TH/1-1

Multi-Scale ITG/TEM/ETG Turbulence Simulations with Real Mass Ratio and β Value

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K computer

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Introduction

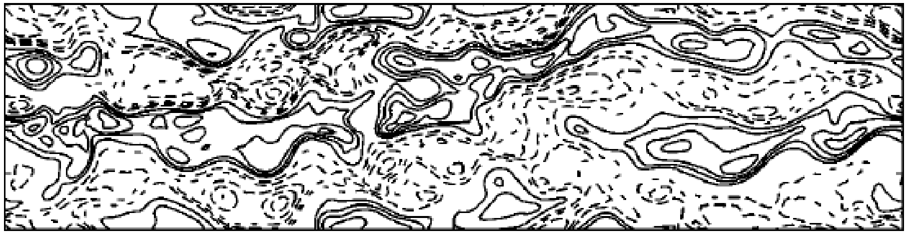
One of the critical issues in ITER is electron heat transport, which is inherently multi-scale physics.

2000 [Jenko00PoP]

A candidate is electron temperature gradient modes (**ETG**).

"Streamers" in ETG turbulence

Poloidal direction



Radial direction

2007 [Candy07PPCF,Waltz08PoP,Görler08PRL]

ETGs give small transport if there are ion temperature gradient and trapped electron modes (**ITG/TEM**).

However, these multi-scale simulations were limited:

- Reduced mass ratio (m_i/m_e=400, 900)
- Electrostatic approximation (β=0)

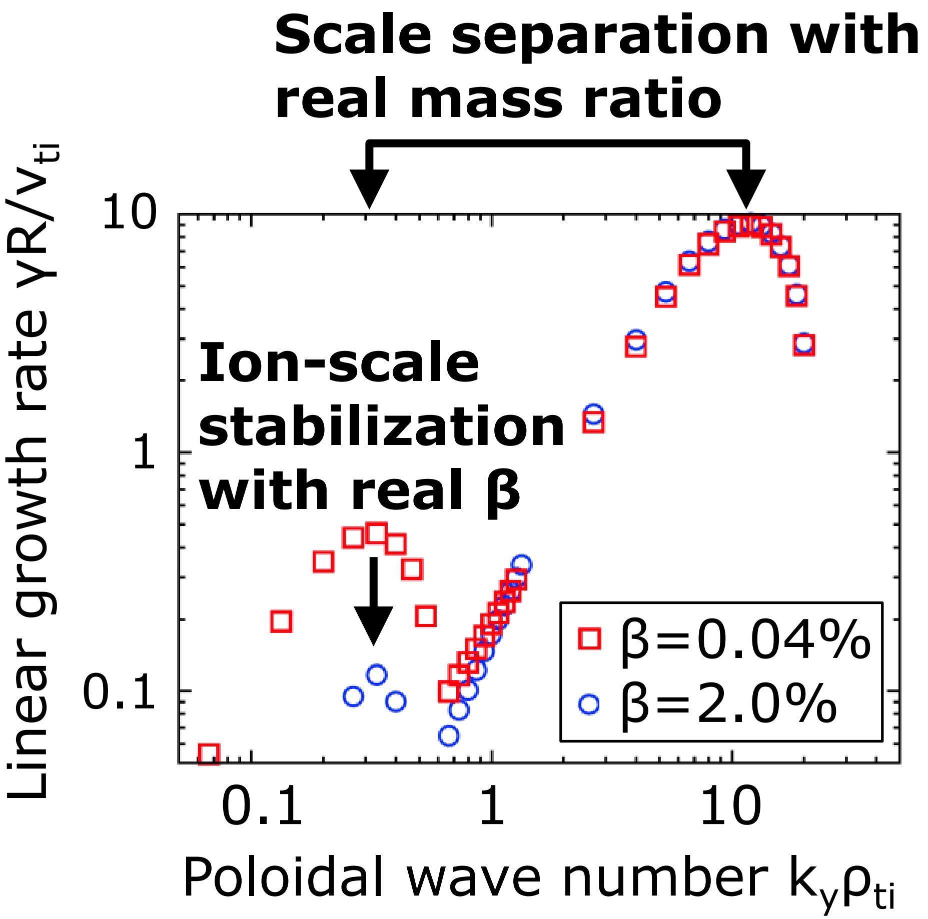
Motivation & Outline

Following points are not yet clarified:

(i) Are there multi-scale interactions even with the real mass ratio and β value?

(ii) If yes, how do the interactions occur?

Linear instabilities from electron to ion scales



Motivation & Outline

Following points are not yet clarified:

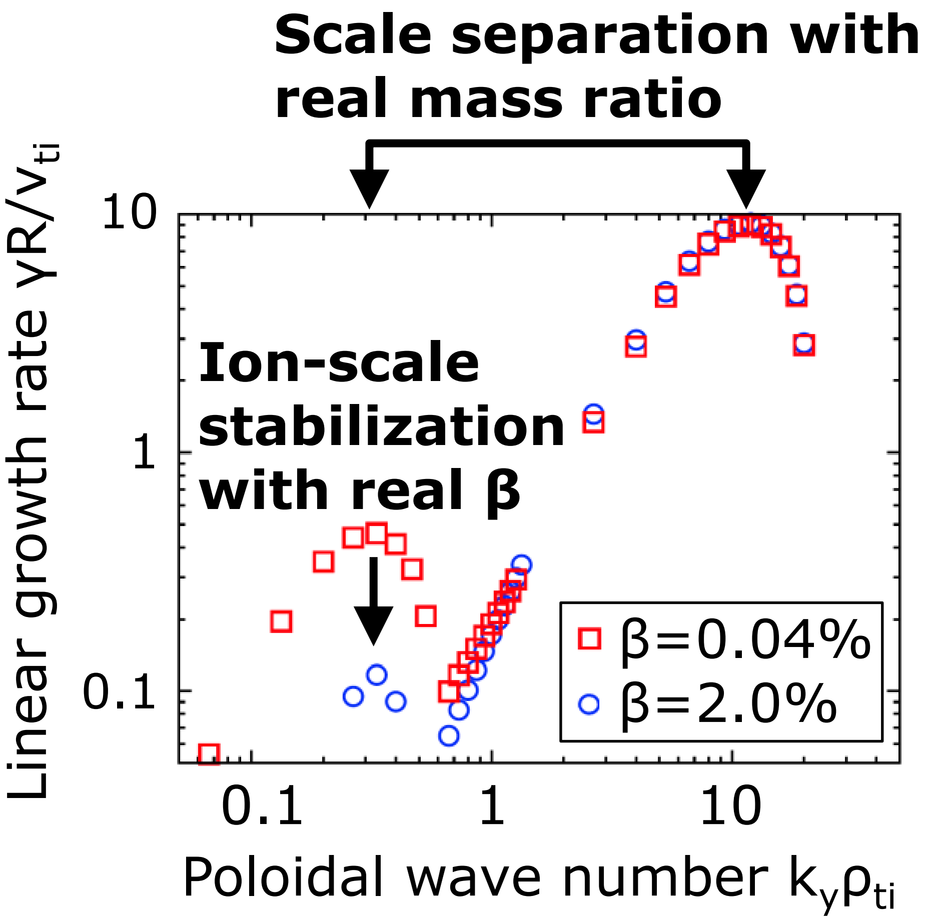
(i) Are there multi-scale interactions even with the real mass ratio and β value?

- **Multi-scale simulation demonstrates cross-scale interactions.**

(ii) If yes, how do the interactions occur?

- **Nonlinear interaction analysis reveals their mechanisms.**

Linear instabilities from electron to ion scales

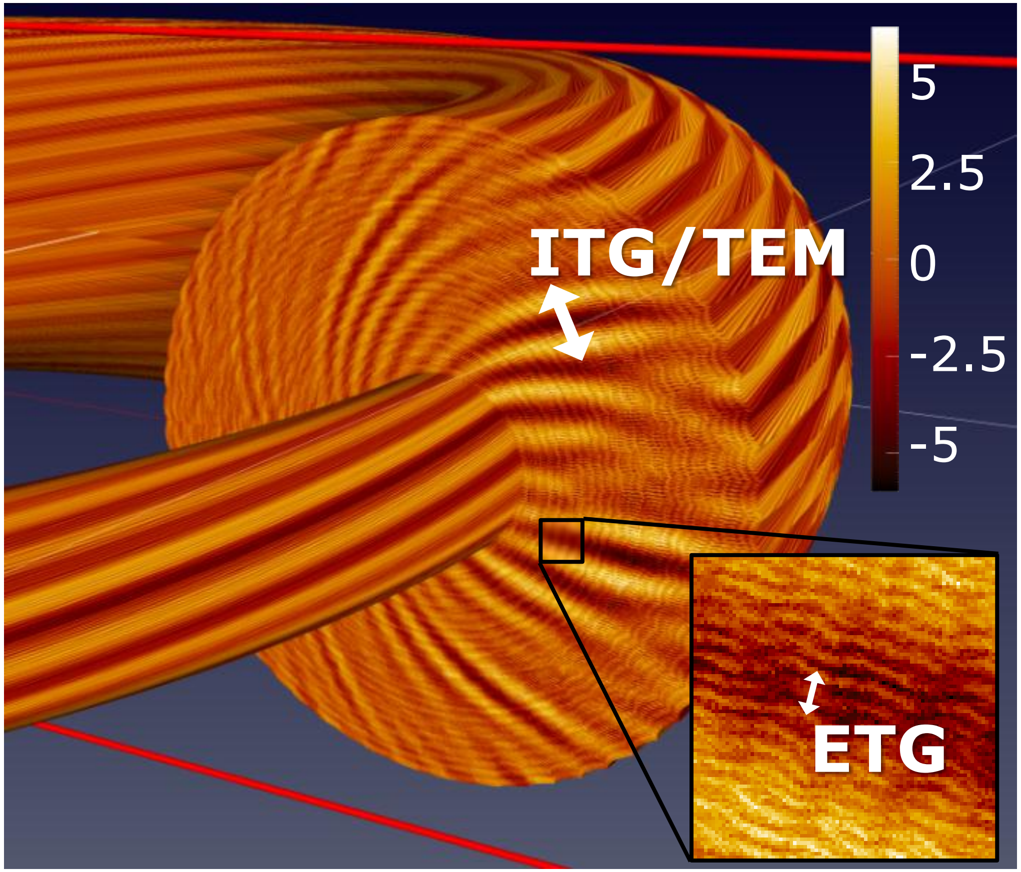


The GKV code [Watanabe06NF,Maeyama13CPC]

- Solve gyrokinetic ions and electrons with electromagnetic fluctuations in a flux-tube geometry.
- Validation with experiments. [Posters:Nakata,Ishizawa,Nunami]
- High scalability allows ITG/TEM/ETG simulations with ~100k CPU cores in ~100 hours. [Maeyama13SC]

