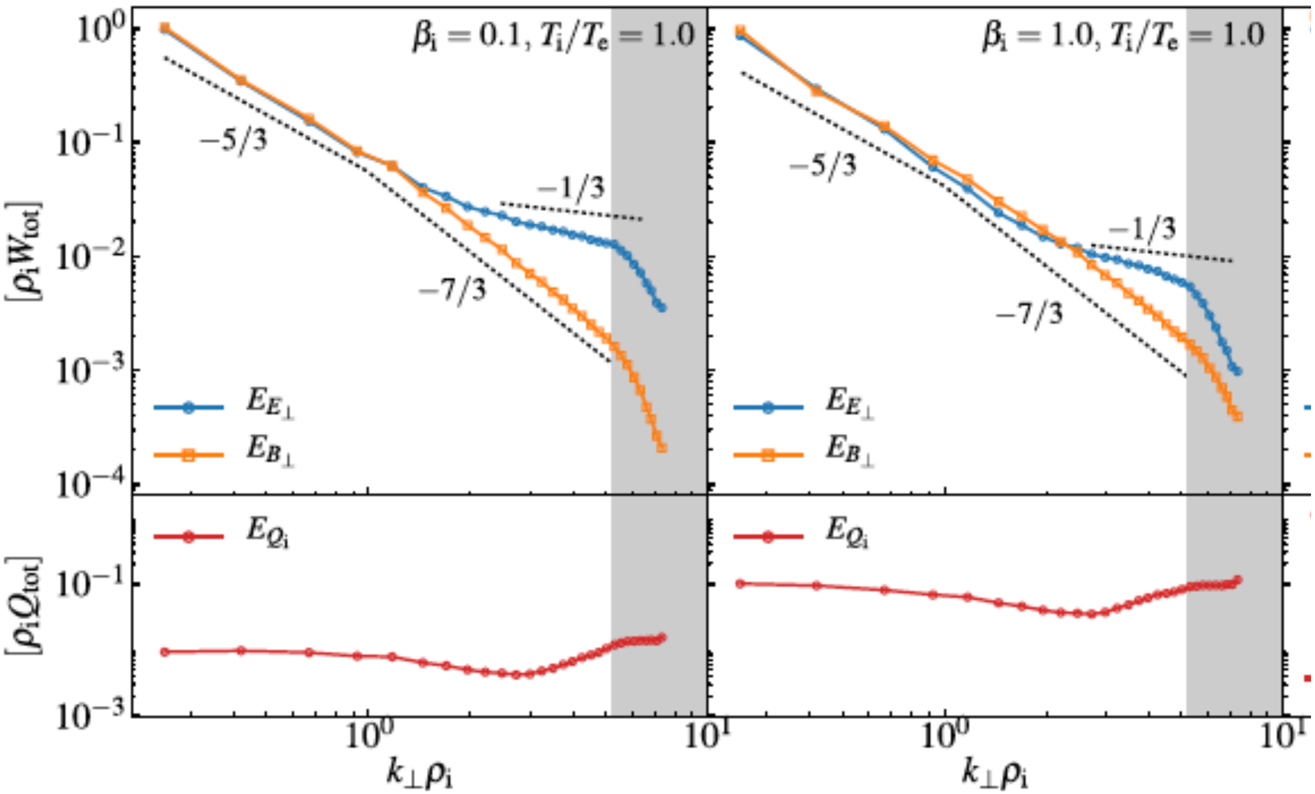
↳ **In low-beta GK plasmas, energy partition is decided at the outer (MHD) scale!**

CAVEATS:

- GK does not have **stochastic ion heating** [Chandran 2010]
- We might not be resolving **multiscale reconnection heating** [cf. Rowan, Sironi, Narayan 2017, 19]

[AAS et al. 2019, JPP/arXiv:1812.09792]

