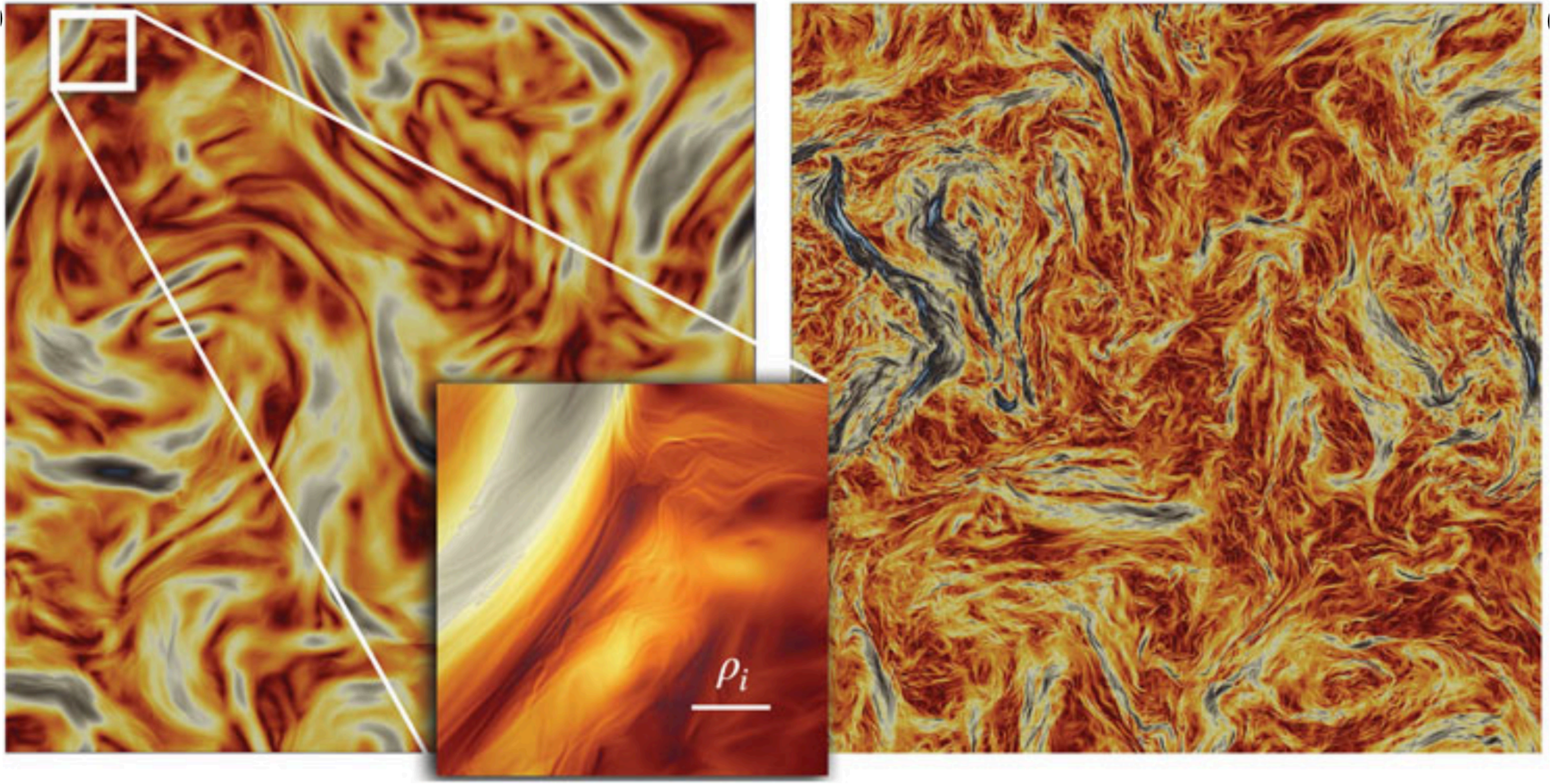
The helicity barrier



Heating and turbulence with imbalance

Model

FLR-MHD – low-β gyrokinetics without electron physics

$$\left(\frac{\partial}{\partial t} + \boldsymbol{u}_\perp \cdot \nabla_\perp\right) \frac{\delta n_e}{n_{0e}} = -\frac{c}{4\pi e n_{0e}} \left(\frac{\partial}{\partial z} + \boldsymbol{b}_\perp \cdot \nabla_\perp\right) \nabla_\perp^2 A_\parallel + \mathcal{D}_{6\nu} \frac{\delta n_e}{n_{0e}},$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{u}_\perp \cdot \nabla_\perp\right) A_\parallel = -c \frac{\partial \varphi}{\partial z} + \frac{c T_{0e}}{e} \left(\frac{\partial}{\partial z} + \boldsymbol{b}_\perp \cdot \nabla_\perp\right) \frac{\delta n_e}{n_{0e}} + \mathcal{D}_{6\nu} A_\parallel,$$

$$\frac{\delta n_e}{n_{0e}} = -\frac{Z}{\tau}\left(1 - \hat{\Gamma}_0\right) \frac{e\varphi}{T_{0e}},$$

$$\Theta_{\boldsymbol{k}}^\pm = -\Omega_i \frac{v_{\mathrm{ph}}(k_\perp)}{k_\perp^2} \frac{\delta n_e}{n_{0e}} \mp \frac{A_\parallel}{\sqrt{4\pi m_i n_{0i}}}.$$

$$v_{\mathrm{ph}}(k_\perp) = \frac{k_\perp \rho_i}{\sqrt{2}} \left(\frac{1}{1 - \hat{\Gamma}_0} + \frac{Z}{\tau}\right)^{1/2} \approx \begin{cases} 1 & k_\perp \rho_i \ll 1, \\ \left(\frac{1}{2} + \frac{Z}{2\tau}\right)^{1/2} k_\perp \rho_i & k_\perp \rho_i \gg 1. \end{cases}$$