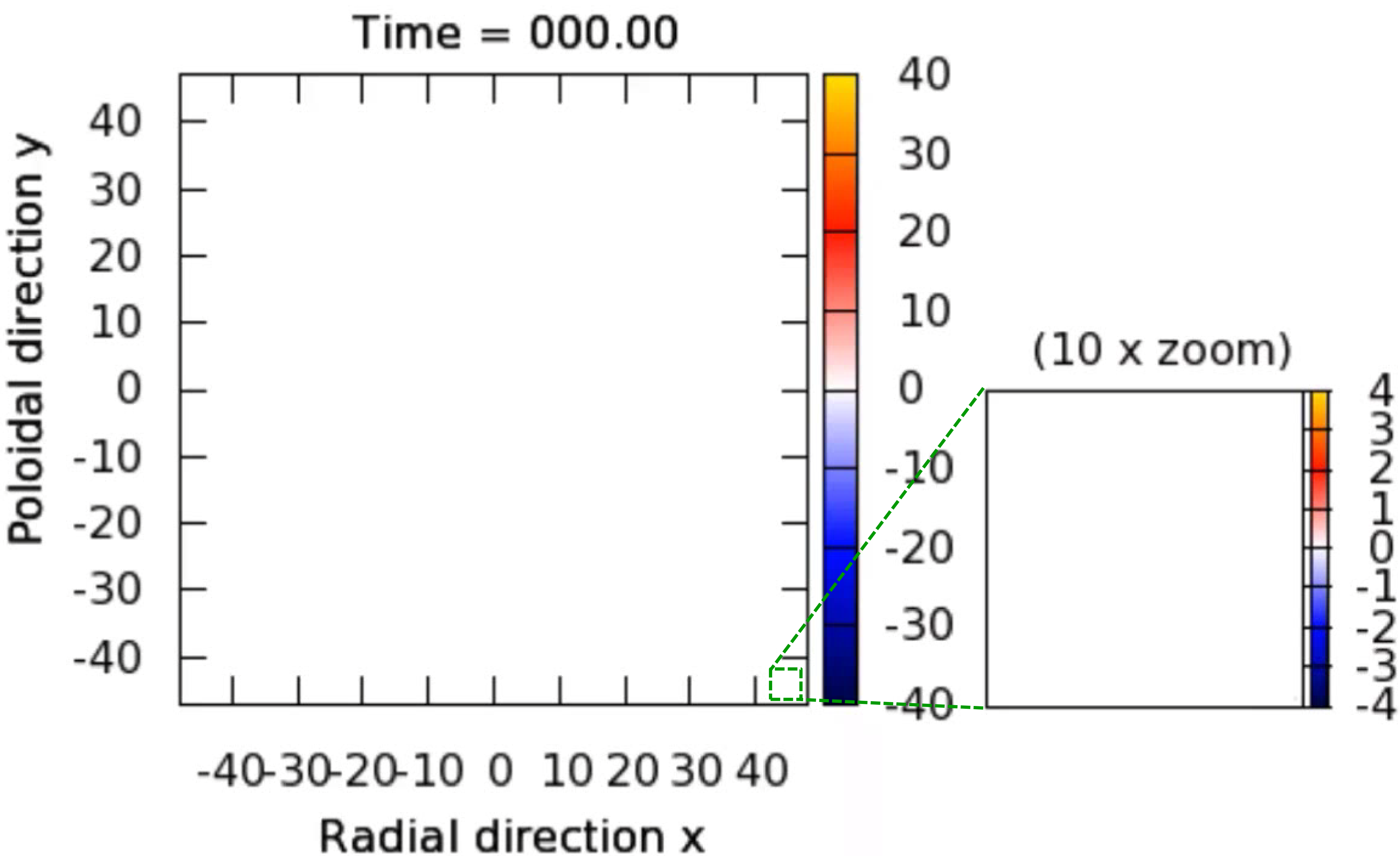
Plasma parameters are Cyclone base case parameters [Dimits00PoP]

- $R/L_{Ti}=R/L_{Te}=6.82$, $R/L_n=2.2$, $T_e=T_i$, $r/R=0.18$, $q=1.4$, $s=0.786$
- Real mass ratio: $m_i/m_e=1836$
- Real β value: $\beta=2.0\%$ (below NZT [Pueschel13PRL])



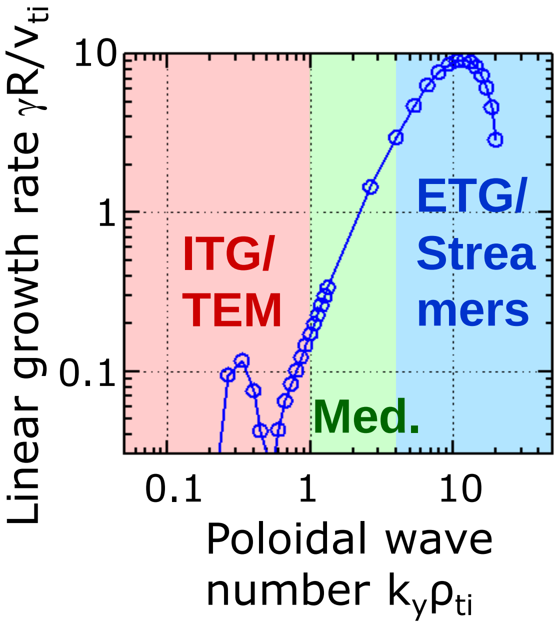
Multi-scale turbulence simulation (β=2.0%)

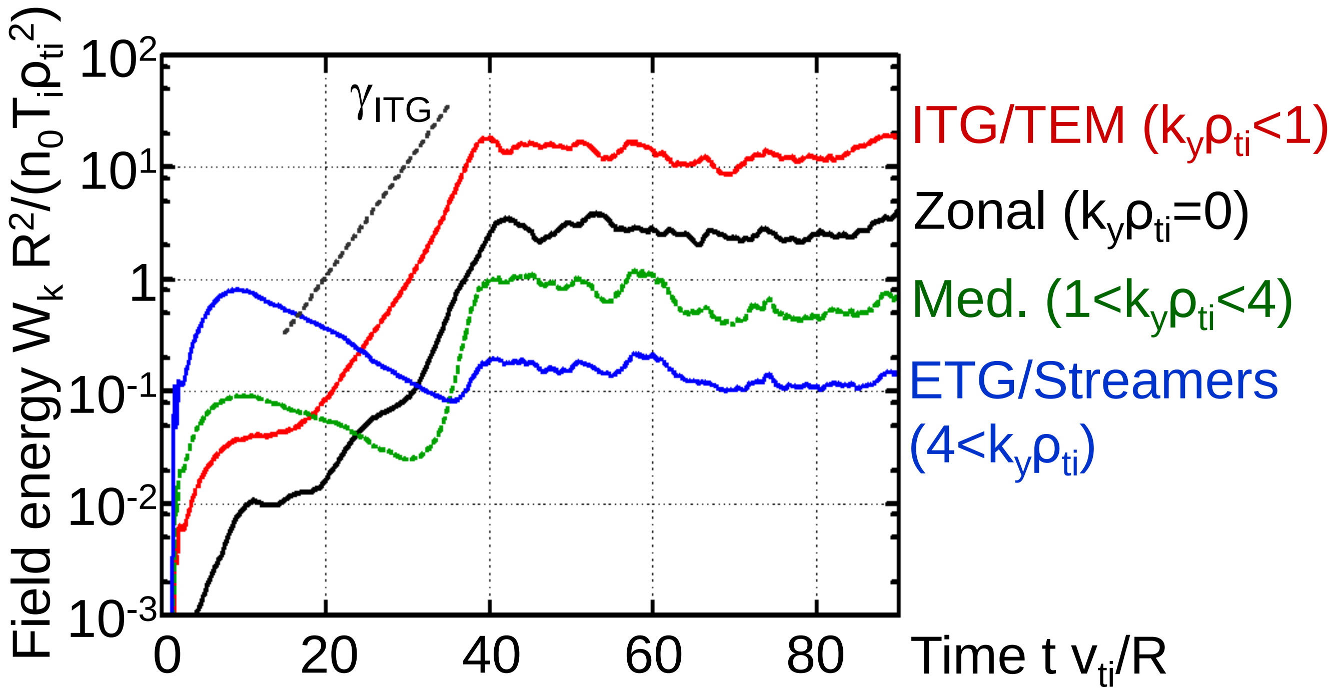
Time evolution of the electrostatic potential fluctuations
(at mid-plane of the flux tube)



Energy spectrum

(β=2.0%)





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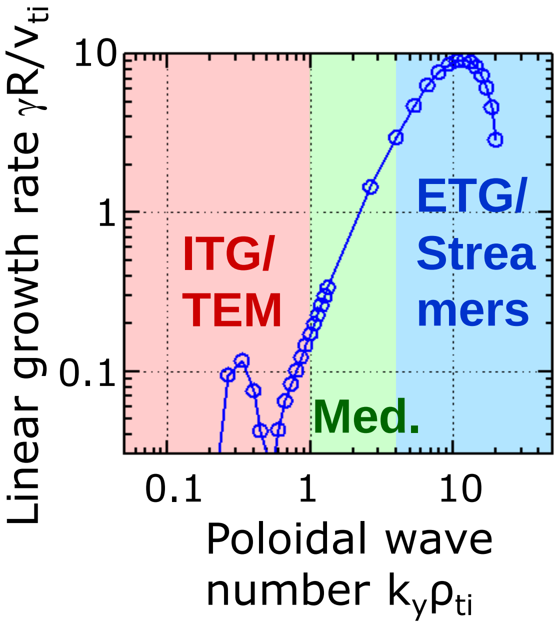