Beta = 1



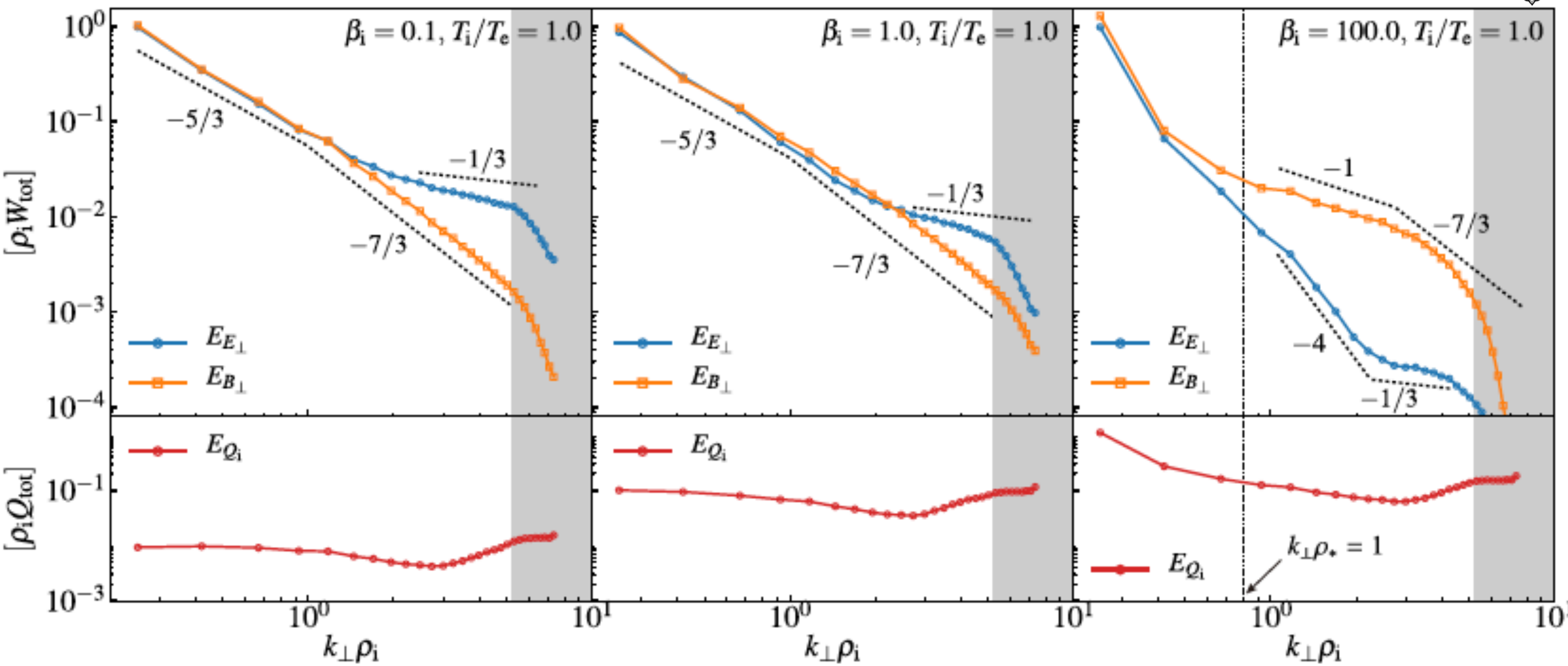
$Q_i/Q_e \cong 0.5$

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

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

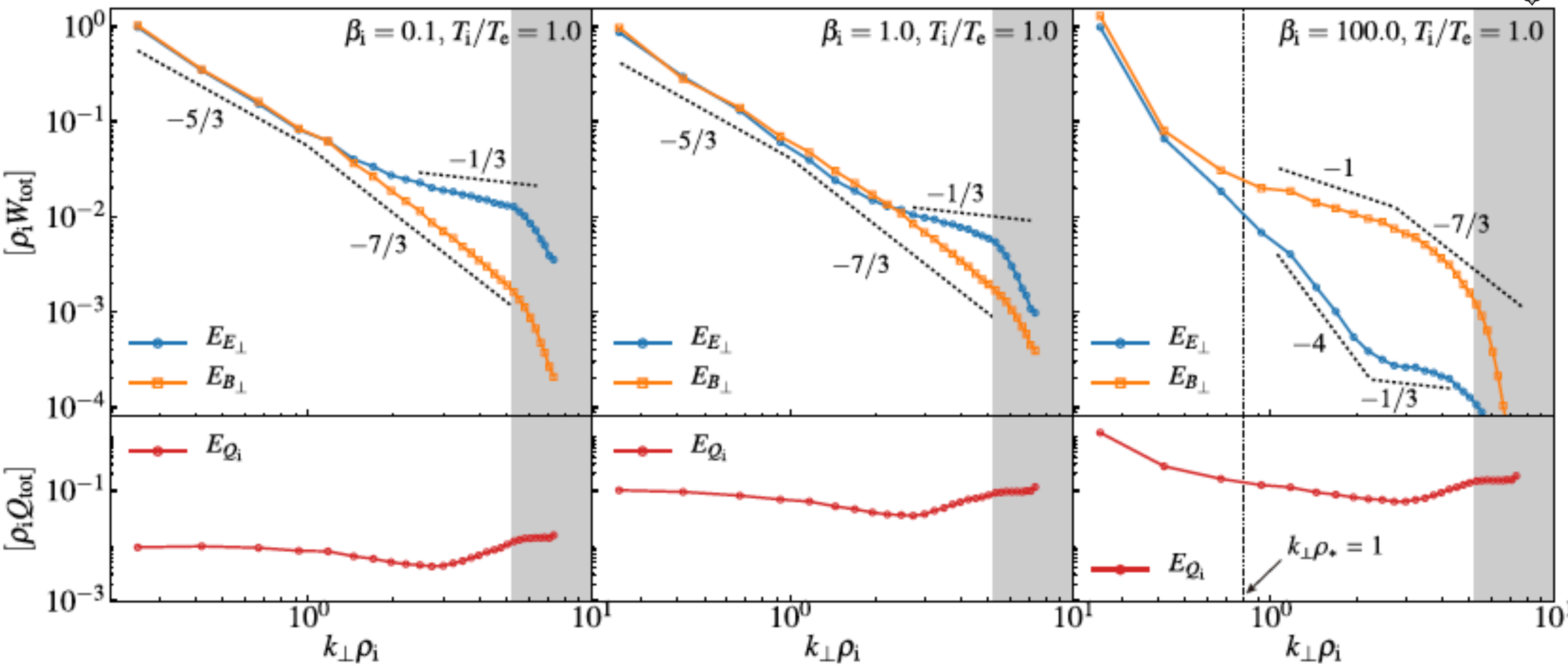
[Kawazura et al. 2019, PNAS 116, 771]

High Beta

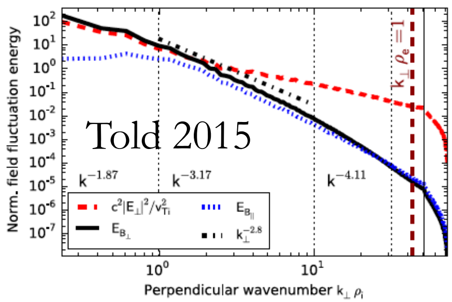


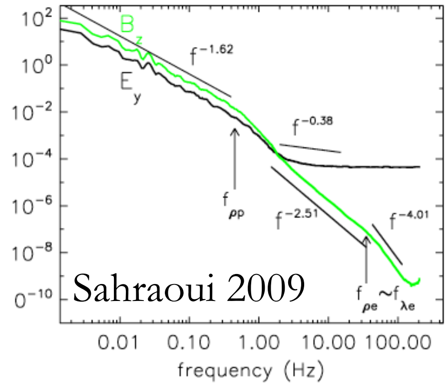
[Kawazura et al. 2019, PNAS 116, 771]