Model

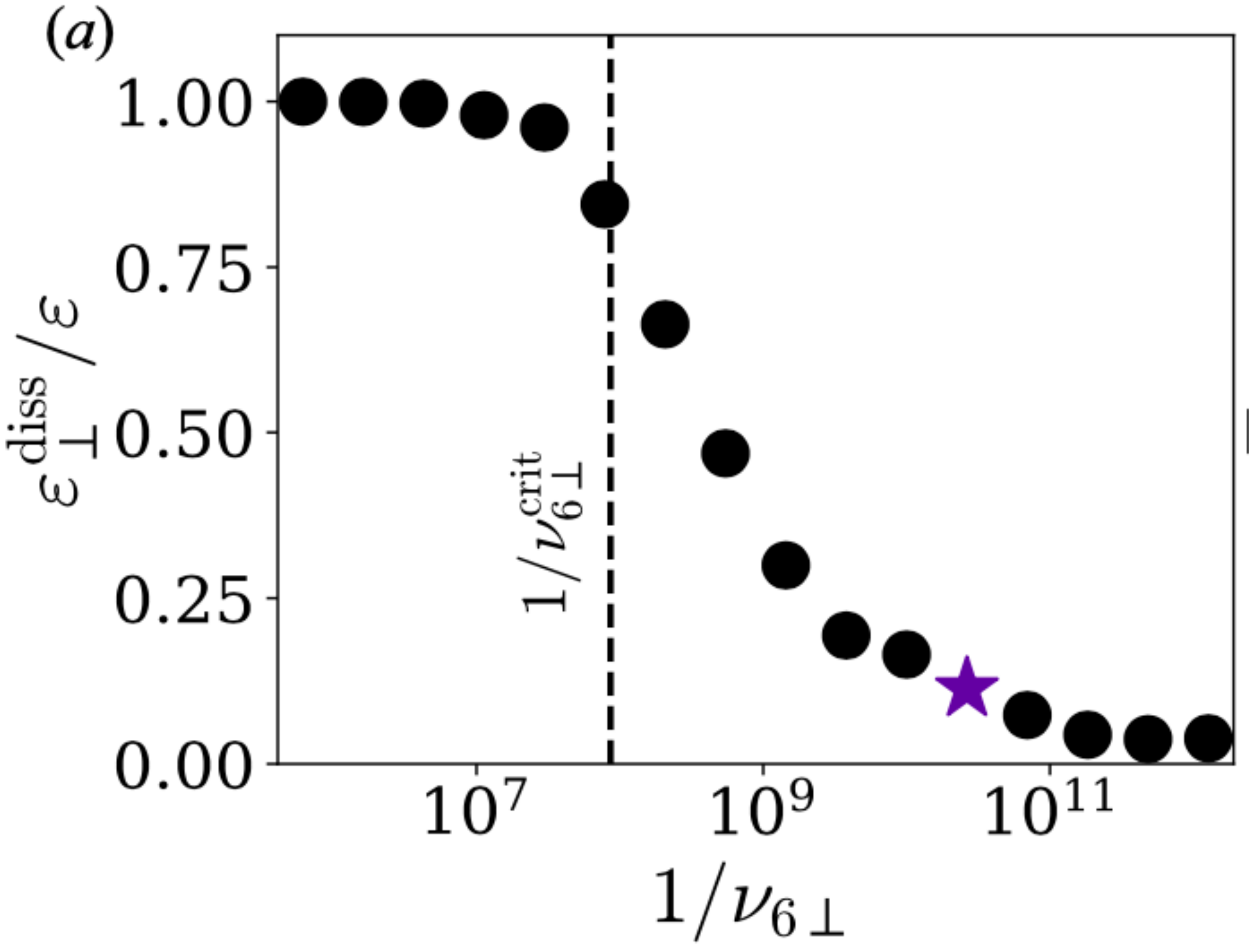
Invariants

$$E = \frac{1}{4}\sum_{\boldsymbol{k}} \left(|k_\perp \Theta_{\boldsymbol{k}}^{+}|^2 + |k_\perp \Theta_{\boldsymbol{k}}^{-}|^2 \right) \qquad \mathcal{H} = \frac{1}{4}\sum_{\boldsymbol{k}} \frac{|k_\perp \Theta_{\boldsymbol{k}}^{+}|^2 - |k_\perp \Theta_{\boldsymbol{k}}^{-}|^2}{v_{\mathrm{ph}}(k_\perp)}$$

$$\sigma_\varepsilon = \frac{|\,\Pi_{\mathscr{H}}(k_\perp)\,|}{\Pi(k_\perp)} \leq \frac{1}{v_{\mathrm{ph}}(k_\perp)}$$

FLR effects strongly modify cascade at $k_\perp \rho_i \ll 1$

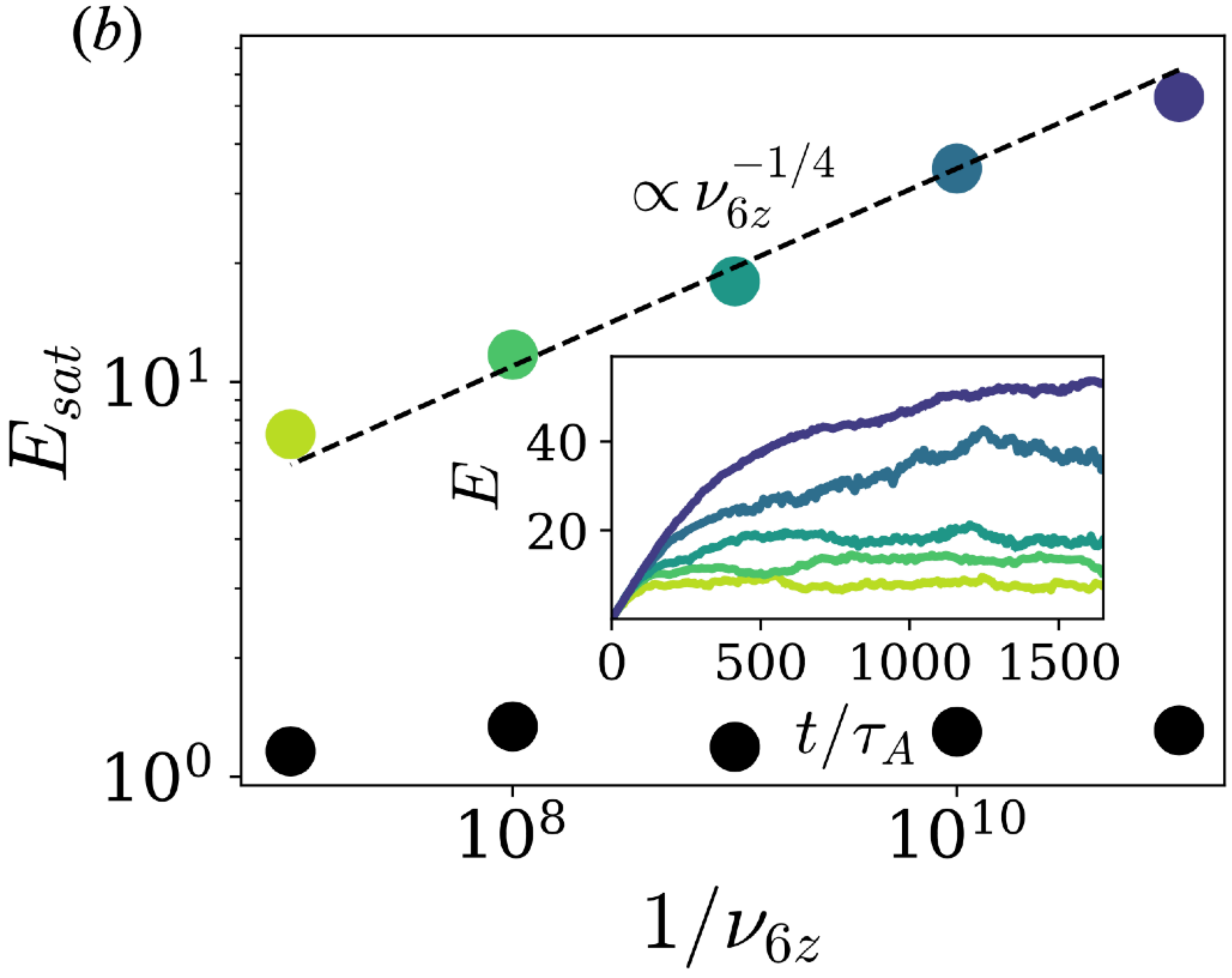
Violation of the zeroth law of turbulence