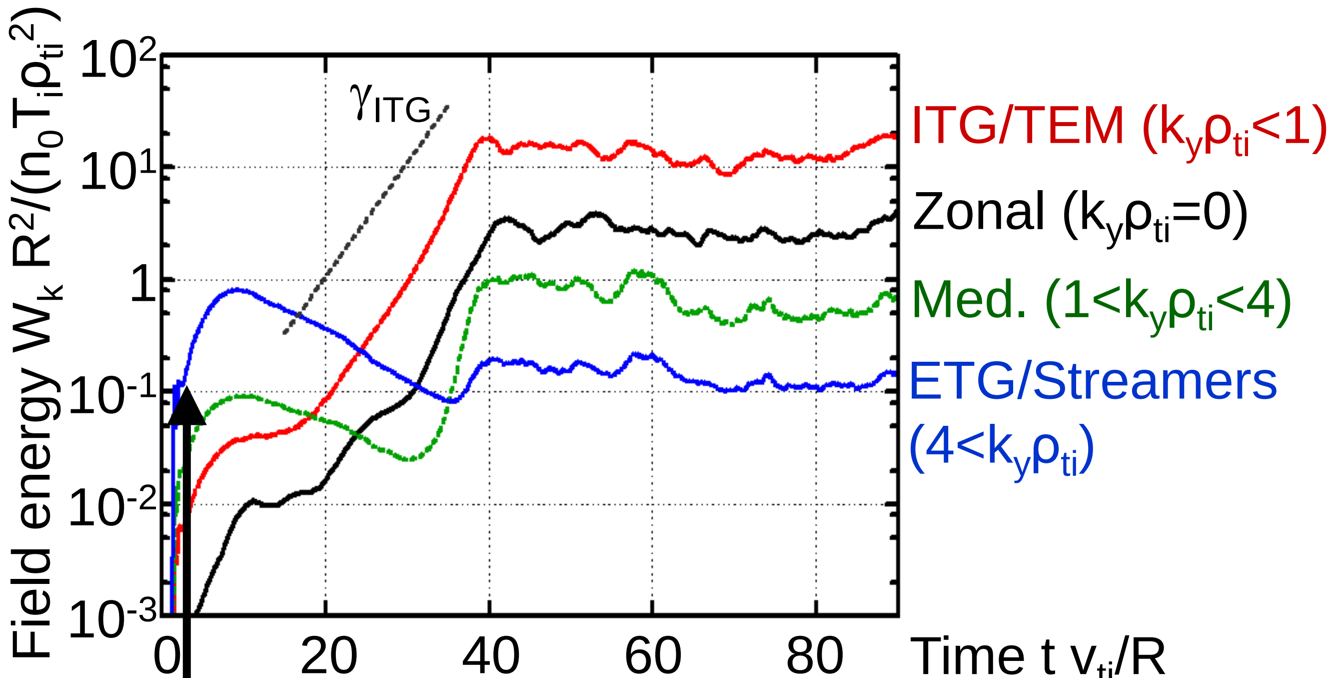

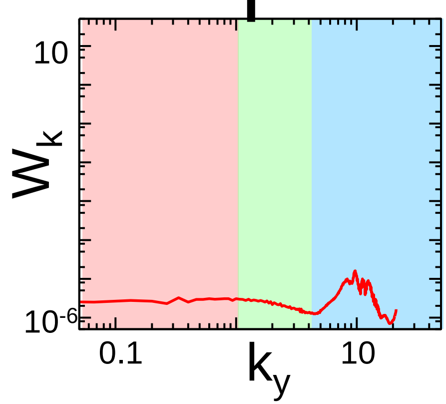

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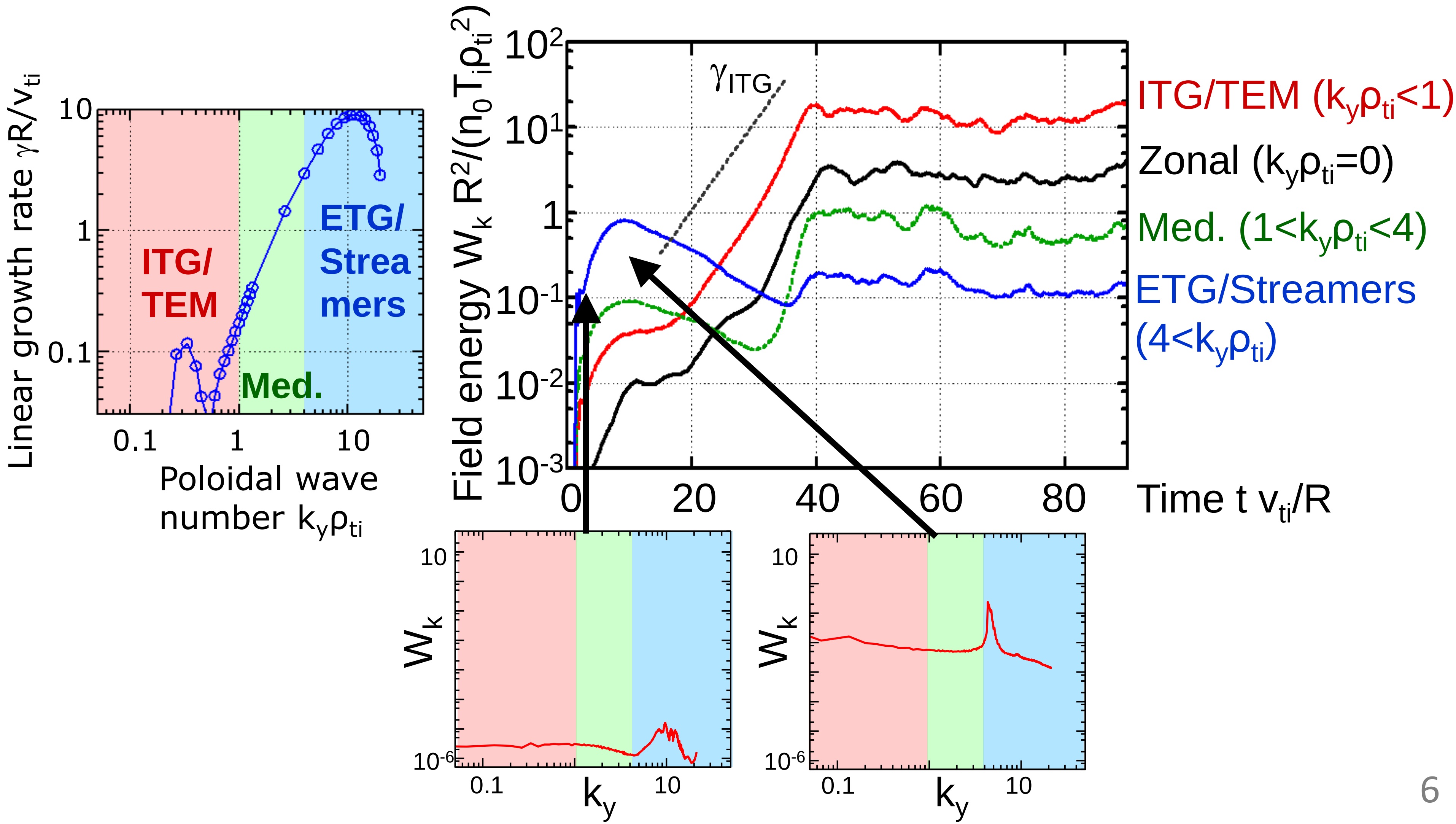

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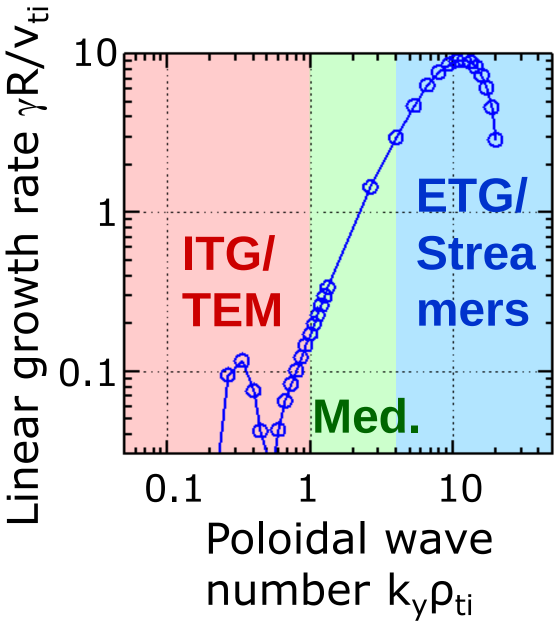

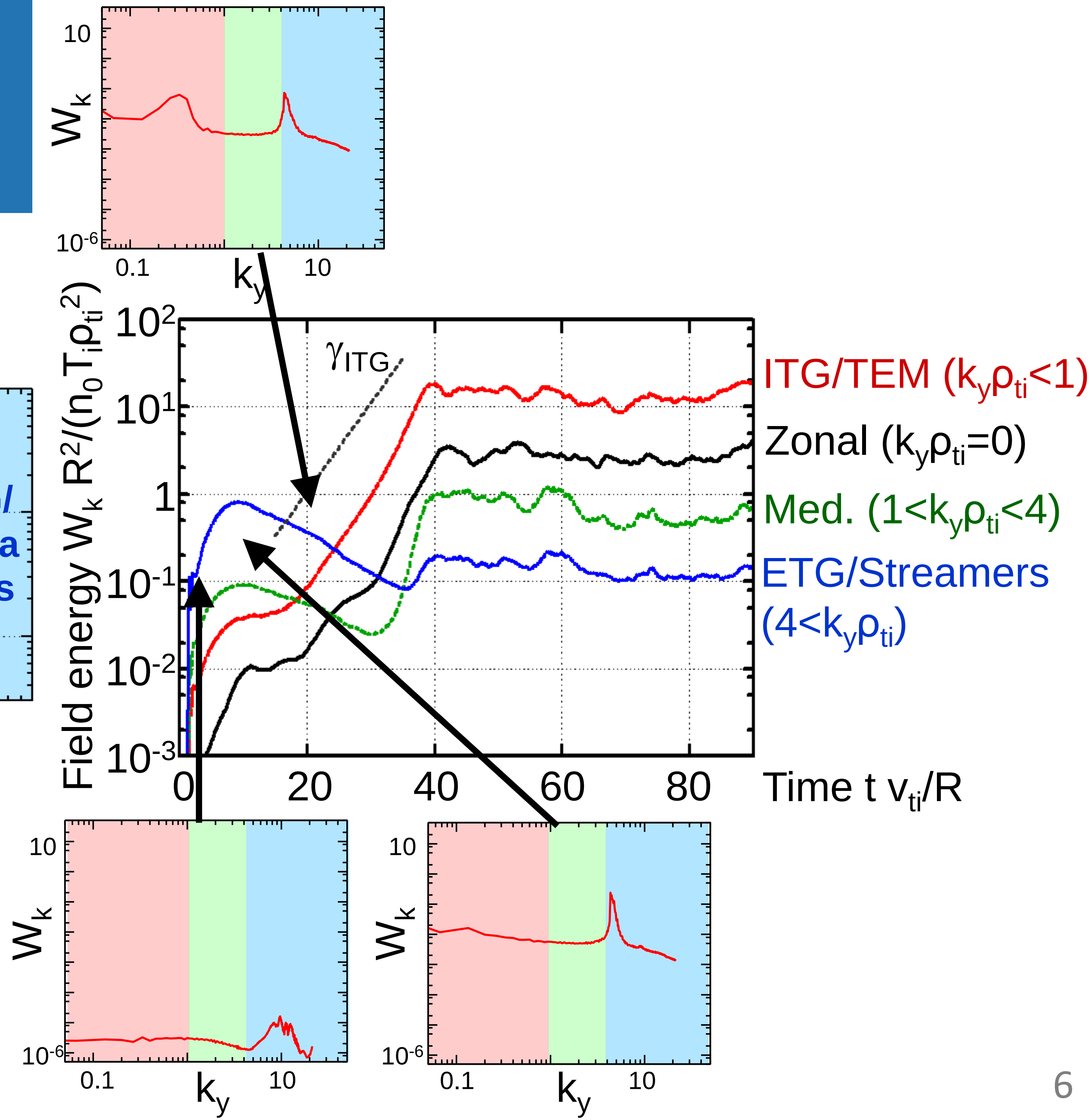

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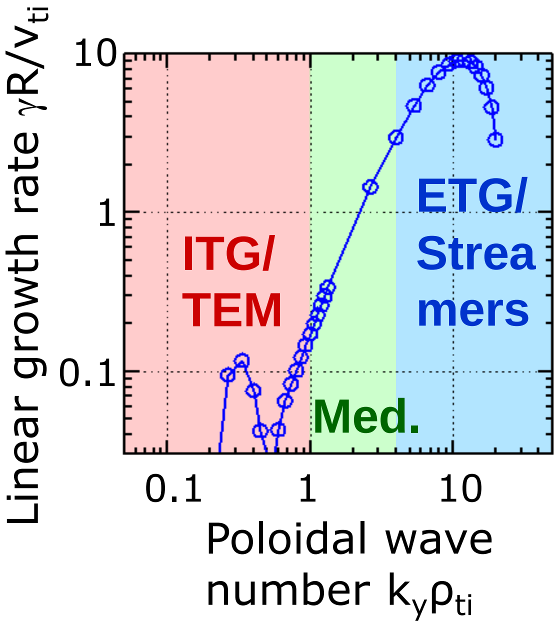