High Beta



These are familiar from simulations and solar wind…

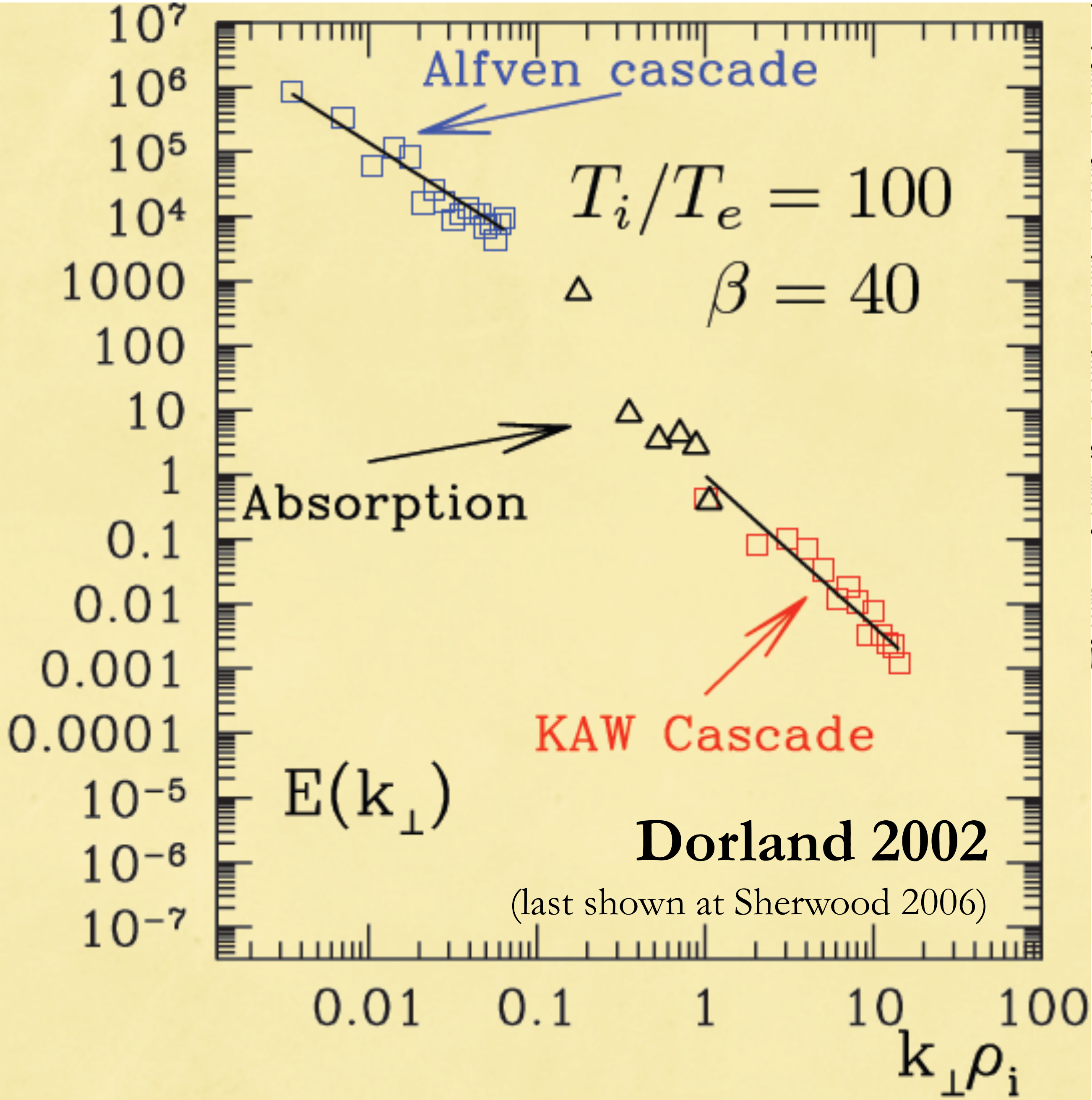


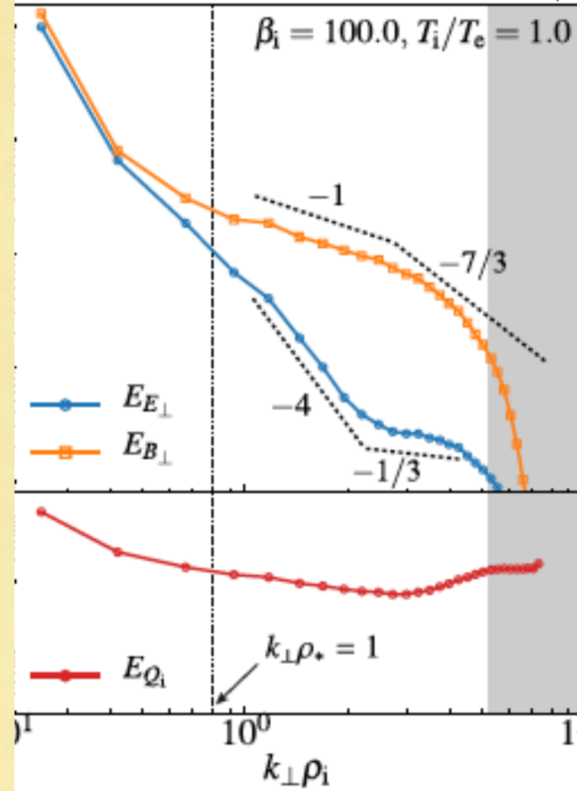


↑

…but this is a **new regime!**

High Beta





↑

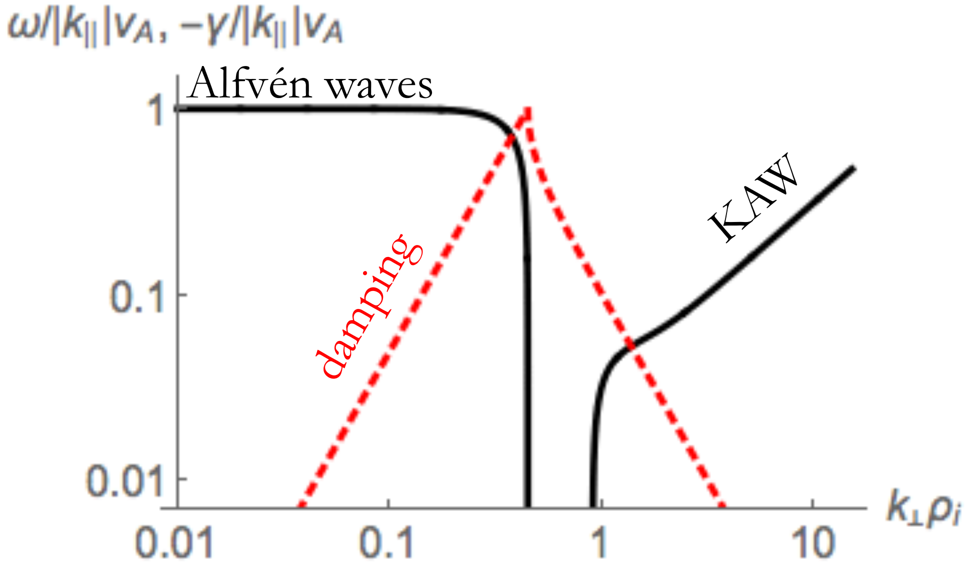
…but this is a **new regime!**

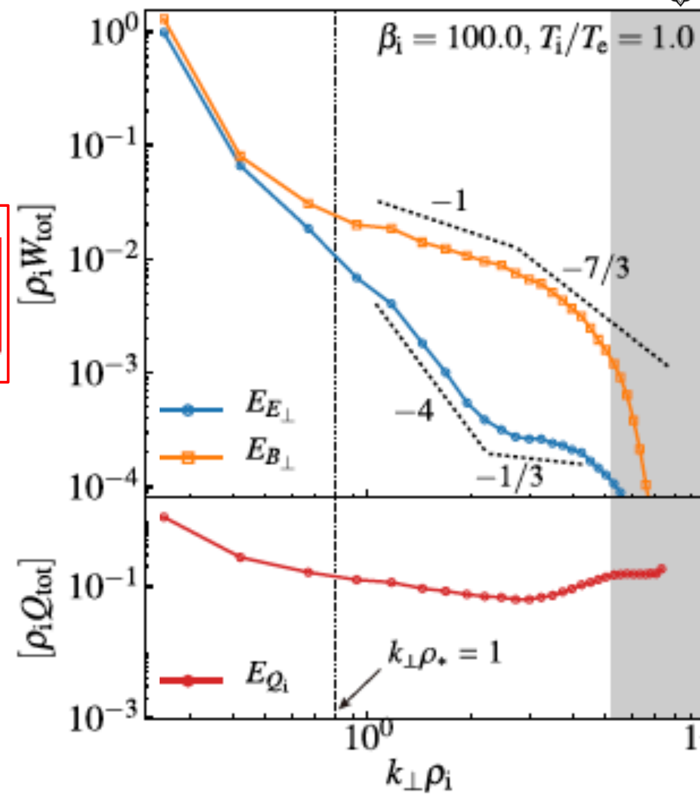
In fact, nothing is new under the Sun...

High Beta

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