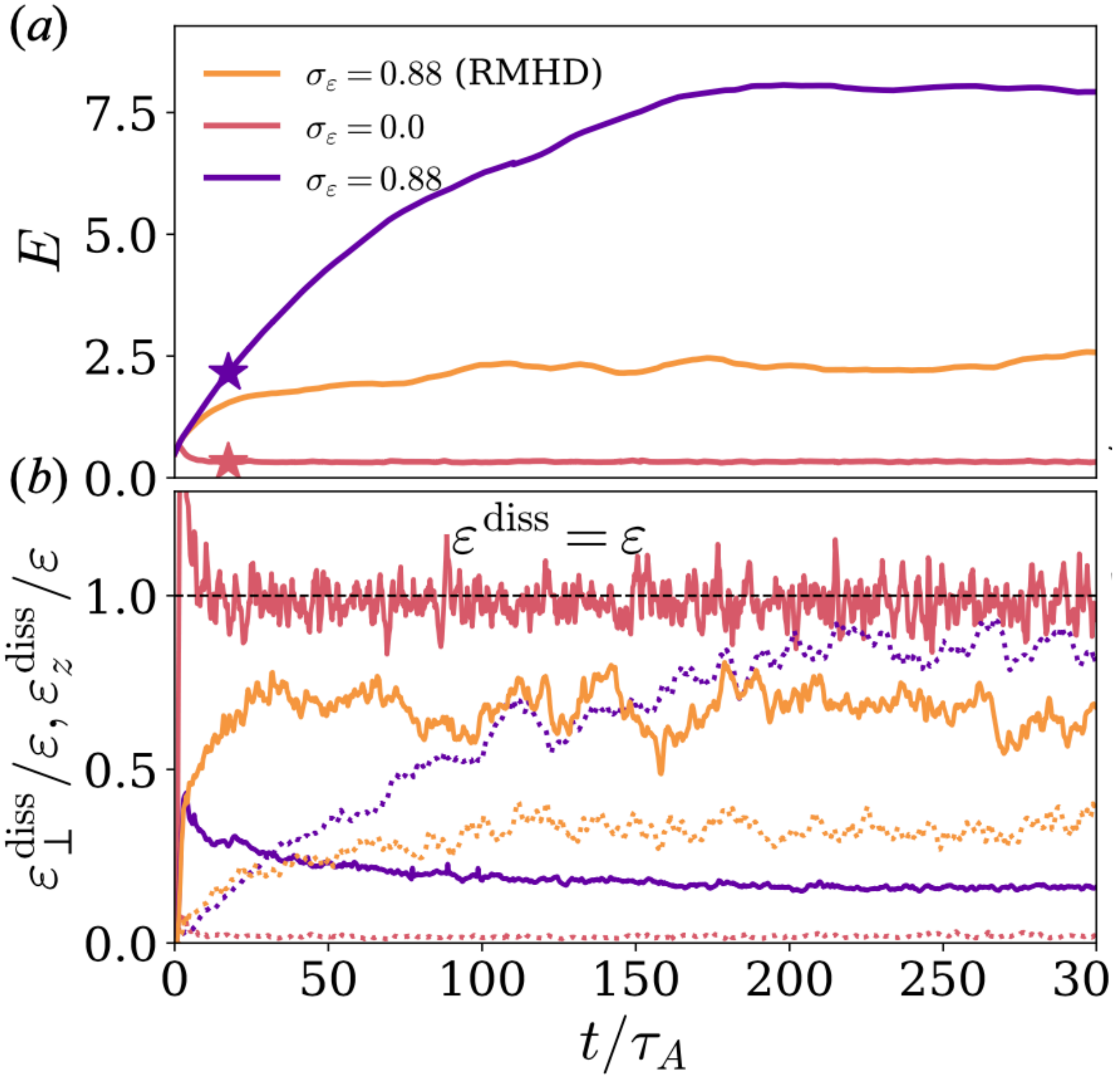


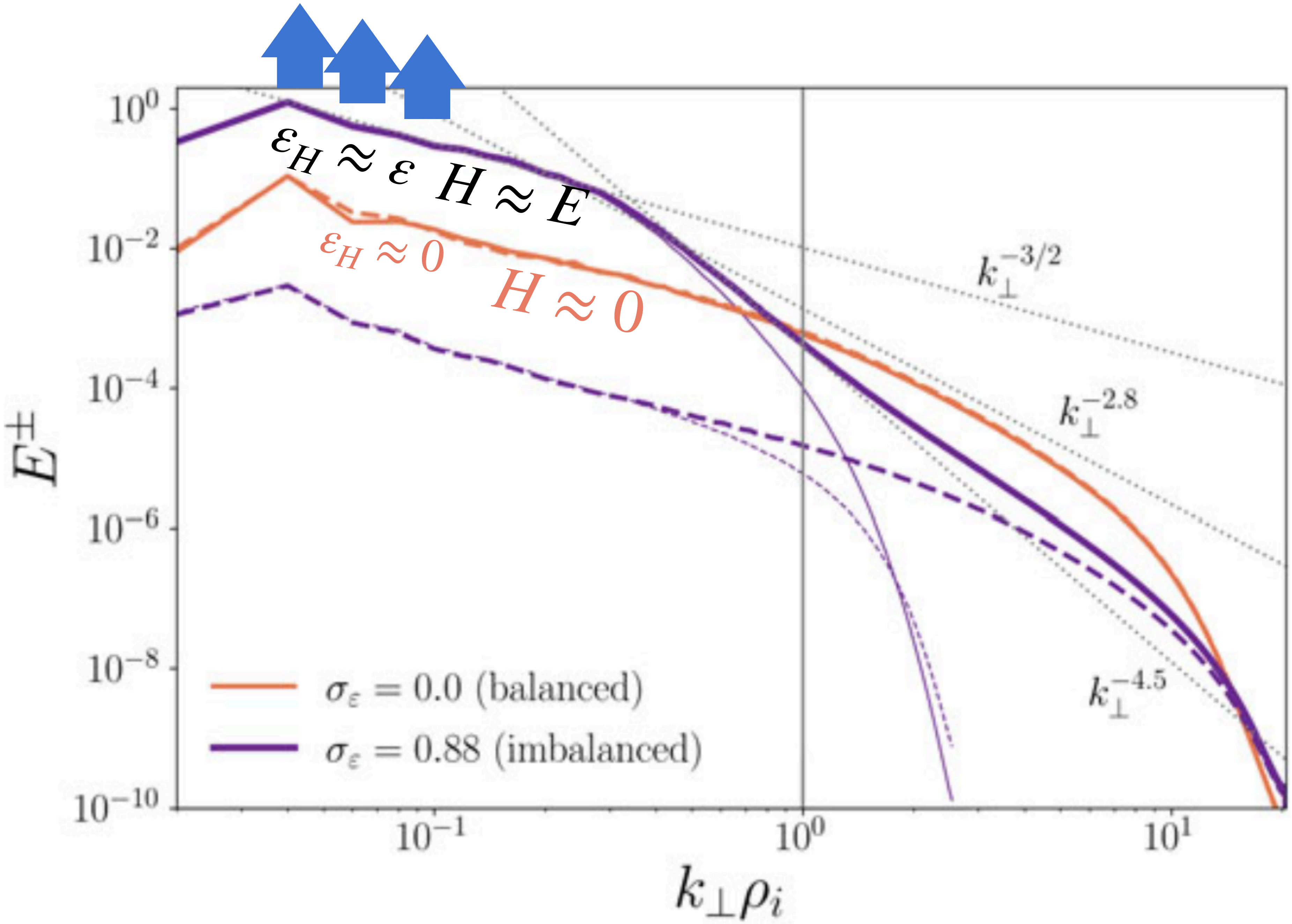
Flux to the small scales →

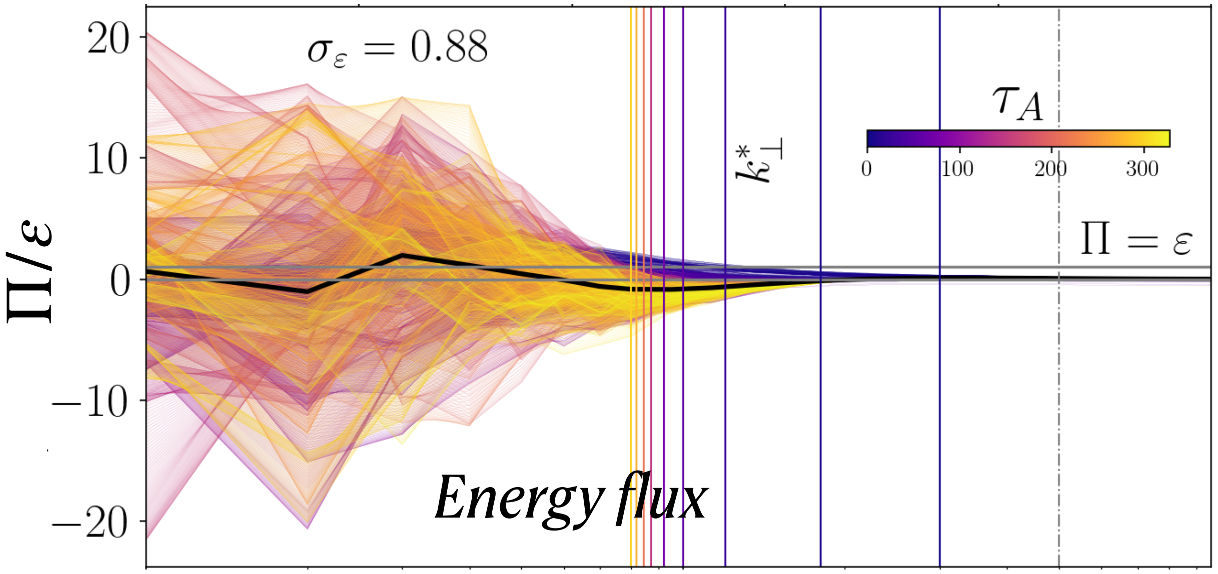
Smaller viscosity →

Parallel dissipation matters – “breaks” gyrokinetics

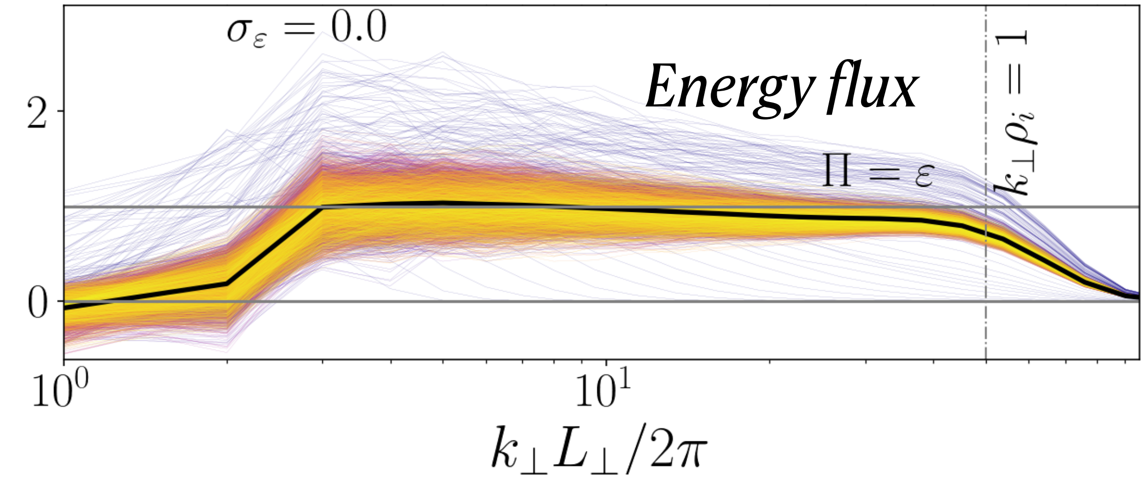


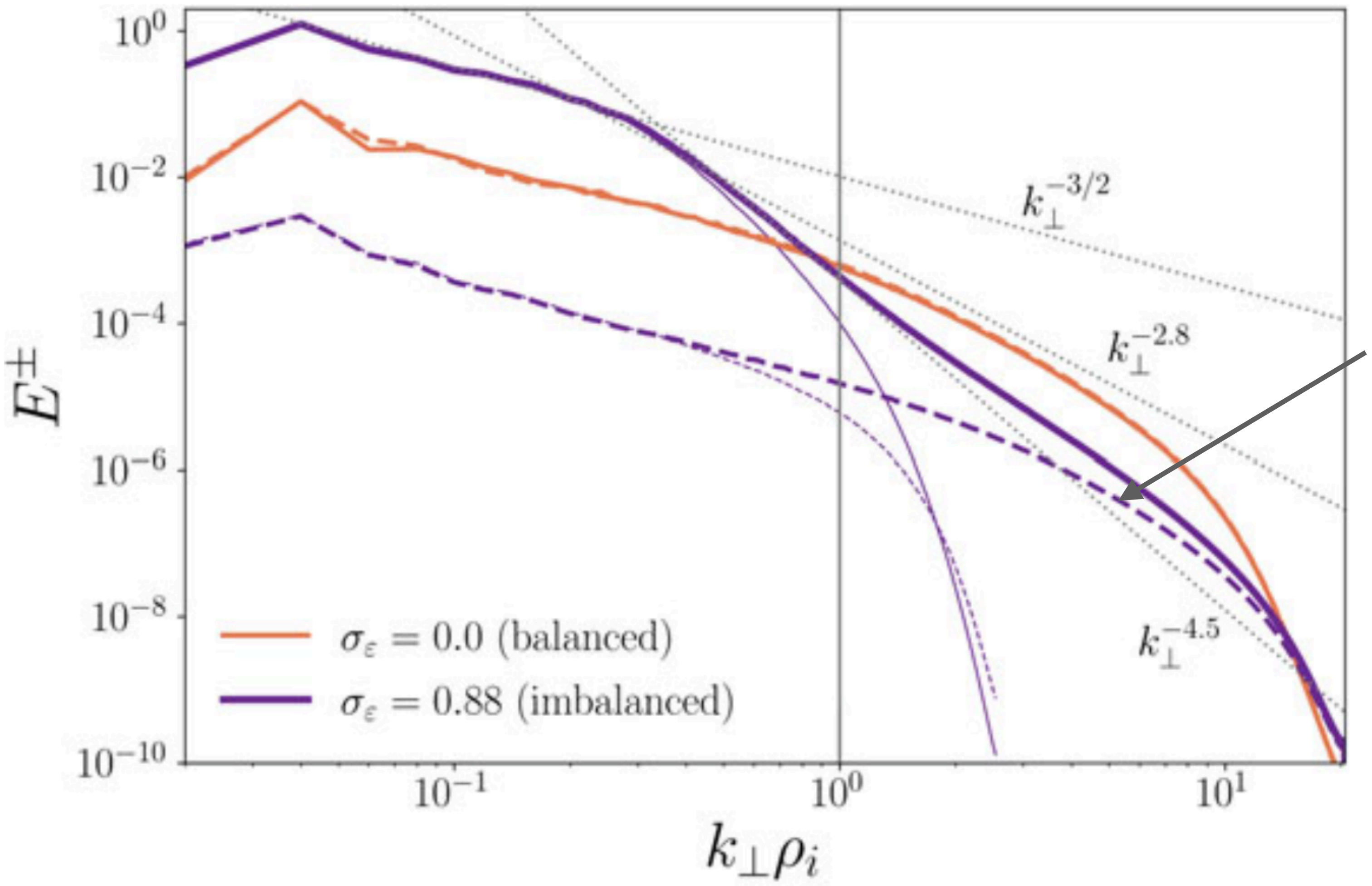