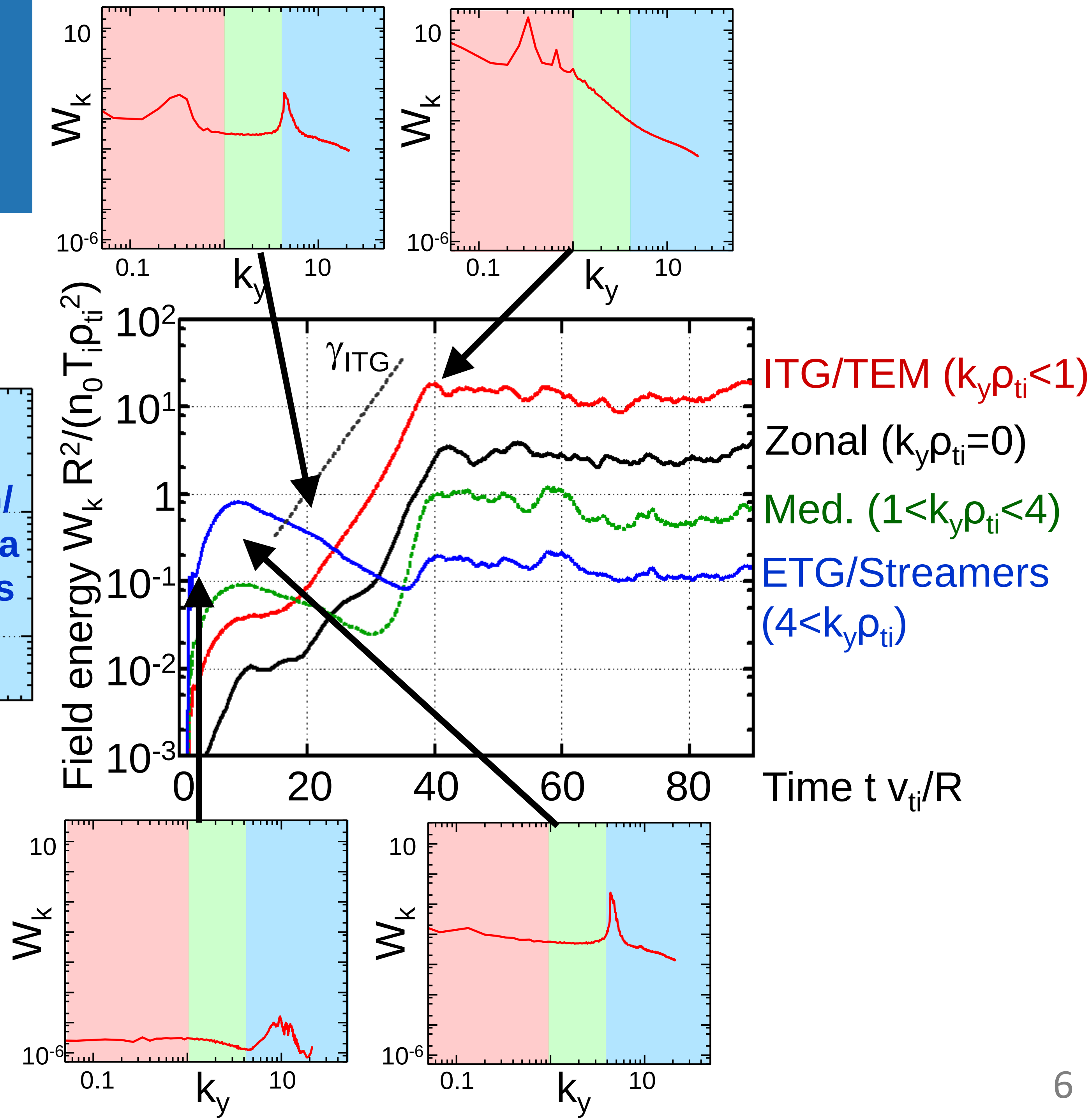

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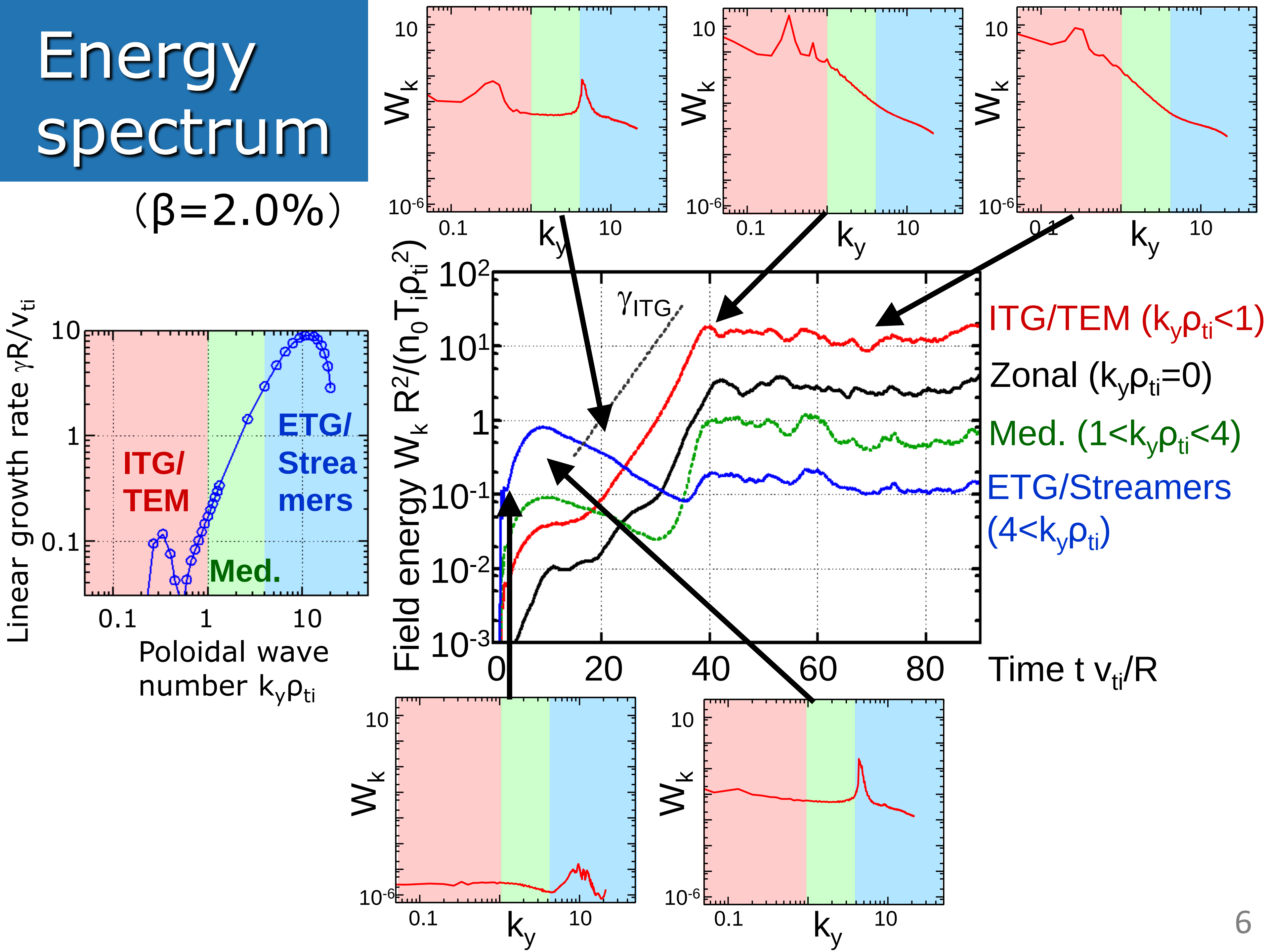
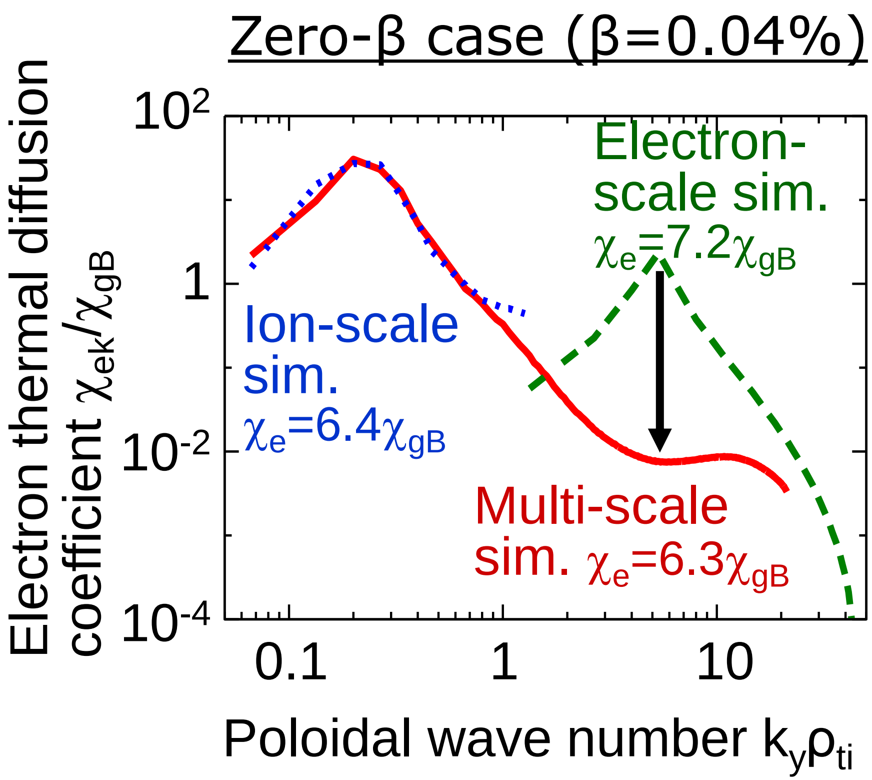
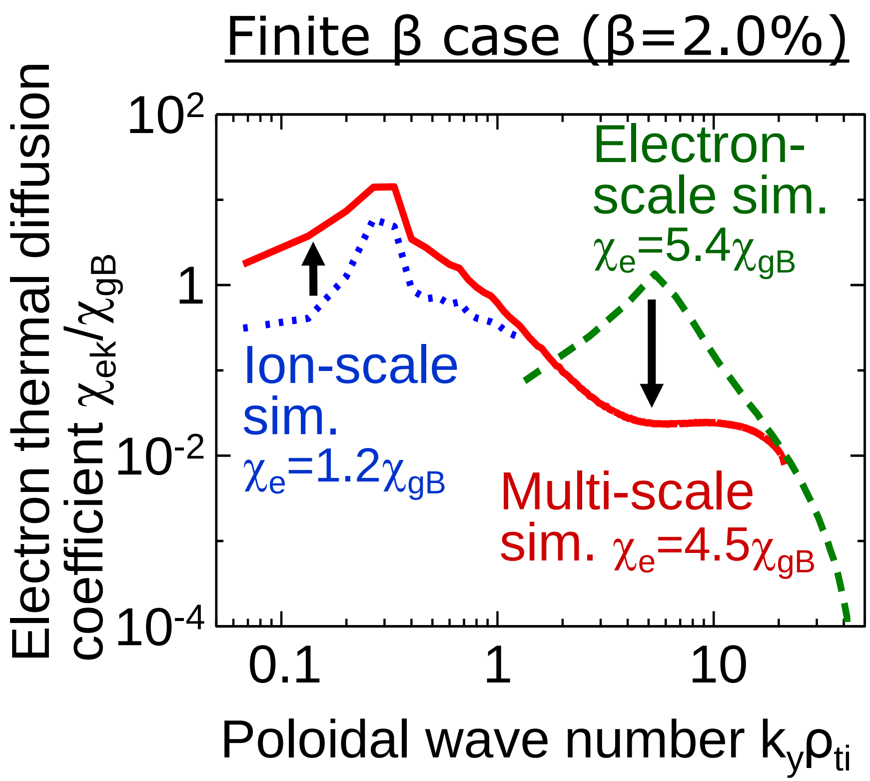


Electron energy diffusion spectrum in multi-scale turbulence is NOT a sum of single-scale ones.

- In zero-β case, due to strong electron-scale suppression, ion-scale simulations give a good estimate.
- In finite-β case, electron-scale suppression is weak. Ion-scale transport is enhanced in multi-scale analysis.





* Ion energy diffusion is similar (see proceedings).

Analysis of nonlinear interactions

Gyrokinetic triad transfer

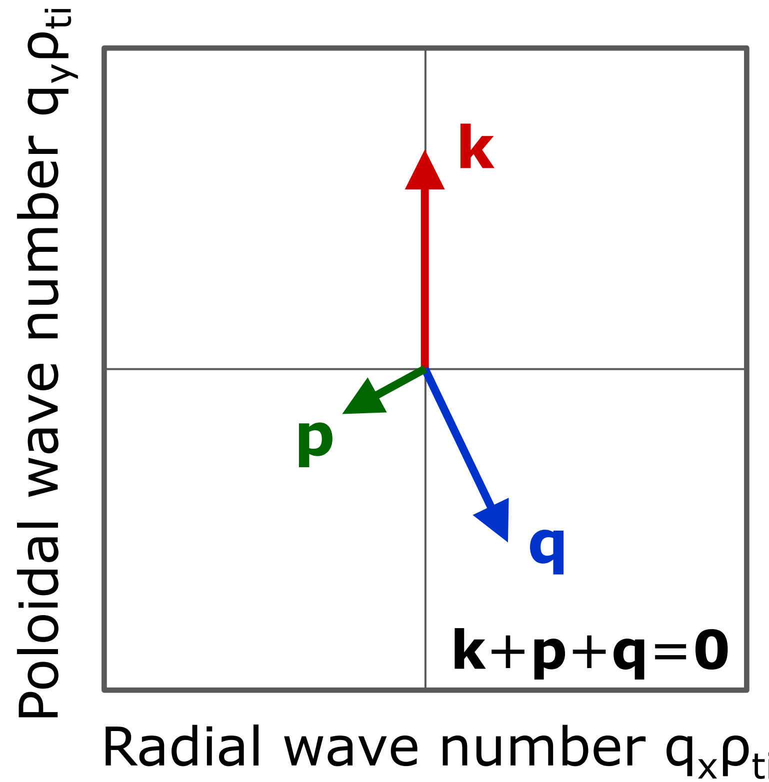
- Mode-to-mode nonlinear transfer of perturbed entropy