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





[Kawazura et al. 2019, PNAS 116, 771]

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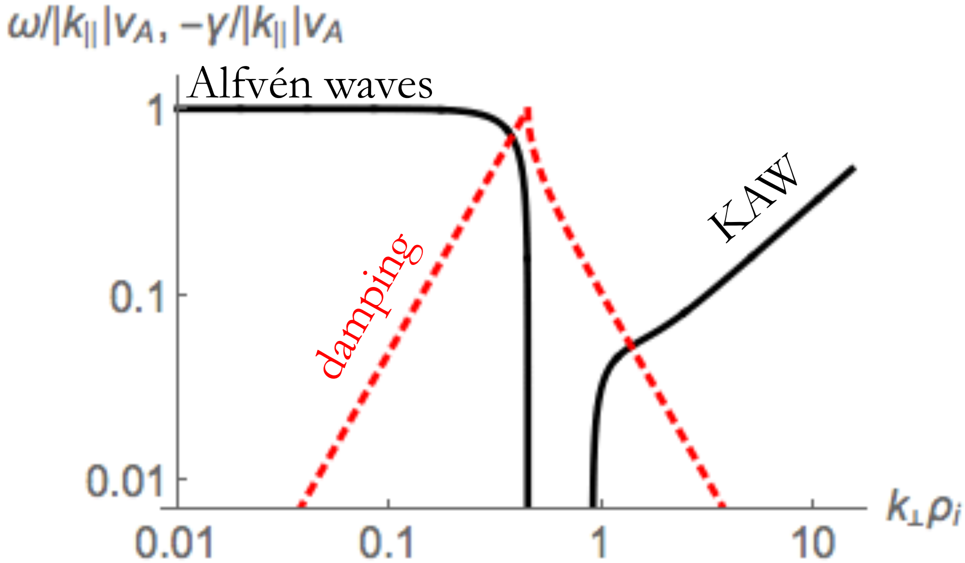

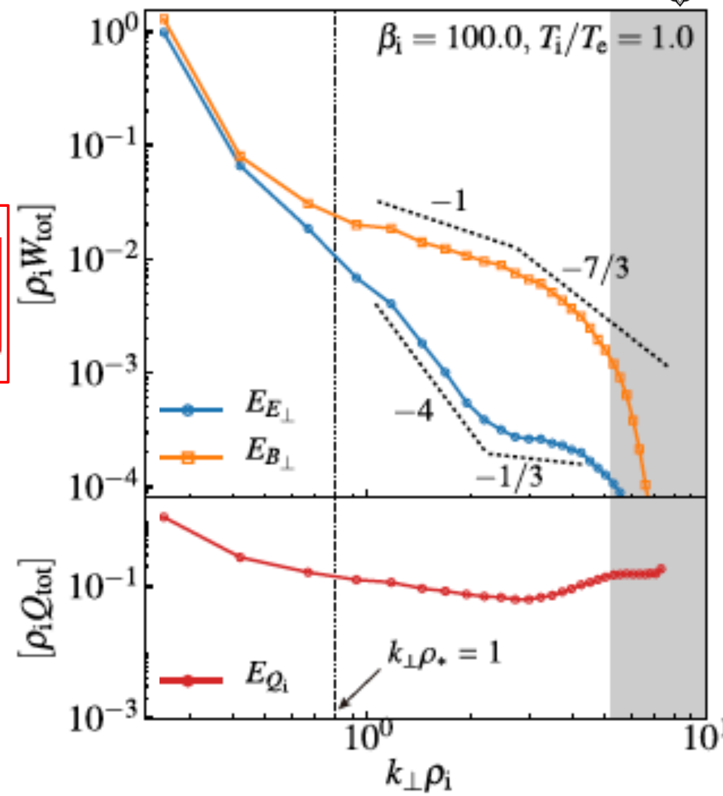

At $k_\perp \rho_* \gg 1$, like an overdamped oscillator: **magnetic fields** (displacements) **not damped,** velocities heavily damped

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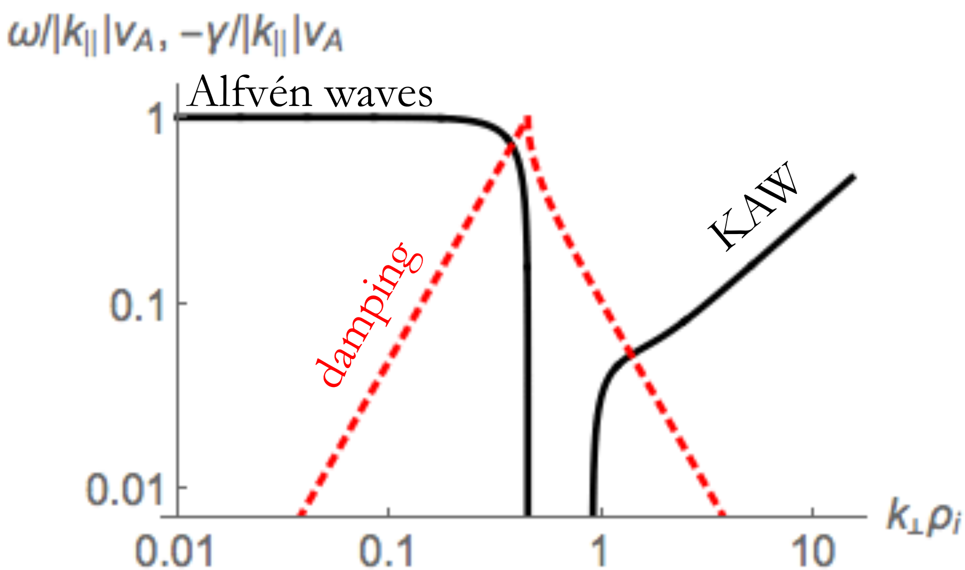