Normal Turbulence $H = 0$





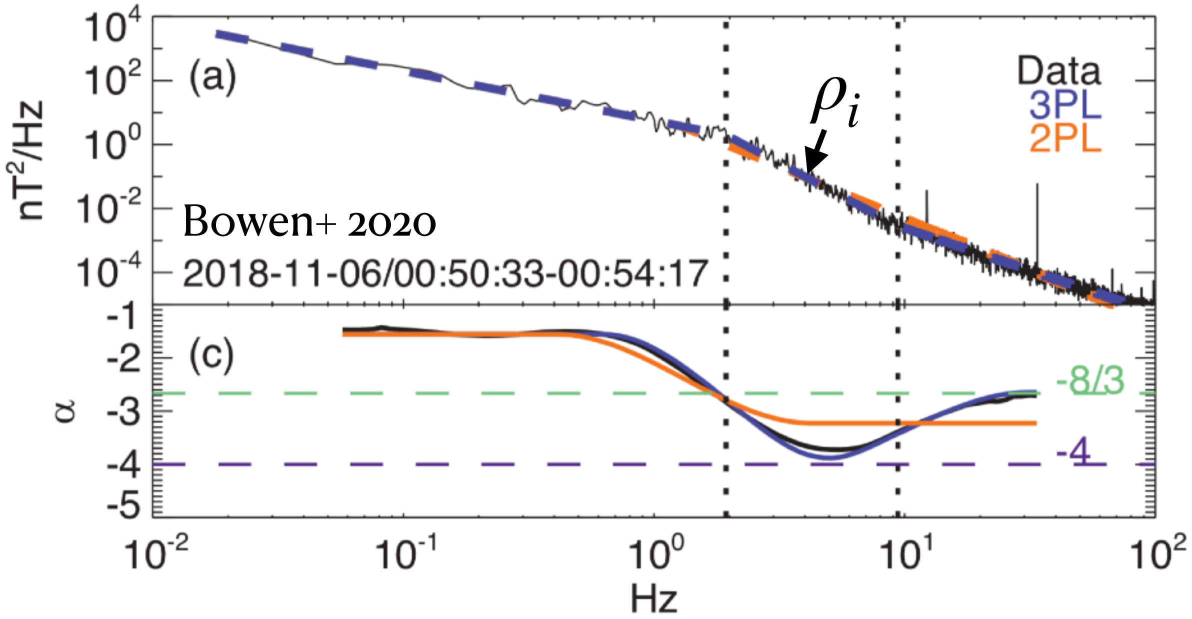
Flux to small scales =
balanced fraction of injected flux

KAW turbulence

$$\frac{Q_i}{Q_e} \approx \frac{\text{Imbalanced fraction}}{\text{Balanced fraction}} = \frac{\varepsilon_H}{\varepsilon - \varepsilon_H} \gg 1 \quad (\text{if } \varepsilon \sim \varepsilon_H)$$