[Nakata12PoP]

$$I_{s\boldsymbol{k}} = \sum_{\boldsymbol{p}} \sum_{\boldsymbol{q}} J_{s\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}}$$

$$J_{s\boldsymbol{k}}^{\boldsymbol{p},\boldsymbol{q}} = \delta_{\boldsymbol{k}+\boldsymbol{p}+\boldsymbol{q},0} \frac{\boldsymbol{b} \cdot \boldsymbol{p} \times \boldsymbol{q}}{2B} \times \mathrm{Re}\left[\left\langle \int dv^3 \left(\bar{\chi}_{s\boldsymbol{p}} g_{s\boldsymbol{q}} - \bar{\chi}_{s\boldsymbol{q}} g_{s\boldsymbol{p}}\right) \frac{T_s g_{s\boldsymbol{k}}}{F_{sM}} \right\rangle\right]$$

(Generalized potential $\bar{\chi}_{s\boldsymbol{k}} = (\bar{\phi}_{\boldsymbol{k}} - v_\parallel \bar{A}_{\parallel \boldsymbol{k}})$、
Nonadiabatic distribution $g_{s\boldsymbol{k}} = f_{s\boldsymbol{k}} + \frac{e_s F_{sM}}{T_s} \bar{\phi}_{\boldsymbol{k}}$)



Electron-scale suppression mechanism:

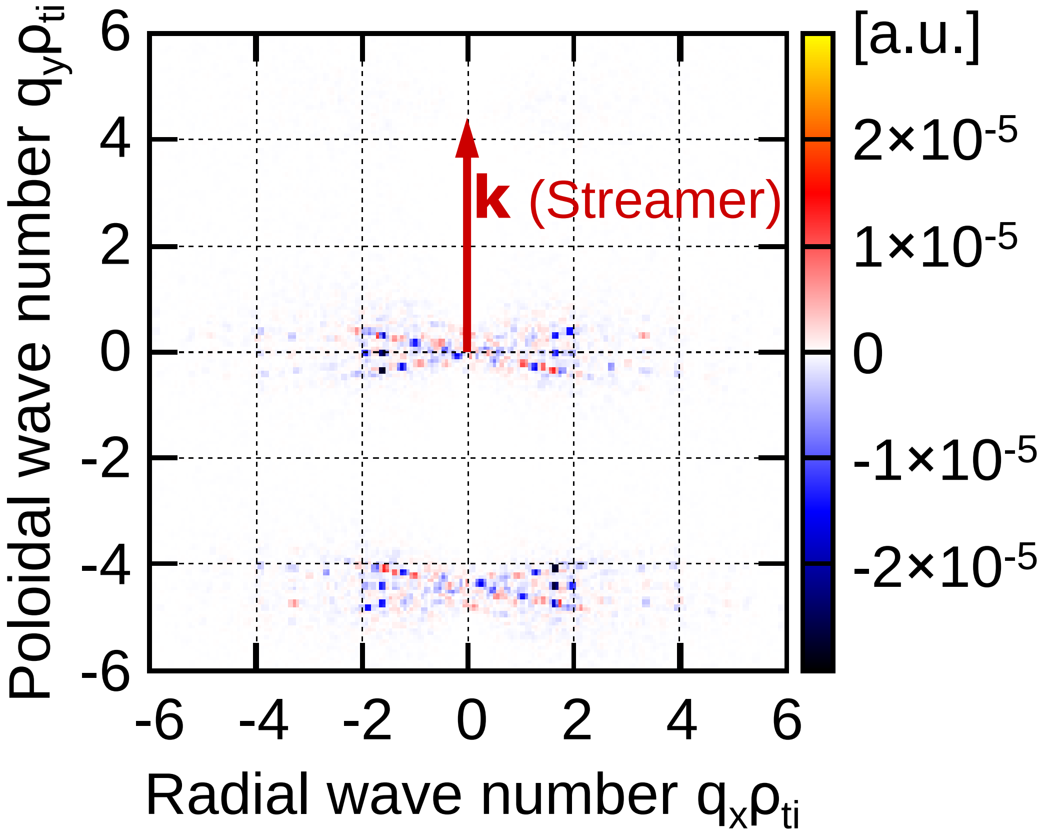
- **Ion-scale ZF shearing? Or, Another structures?**

Ion-scale enhancement mechanism:

- **Inverse cascade to ion-scale turbulence?**
  Or, Damping of ion-scale ZFs?

Suppression of electron-scale streamers by high-k_x ITG/TEM structures.

Triad transfer $\sum_s J_{sk}^{p,q}$ for a streamer
$(k_x\rho_{ti}, k_y\rho_{ti}) = (0, 4.4)$ at $t = 20\text{-}30R/v_{ti}$



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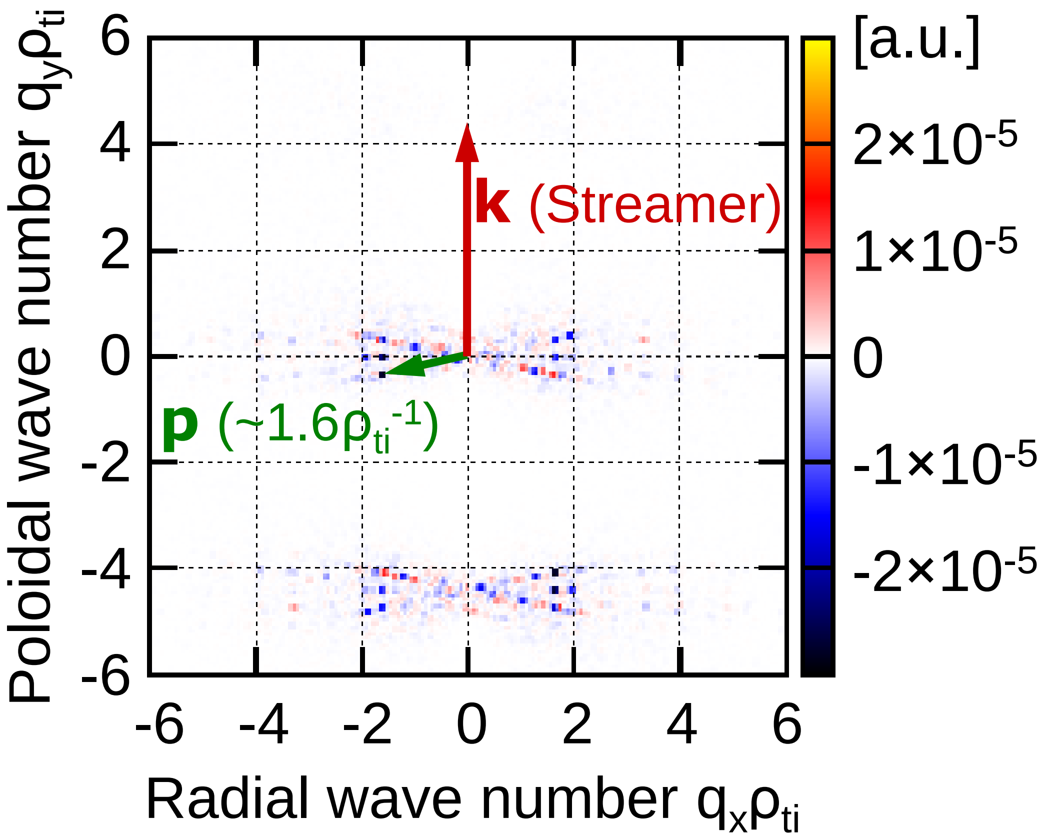
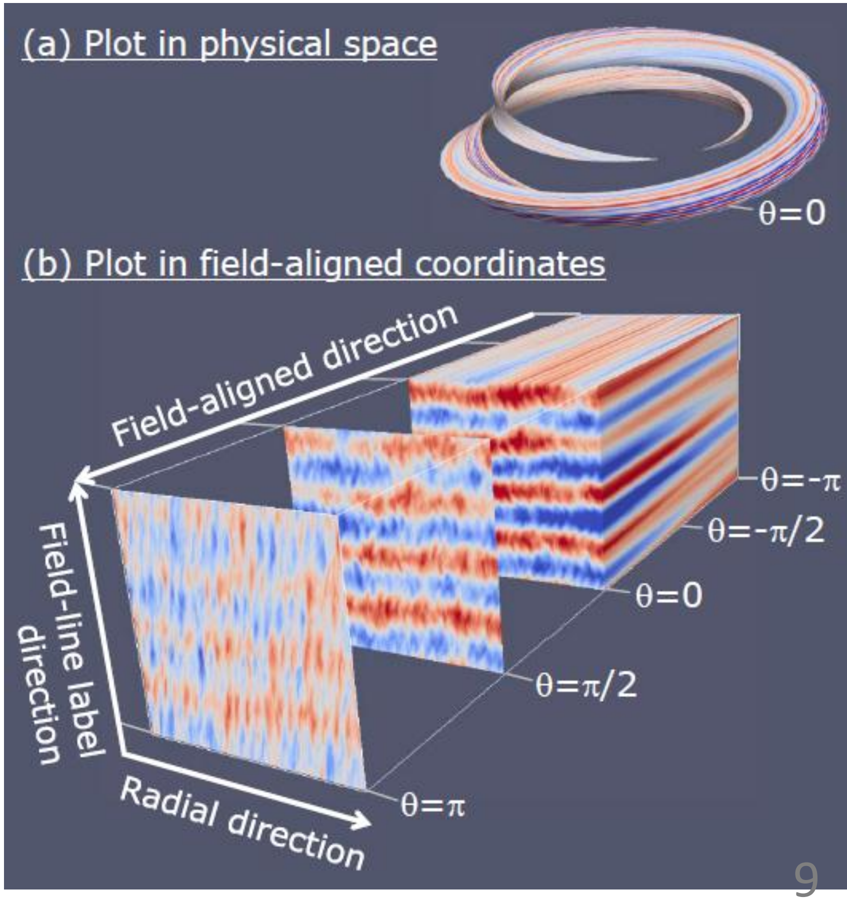


Kinetic electrons create fine radial structures ($k_x\rho_{ti}>1$). [Dominski12JPCS, Maeyama14PoP]



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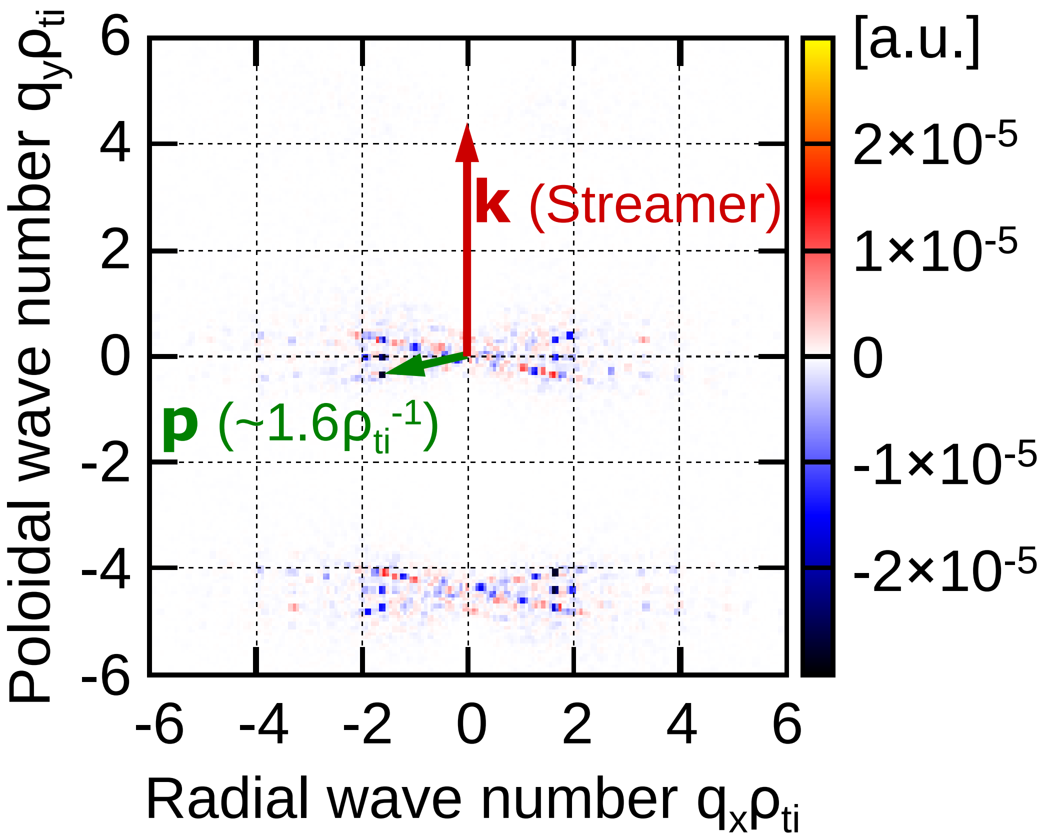