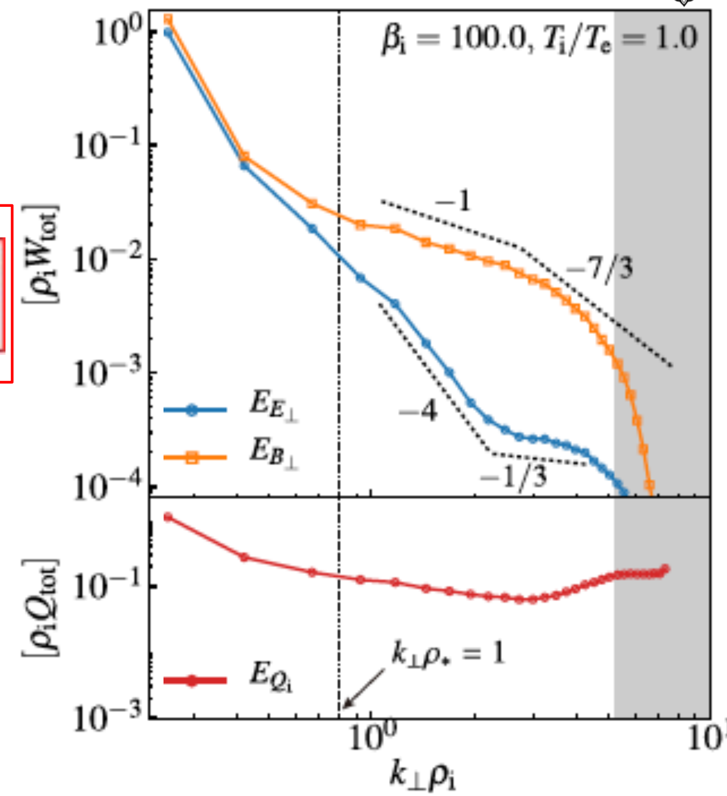

Magnetic-only cascade (fields advected by ρ_*-scale motions)

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

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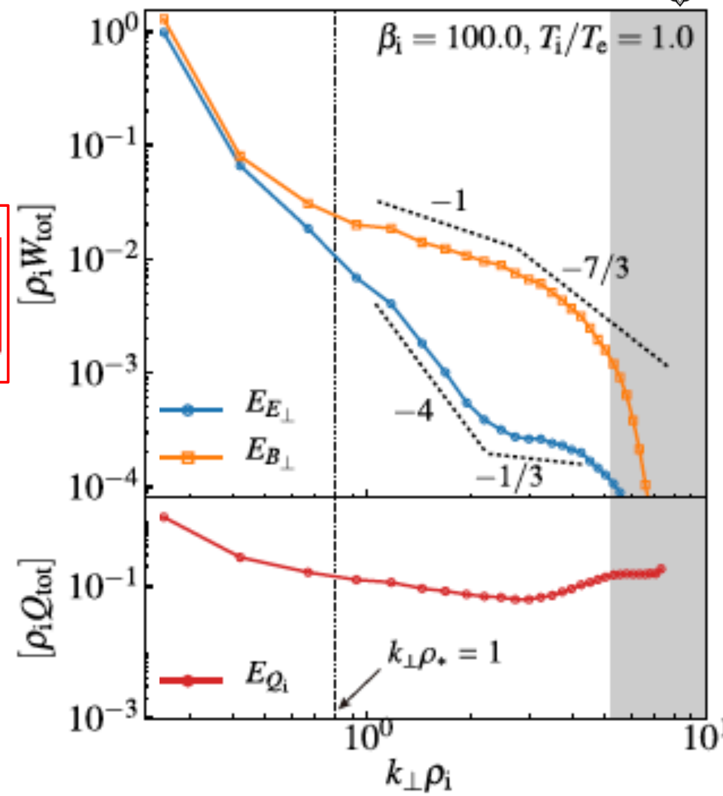

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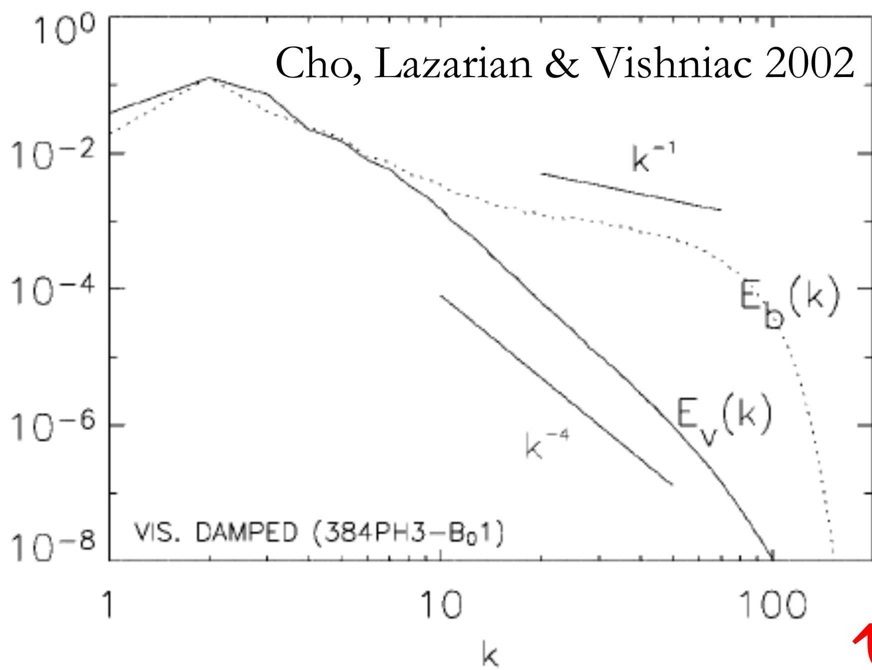

Reminiscent of high-Pm MHD turbulence at subviscous scales

[Kawazura et al. 2019, PNAS 116, 771]