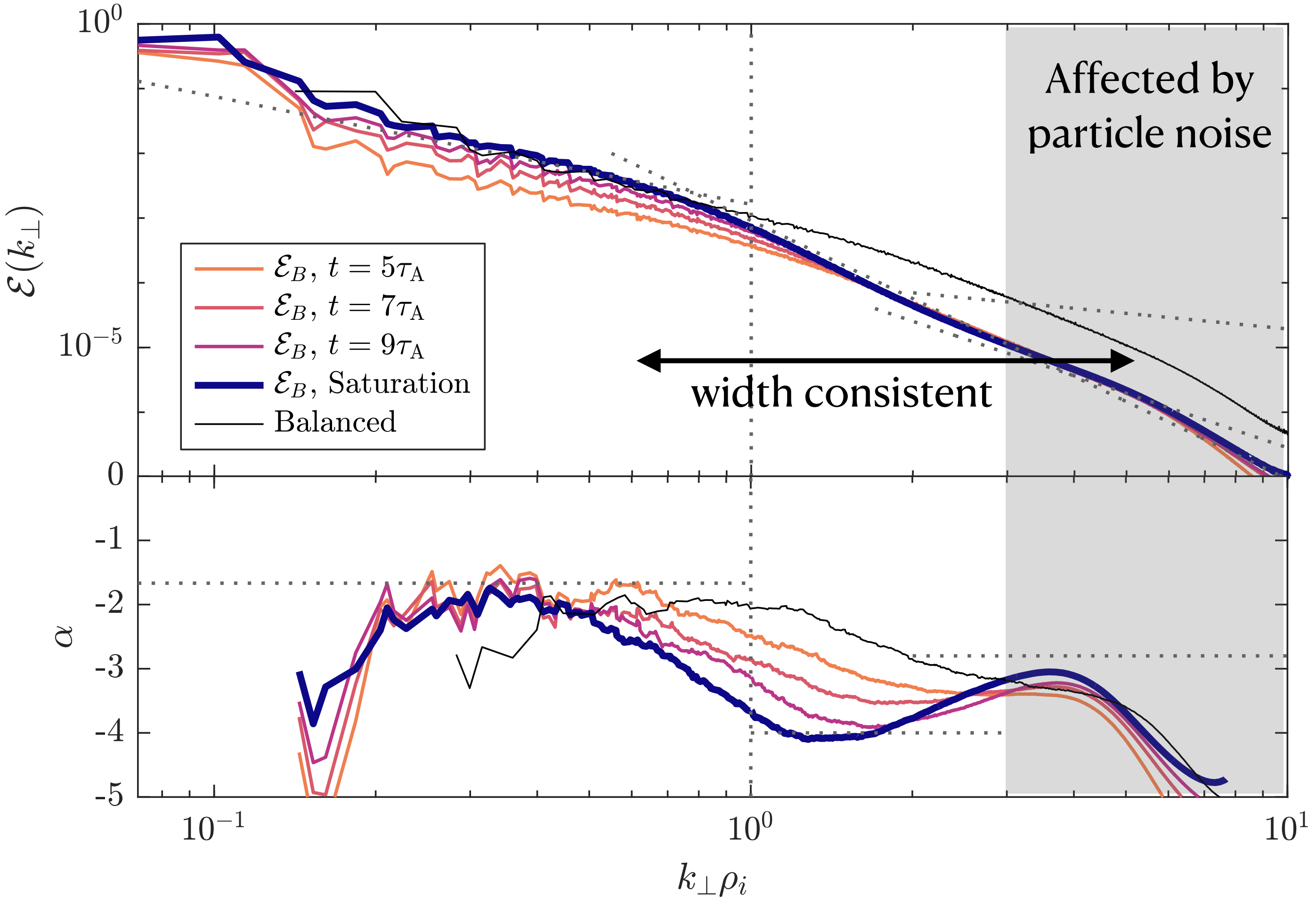
Observational Evidence

Magnetic spectra – transition range

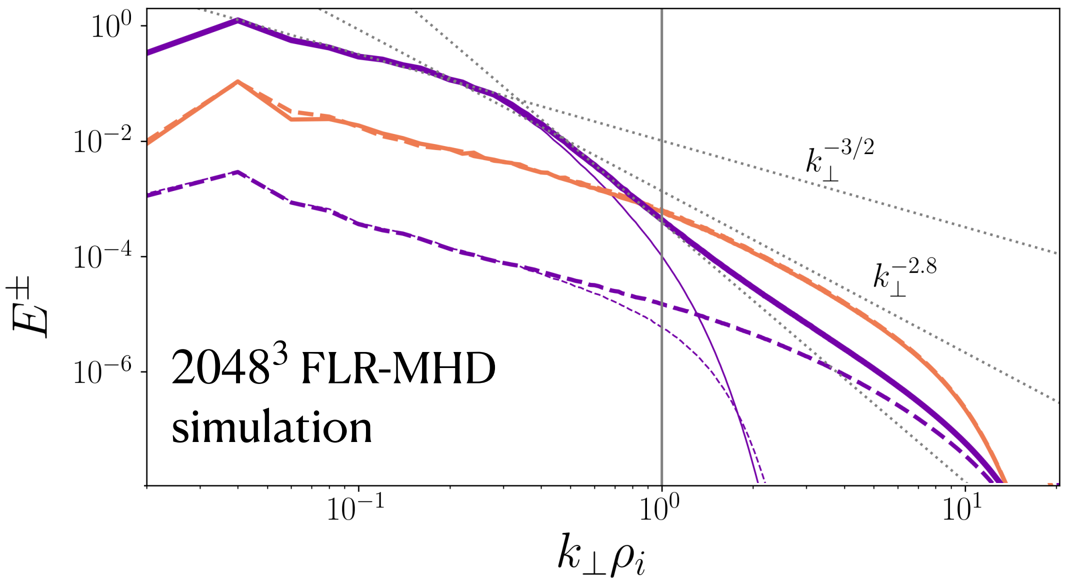


e.g., Leamon+ 1998, Smith+ 2006, Sahraoui+ 2009, Alexandrova+ 2013, Kiyani+ 2015, Bruno+ 2014, Vech+ 2018, Bowen+2020, Zhao+ 2020, Duan+ 2021, Huang+ 2021