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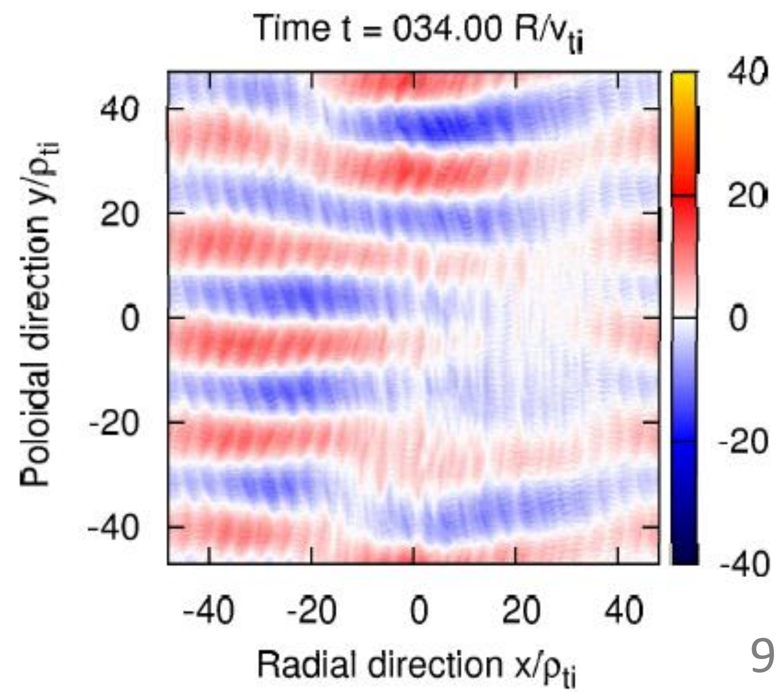
At the reduction phase, these radial structures suppress streamers.



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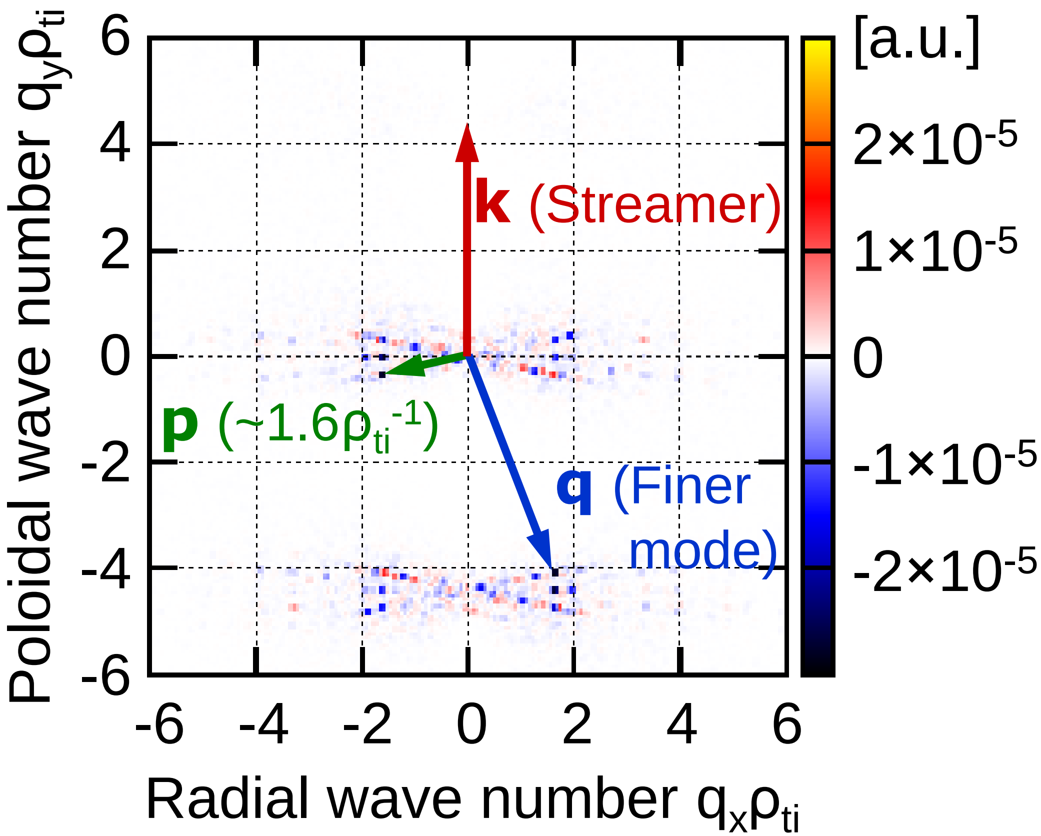

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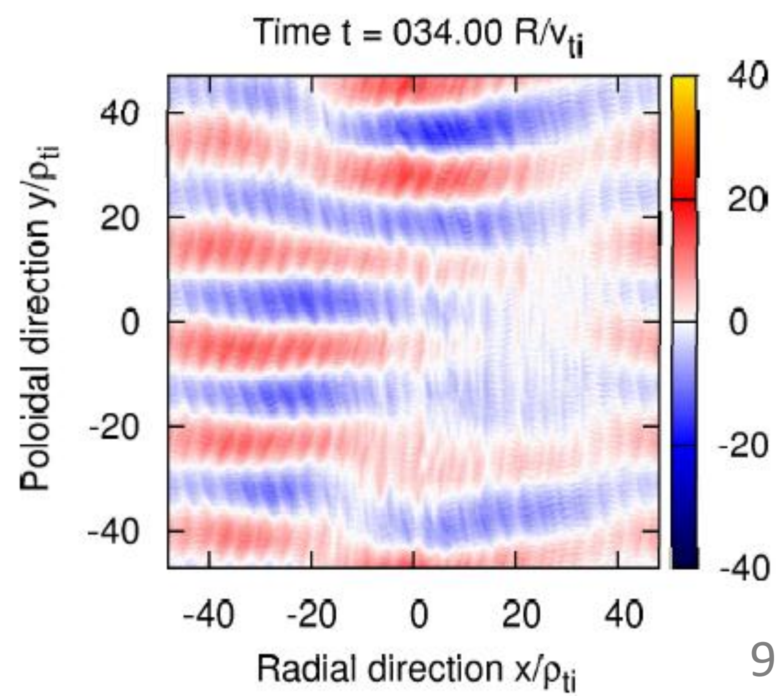
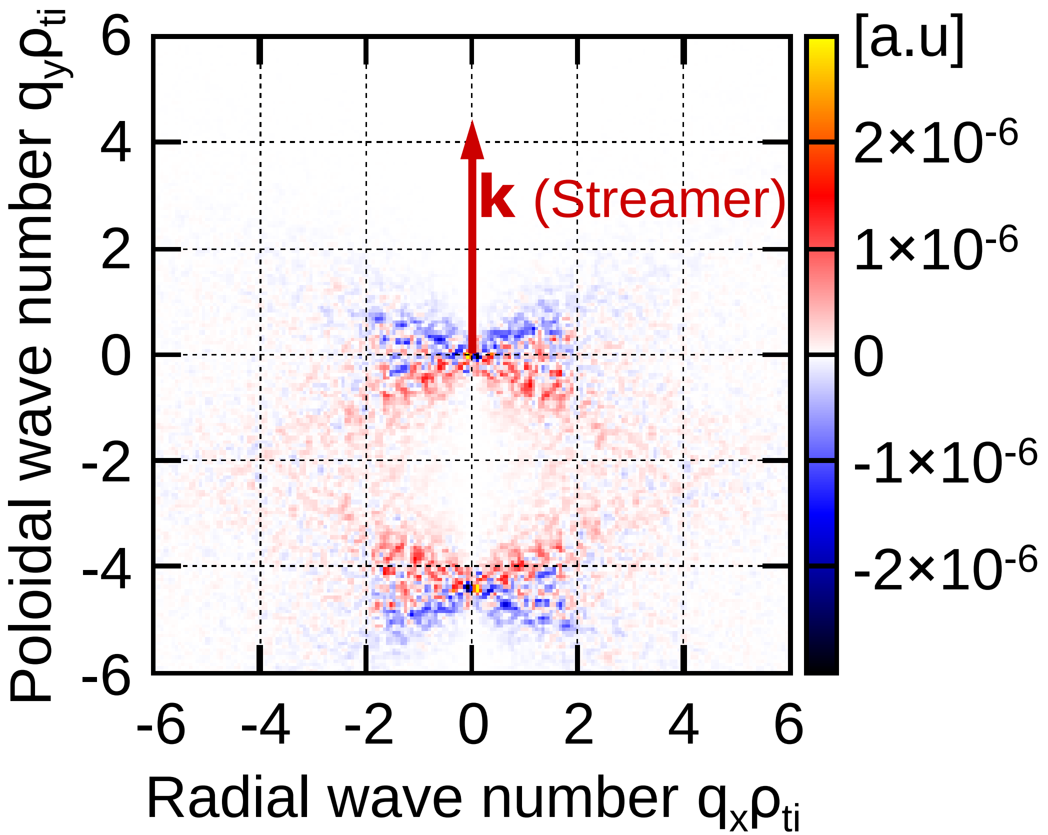
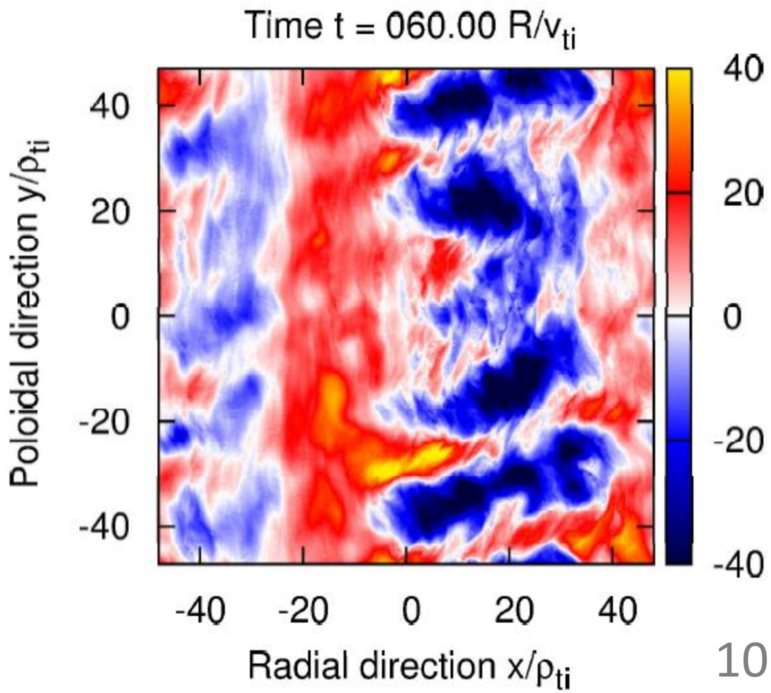


After suppression of ETG/streamers, normal cascade dominates electron scales.

Triad transfer $\sum_s J_{sk}^{p,q}$ for a streamer $(k_x\rho_{ti},k_y\rho_{ti})=(0,4.4)$ at $t=60\text{-}80R/v_{ti}$



At the steady state, normal cascade dominates via the direct coupling with ion-scale turbulent eddies.