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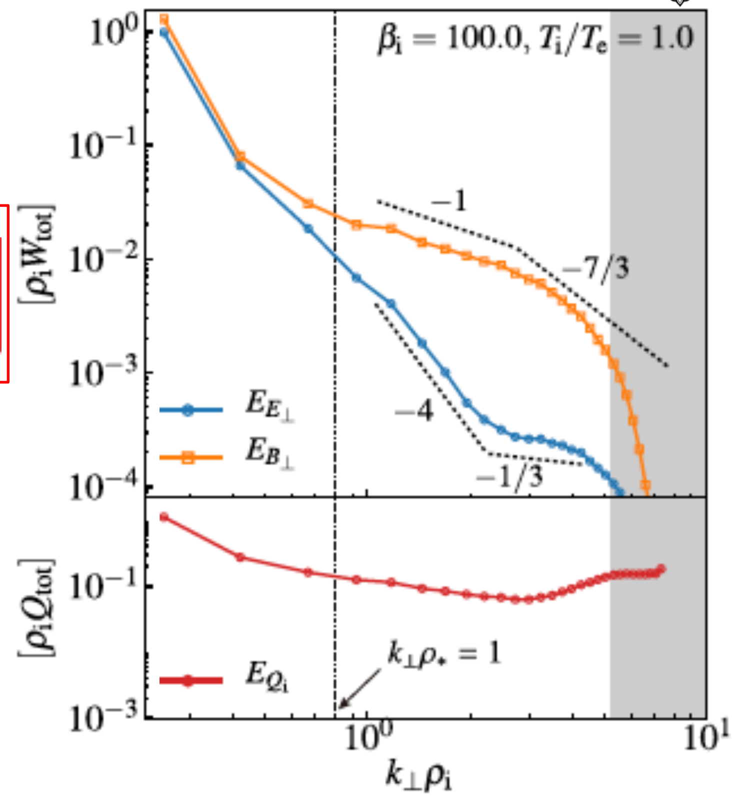
Since $\mathrm{Im}\,\omega \sim |k_\parallel| v_A \sim \tau_{\rm nlin}^{-1}$ at $k_\perp \rho_* \sim 1$, **an order-unity fraction of cascaded energy is converted into ion heat**



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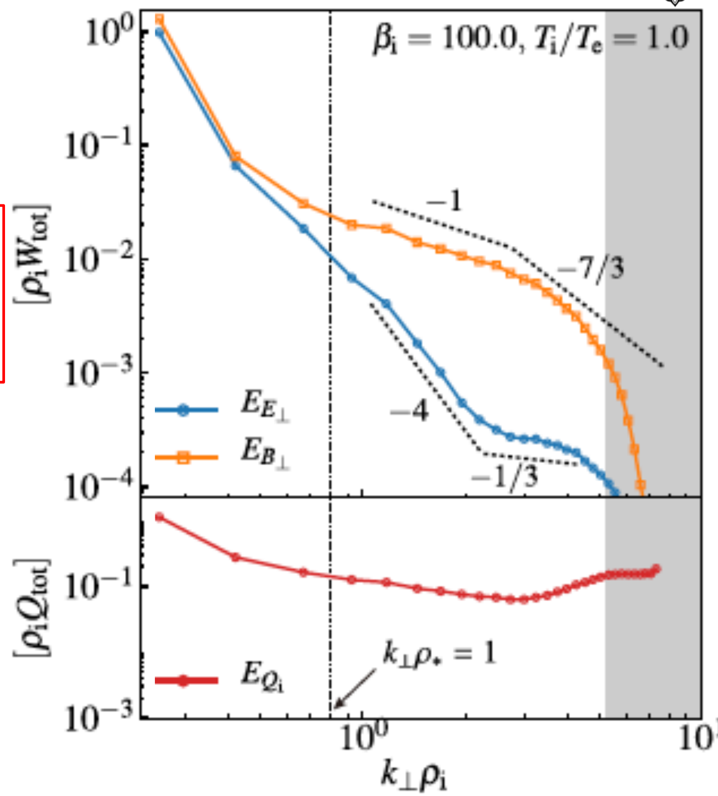
What fraction is what numerics tell us, viz., $Q_i/Q_e \sim 30$



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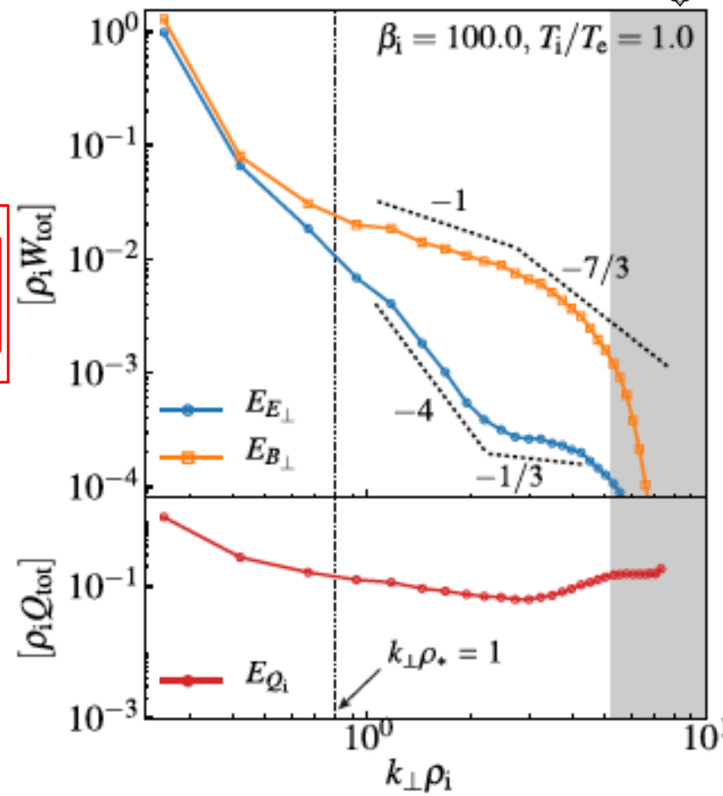