Previous theories, e.g., Schekochihin+ 2009, Sahraoui+ 2010, Meyrand+ 2010, Lion+2010, Voitenko+ 2016, Mallet+ 2017



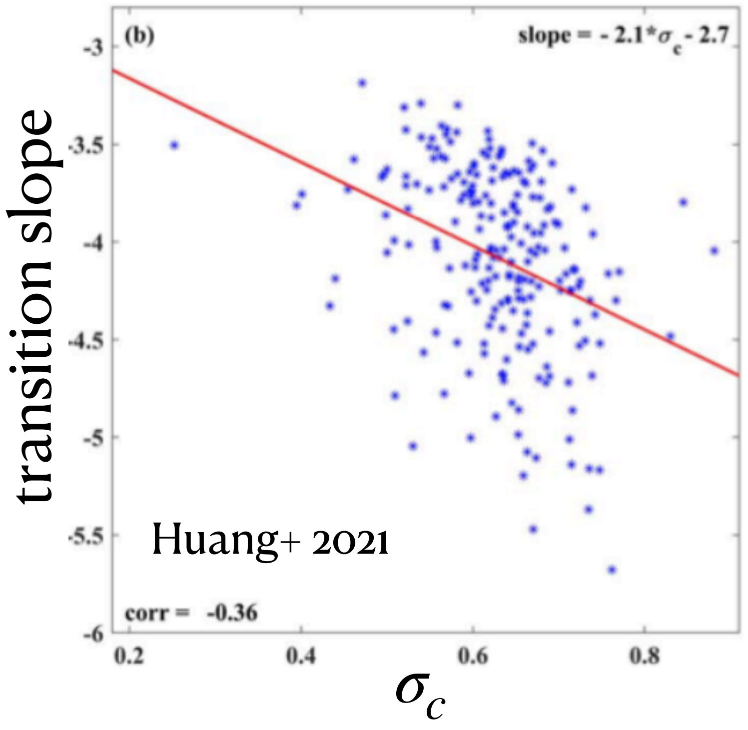
Physically: spectrum re-flattens because the balanced KAW cascade leaks through the barrier.



Observational Evidence

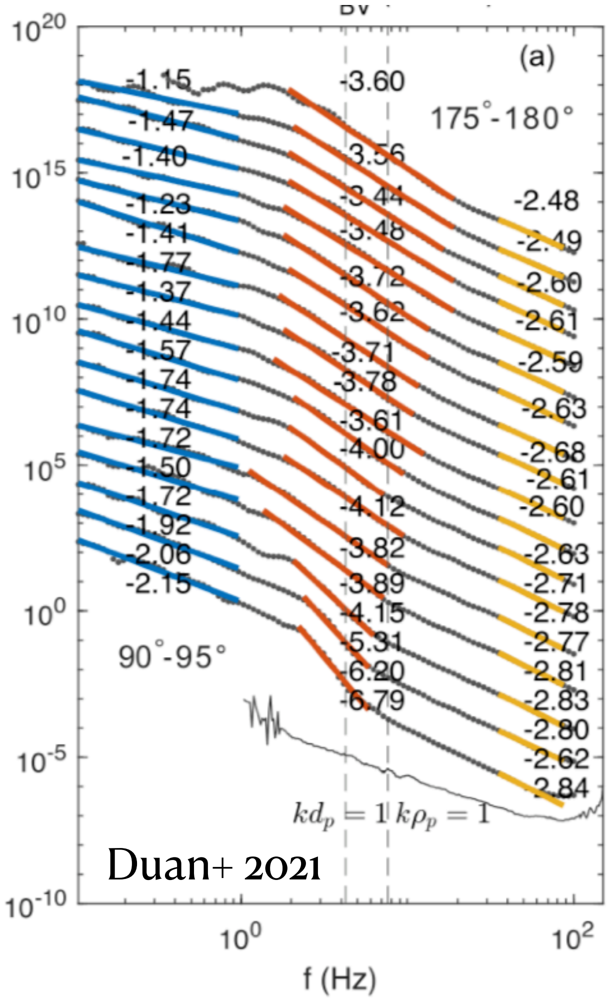
Magnetic spectra – transition range

- Steeper transition range in larger amplitude, lower β, fast wind (higher imbalance)
- **Predictions:** *no transition range in balanced turbulence*
  correlation of break position with imbalance

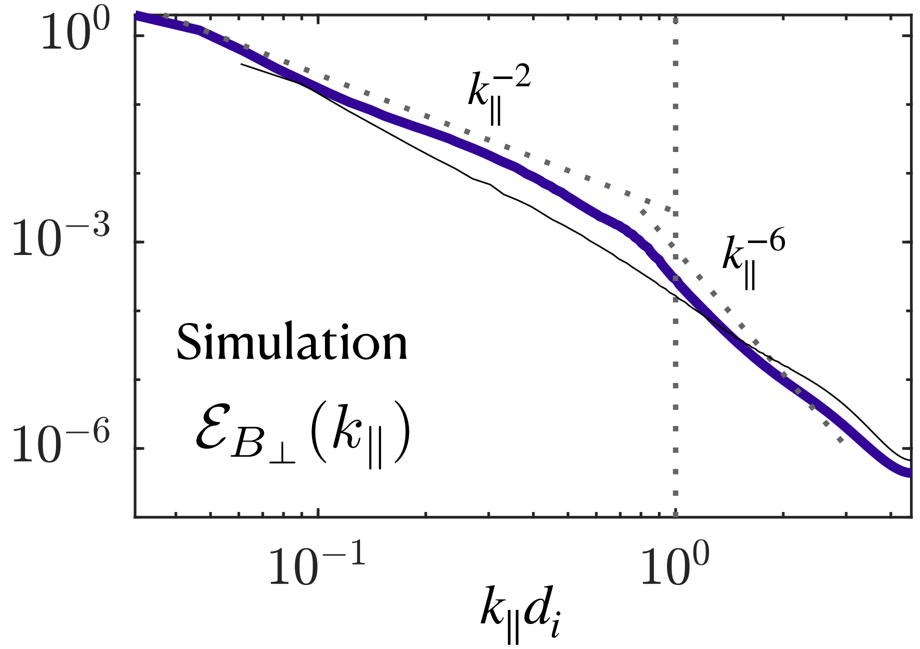


Huang+ 2021

- Parallel spectra show extremely steep transition range
- Anisotropy scaling similar