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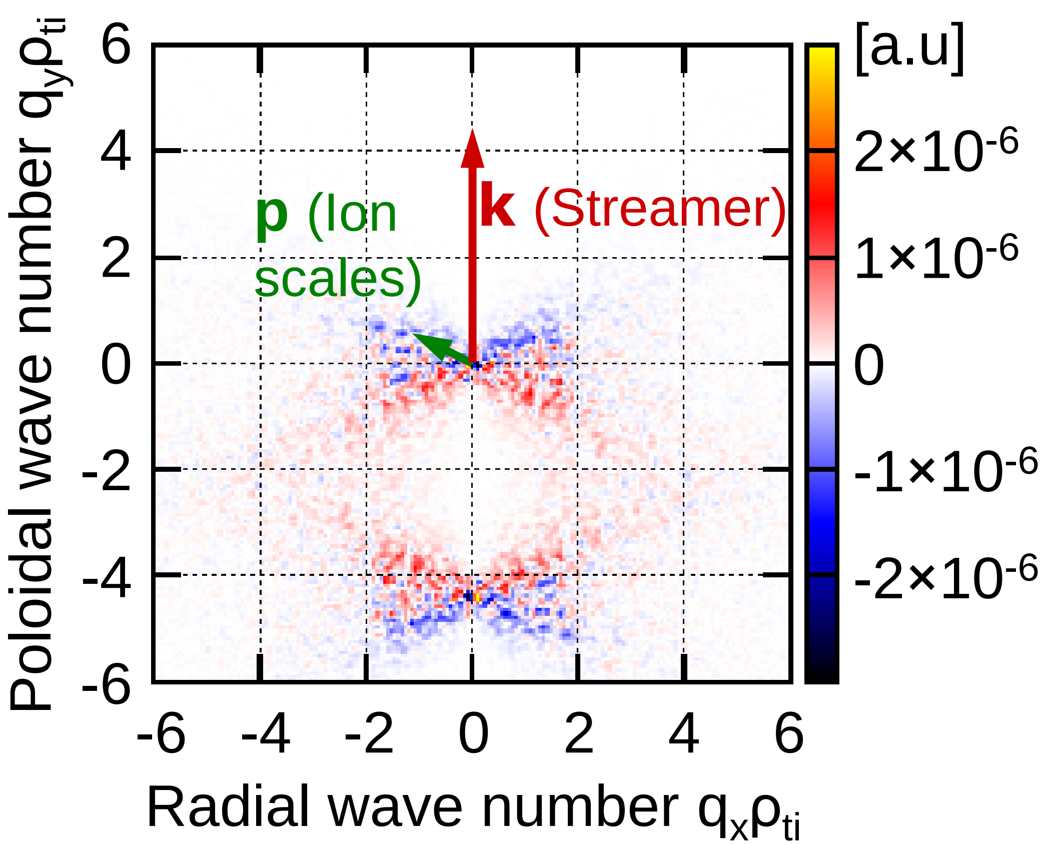

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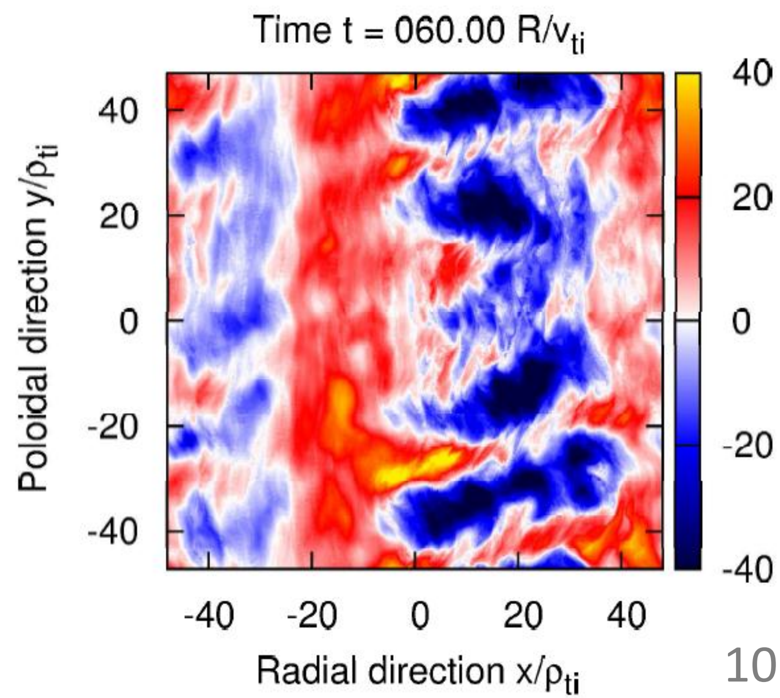

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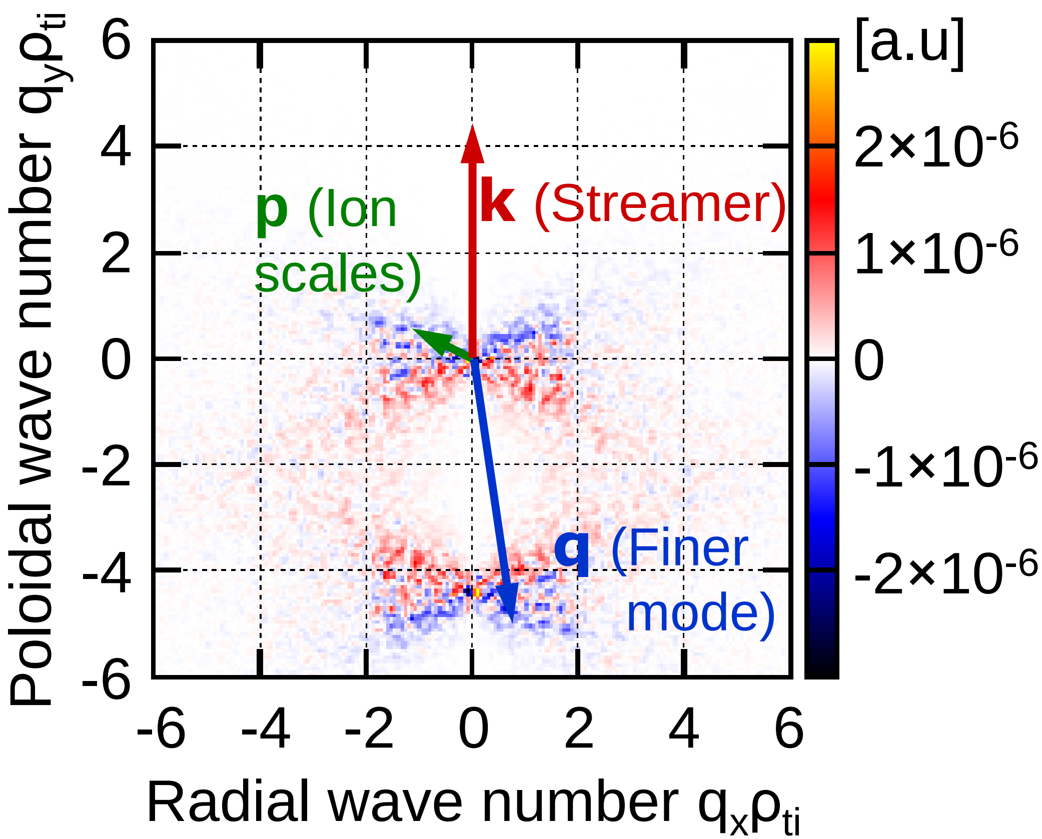

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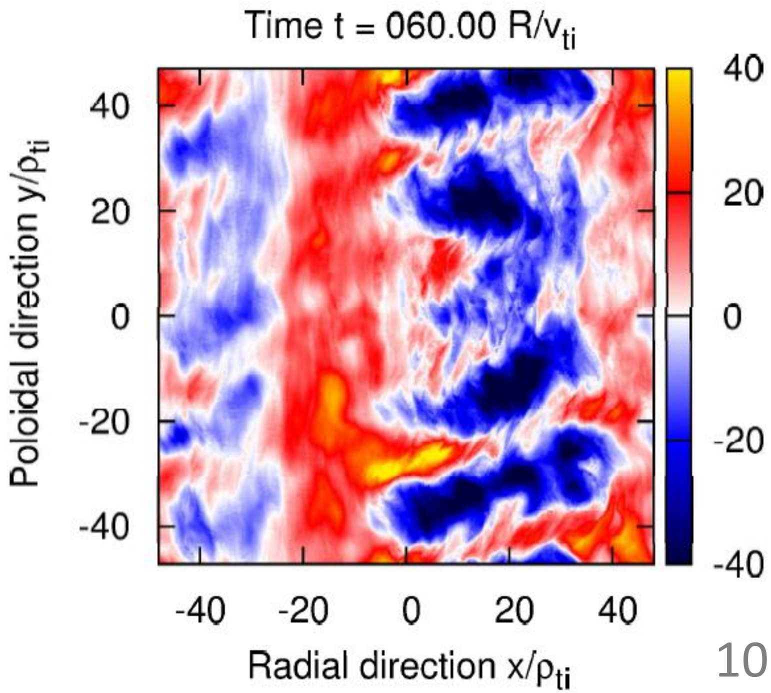


Inefficient zonal mode generation in multi-scale turbulence.

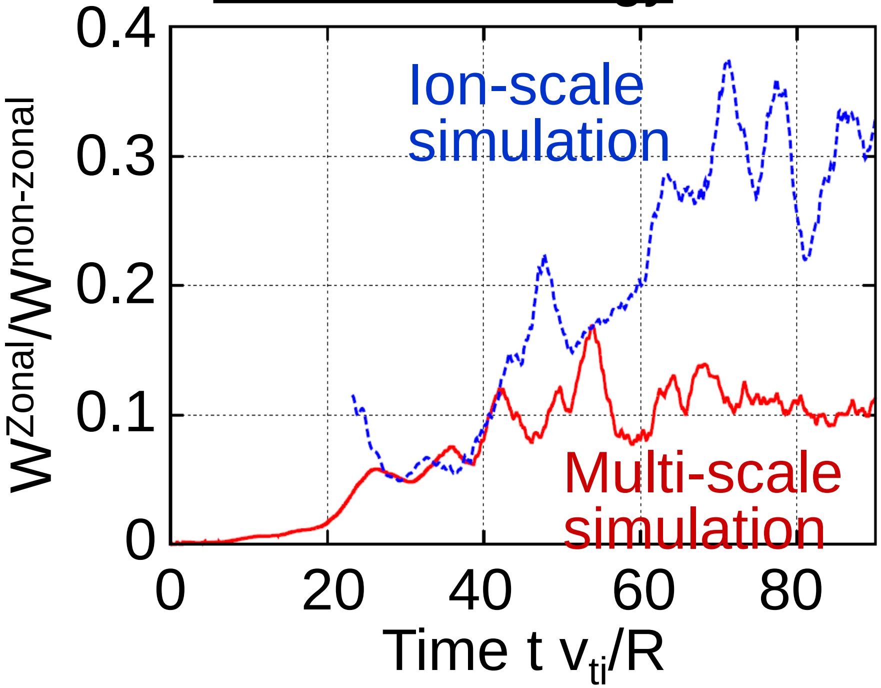
➢ Inverse cascade from electron to ion scales seems not to be responsible.

Comparing multi-scale simulation with single-scale one,

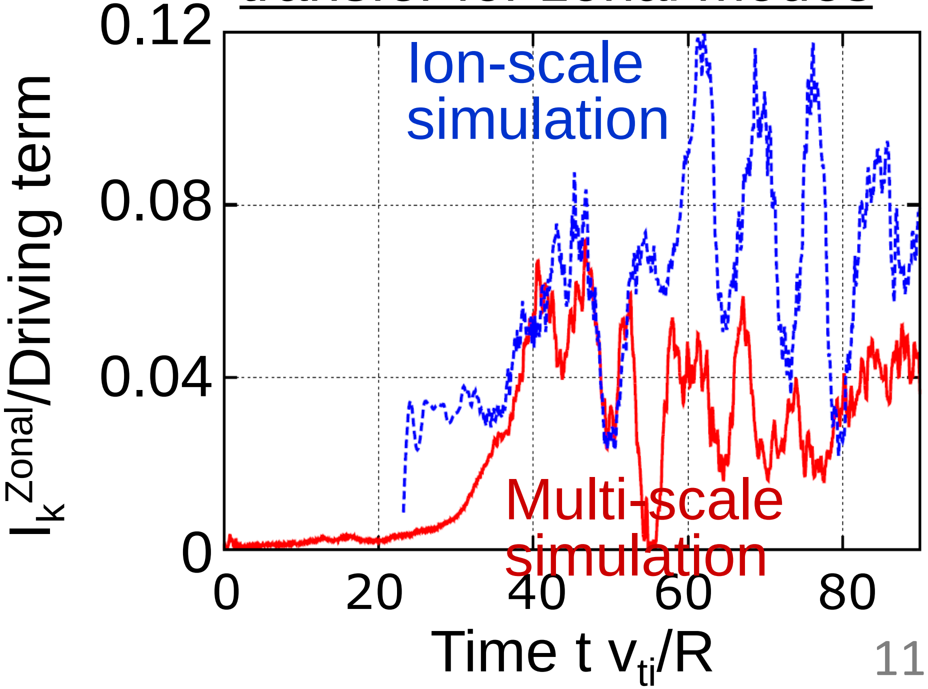
➢ Zonal part of field energy is relatively weak.