What fraction is what numerics tell us, viz., ***$Q_i/Q_e \sim 30$***

Why this number, and why it saturates is to do with

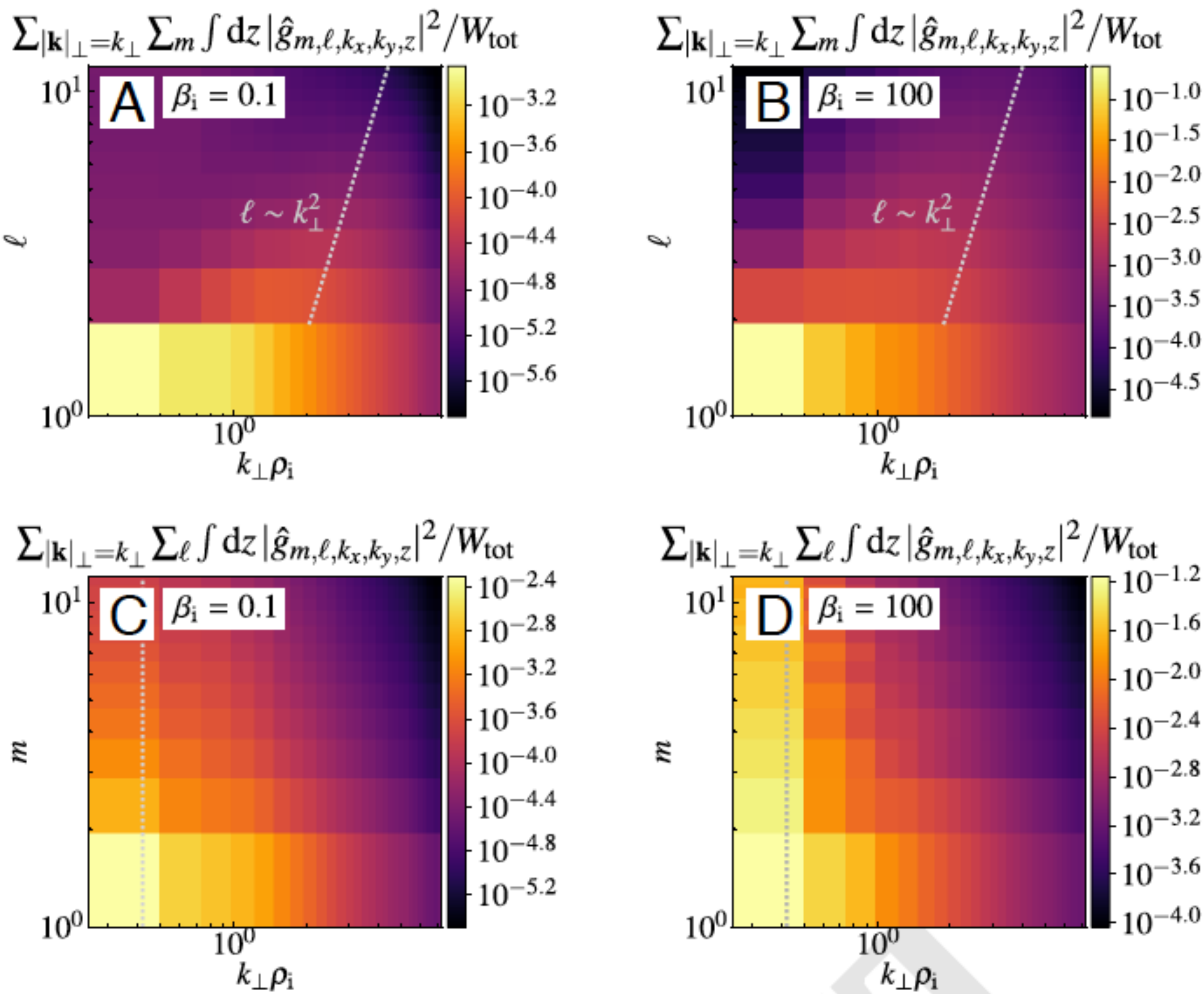
- how efficient Landau damping is in a turbulent environment [cf. AAS et al. 2016, *JPP* **82**, 905820212: echo effect]
- how efficiently energy is channeled from magnetic to KAW cascade

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

Phase-Space Cascades

Laguerre
(dual to $v_\perp$)

Hermite
(dual to $v_\parallel$)



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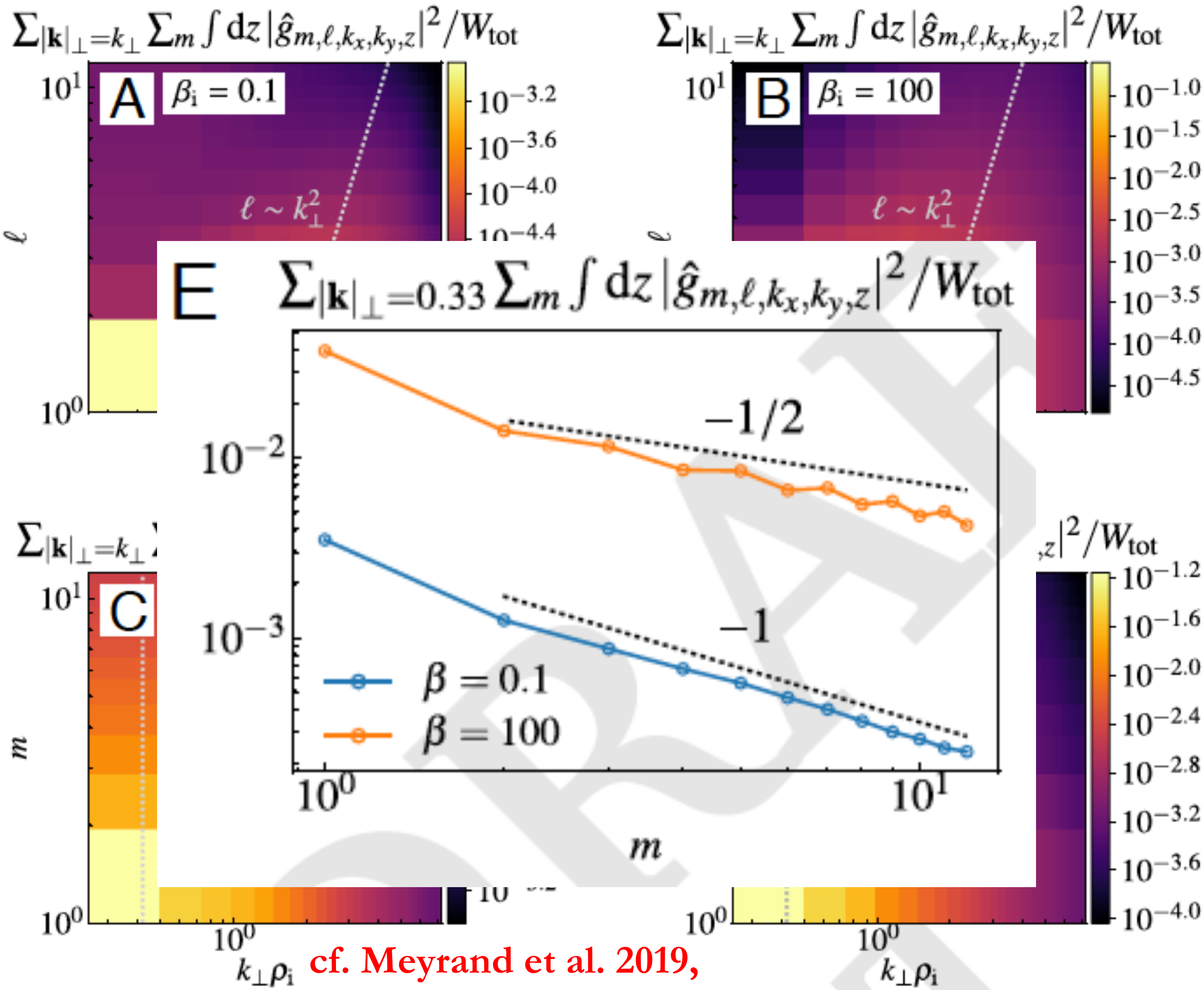