Duan+ 2021

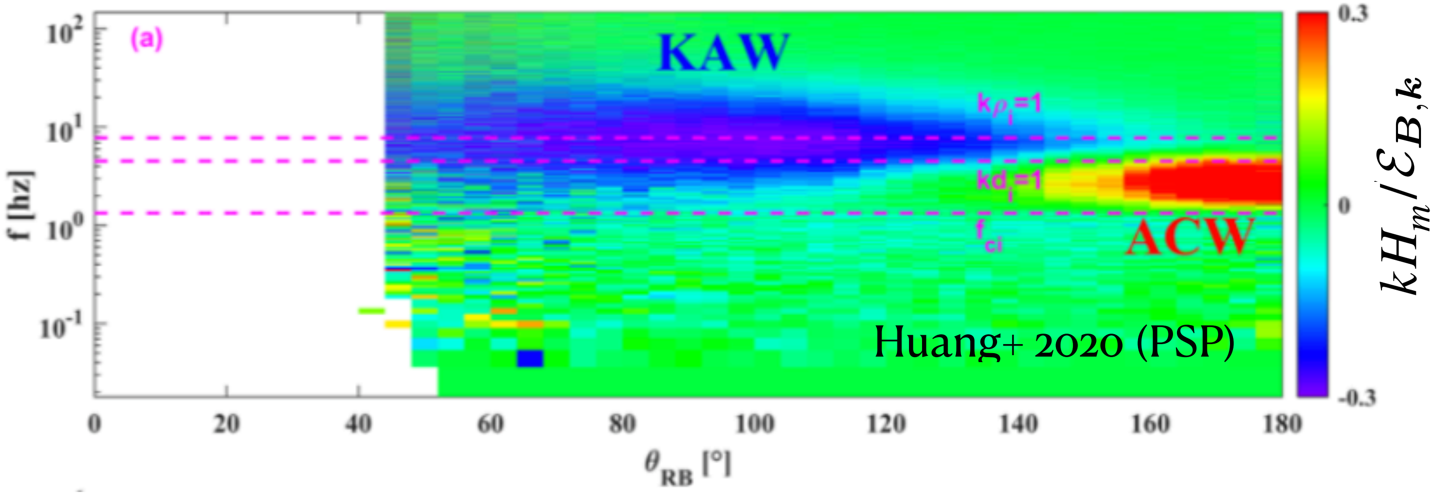


Simulation

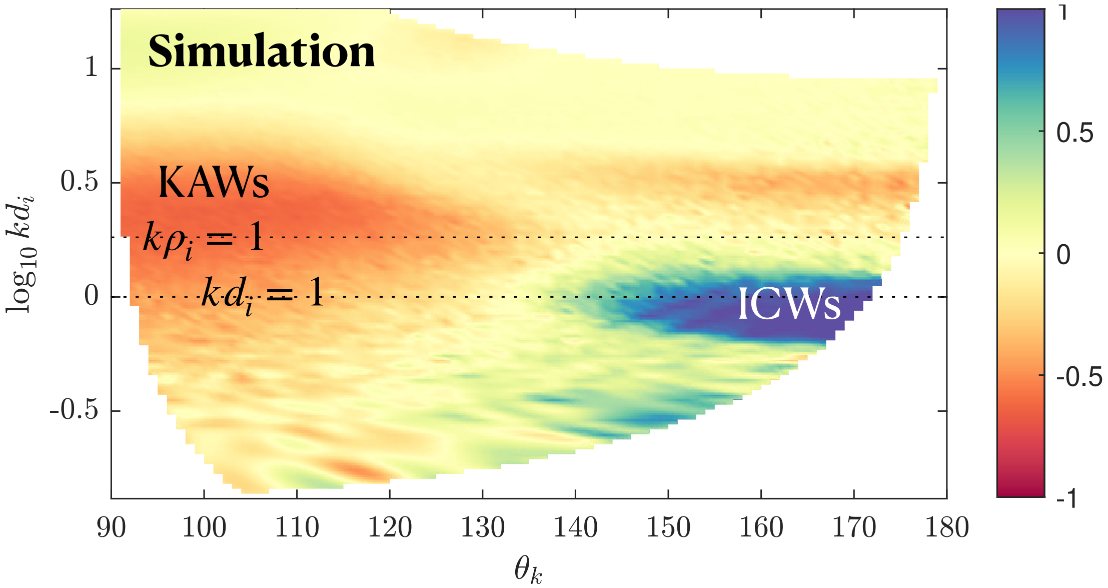
$\mathcal{E}_{B_\perp}(k_\parallel)$

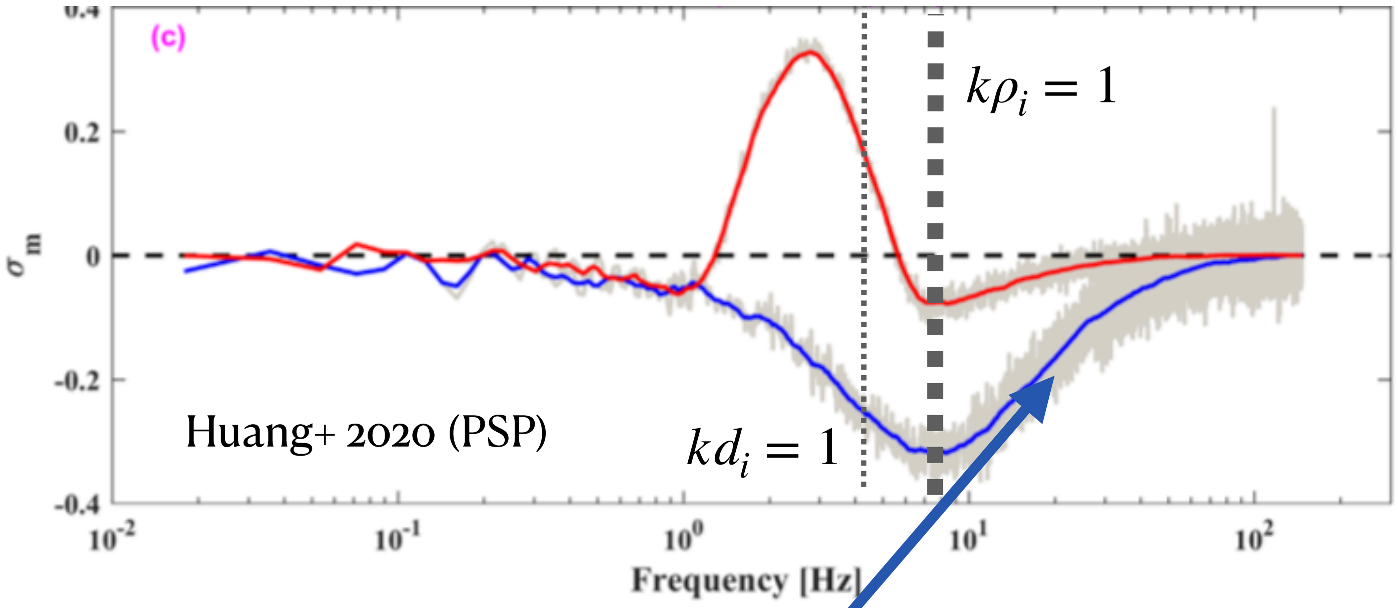
Observational Evidence

Magnetic spectra – helicity



Huang+ 2020 (PSP)





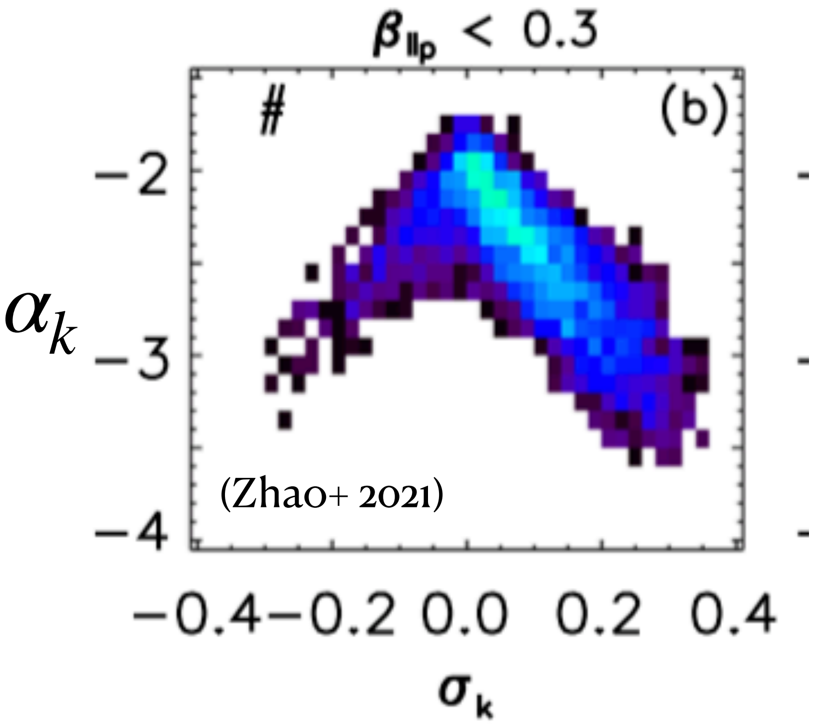
Huang+ 2020 (PSP)