[Kawazura et al. 2019, PNAS 116, 771]

cf. Meyrand et al. 2019, PNAS 116, 1185: "FLUIDISATION" of kinetic plasma

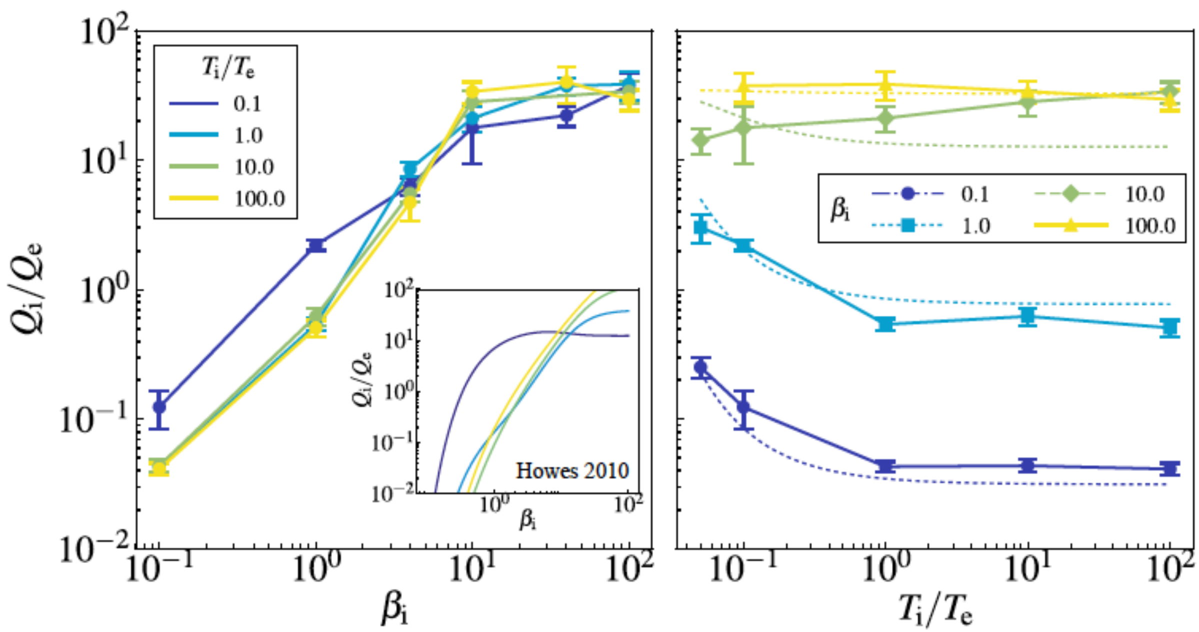
Conclusions

- At **low beta**, i-e energy partition happens at MHD (outer) scale:

  $\boldsymbol{Q_i/Q_e}$ **= compressive/Alfvénic** [AAS et al. 2019, JPP/arXiv:1812.09792]

- At **high beta**, i-e energy partition happens just above ion Larmor scale; for an Alfvénic cascade, $\boldsymbol{Q_i/Q_e \to 30}$

  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. 2019, PNAS 116, 771]

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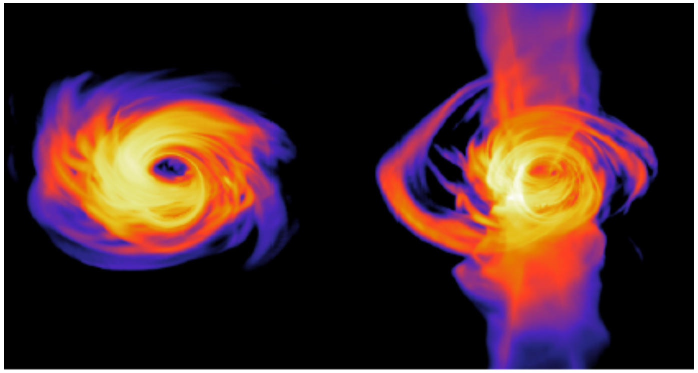
- **Astrophysically**, this amount of ion heating is not dominant enough to explain low luminosity of Sgr A* without assuming low accretion enabled by significant outflows;
  within that, the very low electron heating at low beta turns out to be crucial for **the jet showing up in emission**



from Chael, Rowan, Narayan et al. 2018, MNRAS 478, 5209

[Kawazura et al. 2019, PNAS 116, 771] **more** $\boldsymbol{Q_e}$ **less** $\boldsymbol{Q_e}$

Conclusions

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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. 2019, PNAS 116, 771]

Conclusions

Fusion-to-Astro synergy is not just PR for NSF-DoE,
*thinking across that divide is both possible and worthwhile**

Cowley Dorland Hammett Quataert

Howes TenBarge Barnes Kawazura Told Bañon Kunz Klein

first AstroGK simulations & models

this work (hybrid GK simulations)

GENE full-GK simulations

pressure-aniso. GK theory

---

*Astro-to-fusion route is also promising: e.g., the idea of **critically balanced turbulence** has successfully migrated from astro-MHD to fusion-ITG [Barnes et al. 2011, PRL 107, 115003].

J. Plasma Phys. (2018), *vol.* 84, 715840201
doi:10.1017/S0022377818000296

Astrophysical gyrokinetics: turbulence in pressure-anisotropic plasmas at ion scales and beyond

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[3]Princeton Center for Theoretical Science, Princeton University, Jadwin Hall, Princeton, NJ 08544, USA

[4]Chalmers University of Technology, 41296 Gothenburg, Sweden

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(Received 28 November 2017; revised 20 March 2018; accepted 20 March 2018)

We present a theoretical framework for describing electromagnetic kinetic turbulence in a multi-species, magnetized, pressure-anisotropic plasma. The turbulent fluctuations are assumed to be small compared to the mean field, to be spatially anisotropic with respect to it and to have frequencies small compared to the ion cyclotron frequency. At scales above the ion-Larmor radius, the theory reduces to the pressure-anisotropic generalization of kinetic reduced magnetohydrodynamics (KRMHD) formulated by Kunz *et al.* (*J. Plasma Phys.*, vol. 81, 2015, 325810501). At scales at and below the ion-Larmor radius, three main objectives are achieved. First, we analyse the

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