Natural explanation for $H_m \to 0$ at $k_\perp \rho_i > 1$

e.g., Huang+2020, Woodham+2021 SH45A-2355

Physically: **balanced small-scale cascade**

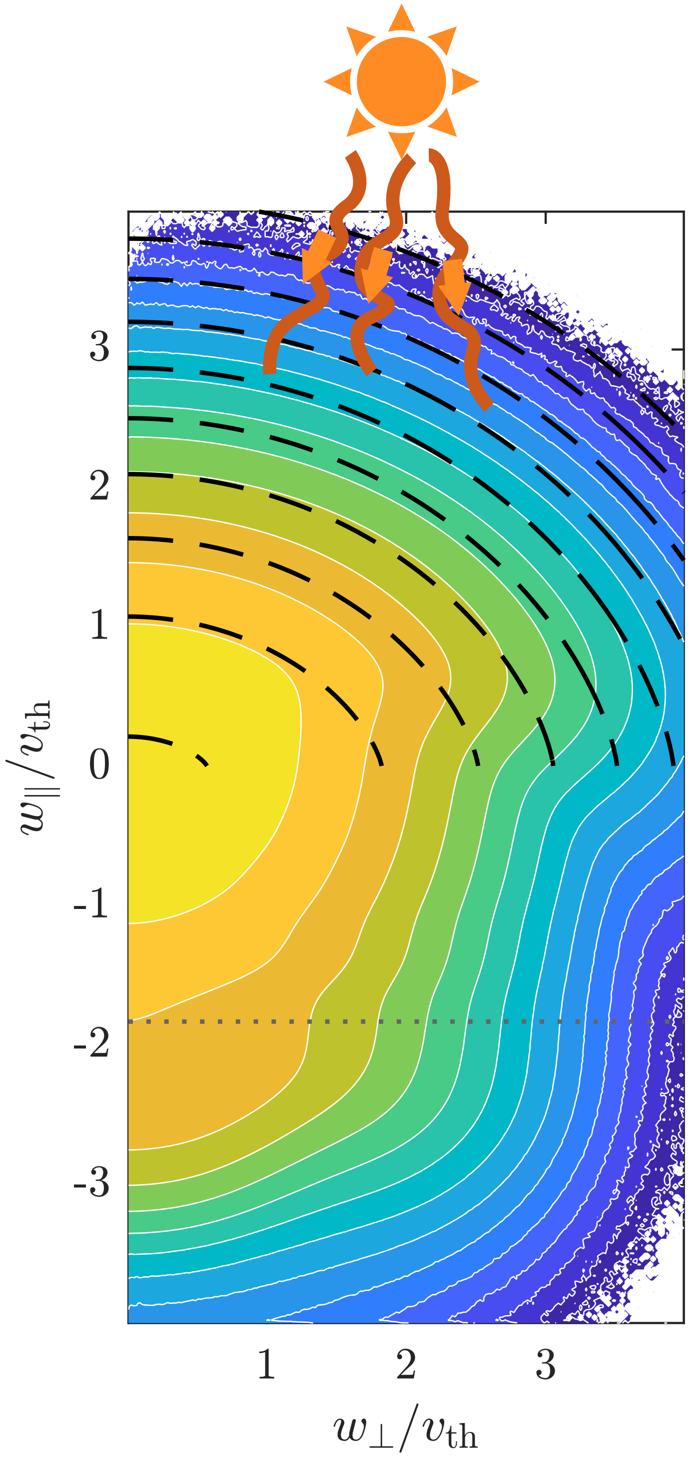
Helicity correlated with transition-range slope



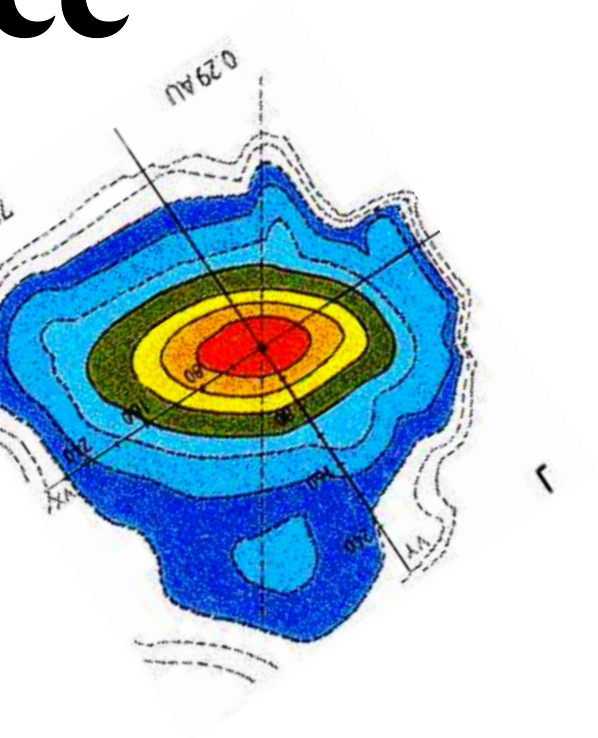
(Zhao+ 2021)

Observational Evidence

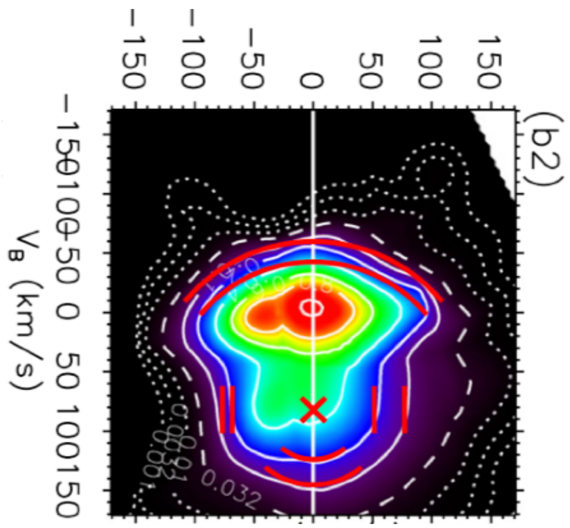
Distribution function



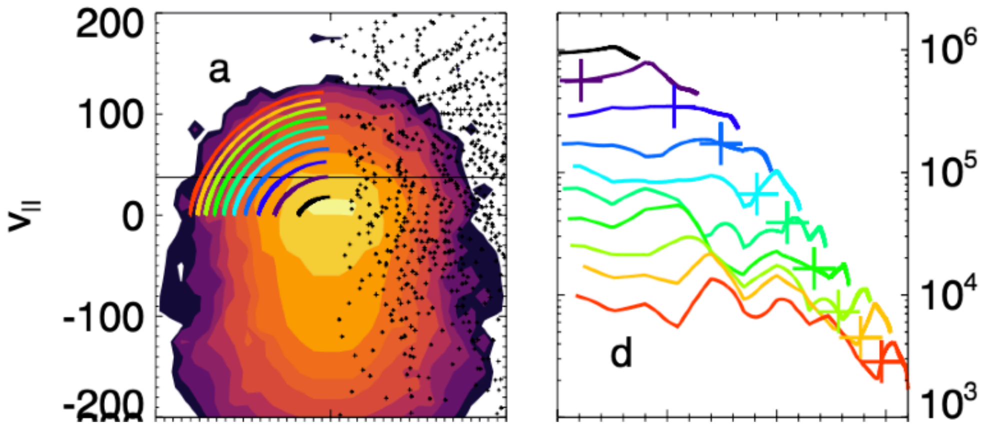
Helios 0.3AU (Marsch+ 1982)



WIND (He+ 2015)



PSP (Bowen+ 2021)



Beam: velocity $\simeq 1.2 - 1.5 v_A$

direction matches AW direction (He+ 2015b)