➢ Inefficient zonal mode generation is observed.

Ratio of zonal to non-zonal field energy



Nonlinear entropy transfer for zonal modes

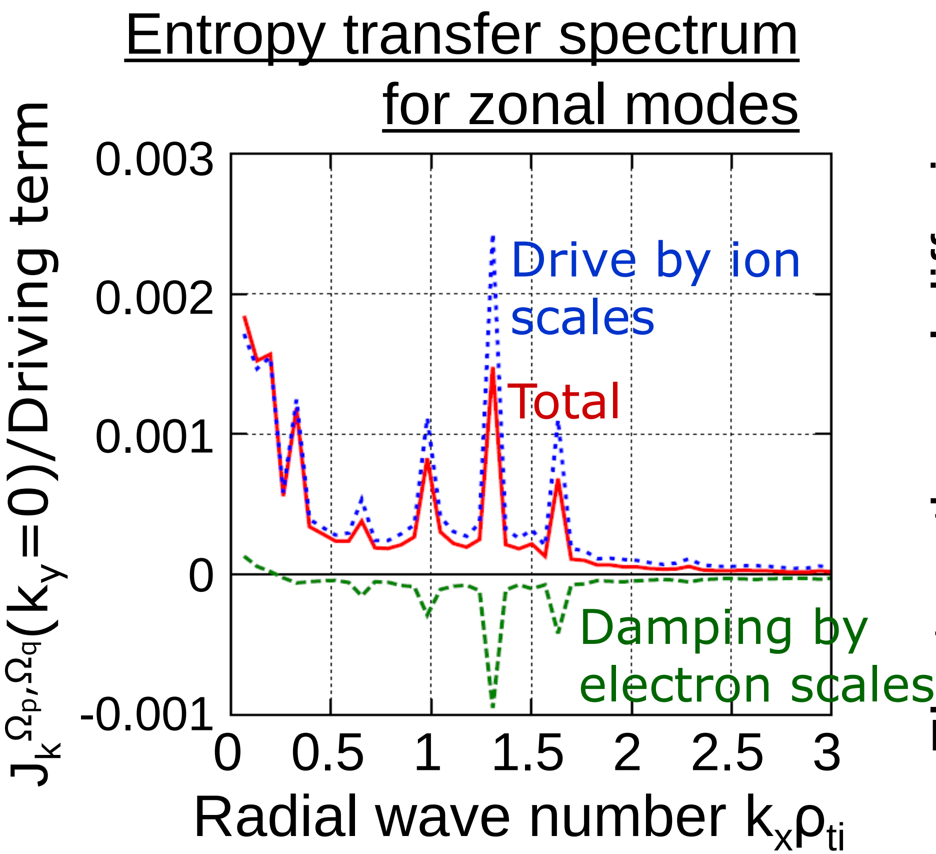


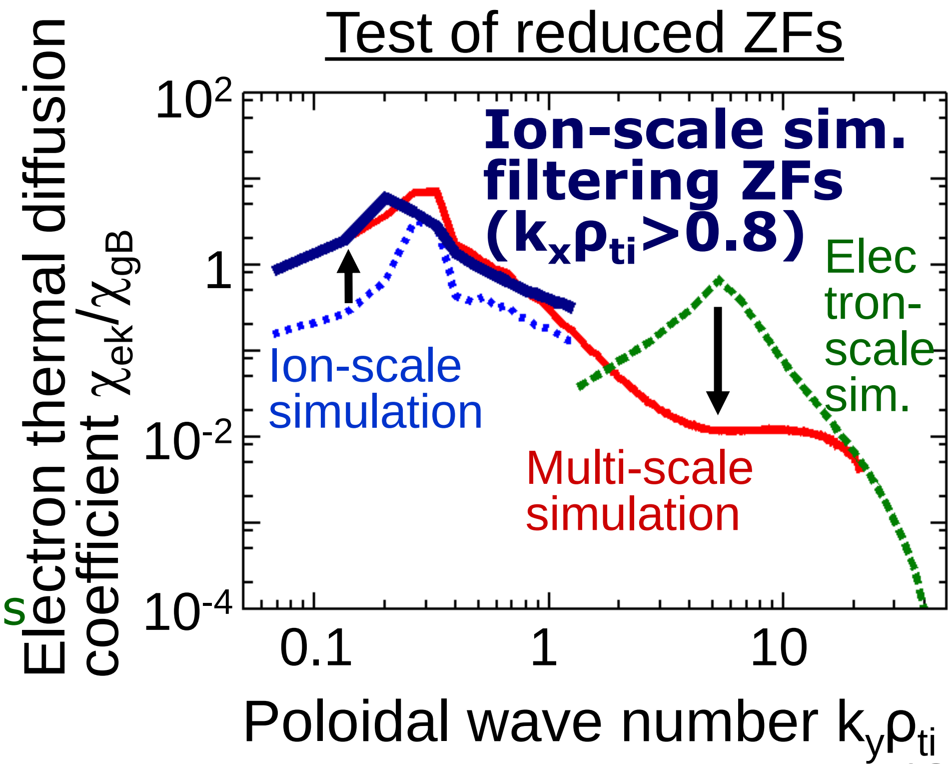
Enhancement of ion-scale turbulence is caused by damping of zonal modes.

Splitting ion- and electron-scale contributions clarifies

- Electron-scale turbulence has damping effects on zonal modes around $k_x\rho_{ti}\sim 1$.

→ The reduction of ZF shearing enhances transport.





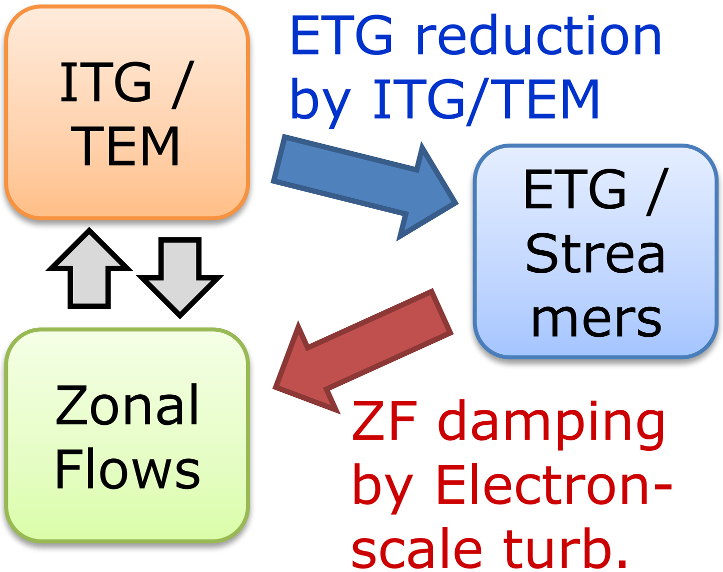
Summary and discussion

We have first analyzed multi-scale ITG/TEM/ETG turbulence with real mass ratio and β value.

- We have demonstrated the existence of multi-scale interactions even with real mass ratio.
  - ETG/Streamers are suppressed by ITG/TEM turbulence.
- ITG stabilization by finite-β effects makes electron-scale contributions non-negligible.
  - We newly found that electron-scale turbulence can enhance ion-scale turbulent transport.

Summary and discussion

In terms of turbulence physics



✓ Normal cascade via coupling with ITG/TEM turbulent eddies dominates electron scales.

✓ Electron-scale turbulence acts as effective damping of ZFs.

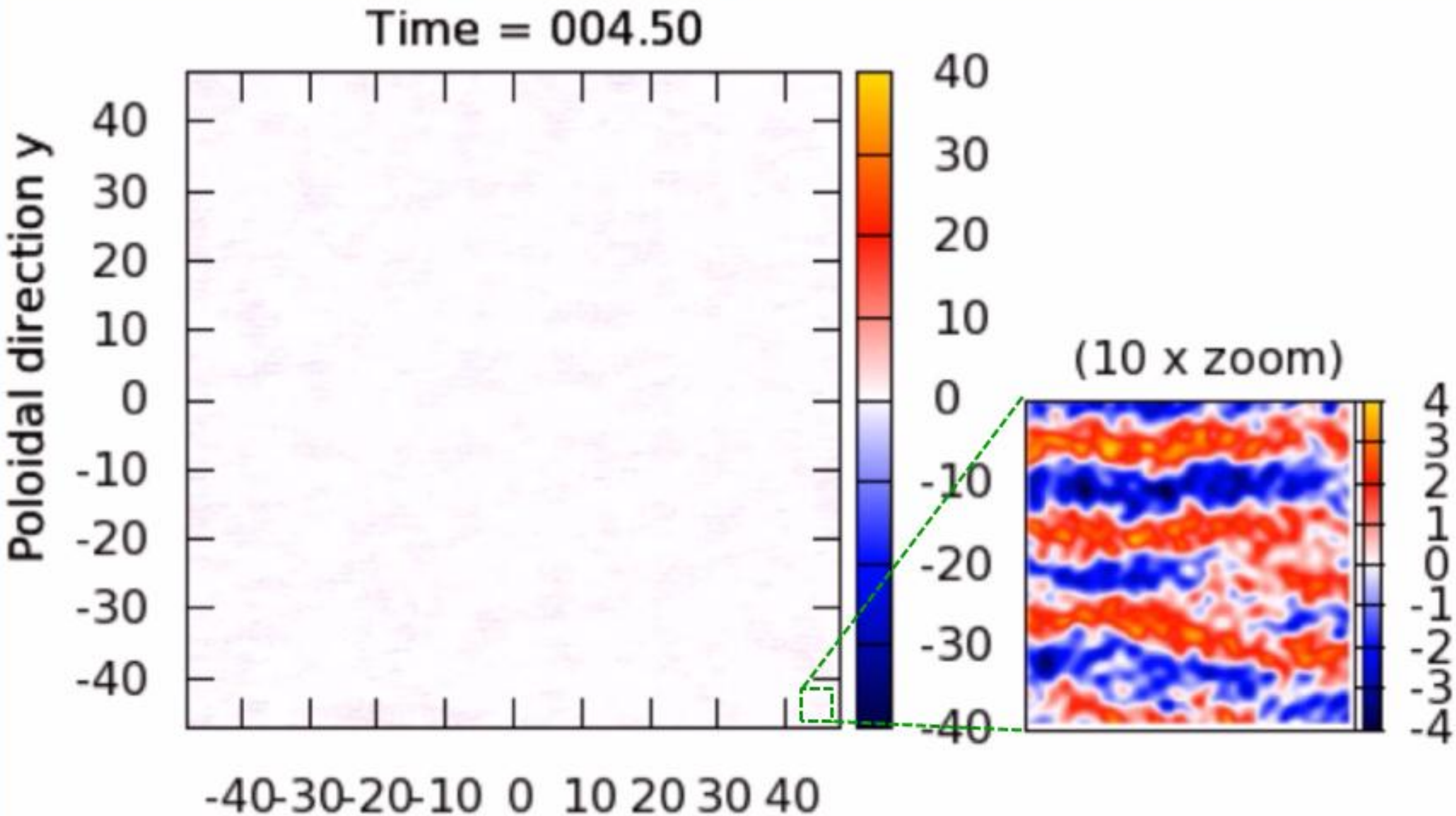
In terms of transport level estimation

- ➢ Multi-scale spectrum is NOT a sum of single scales.
- ➢ When ITGs are highly unstable, ion-scale simulations give a good estimate of transport levels.
- ➢ In high-β regimes, electron scales can be important.
  - Effective damping of ion-scale ZFs

Multi-scale turbulence simulation (β=2.0%)

Time evolution of the electrostatic potential fluctuations

(at mid-plane of the flux tube)



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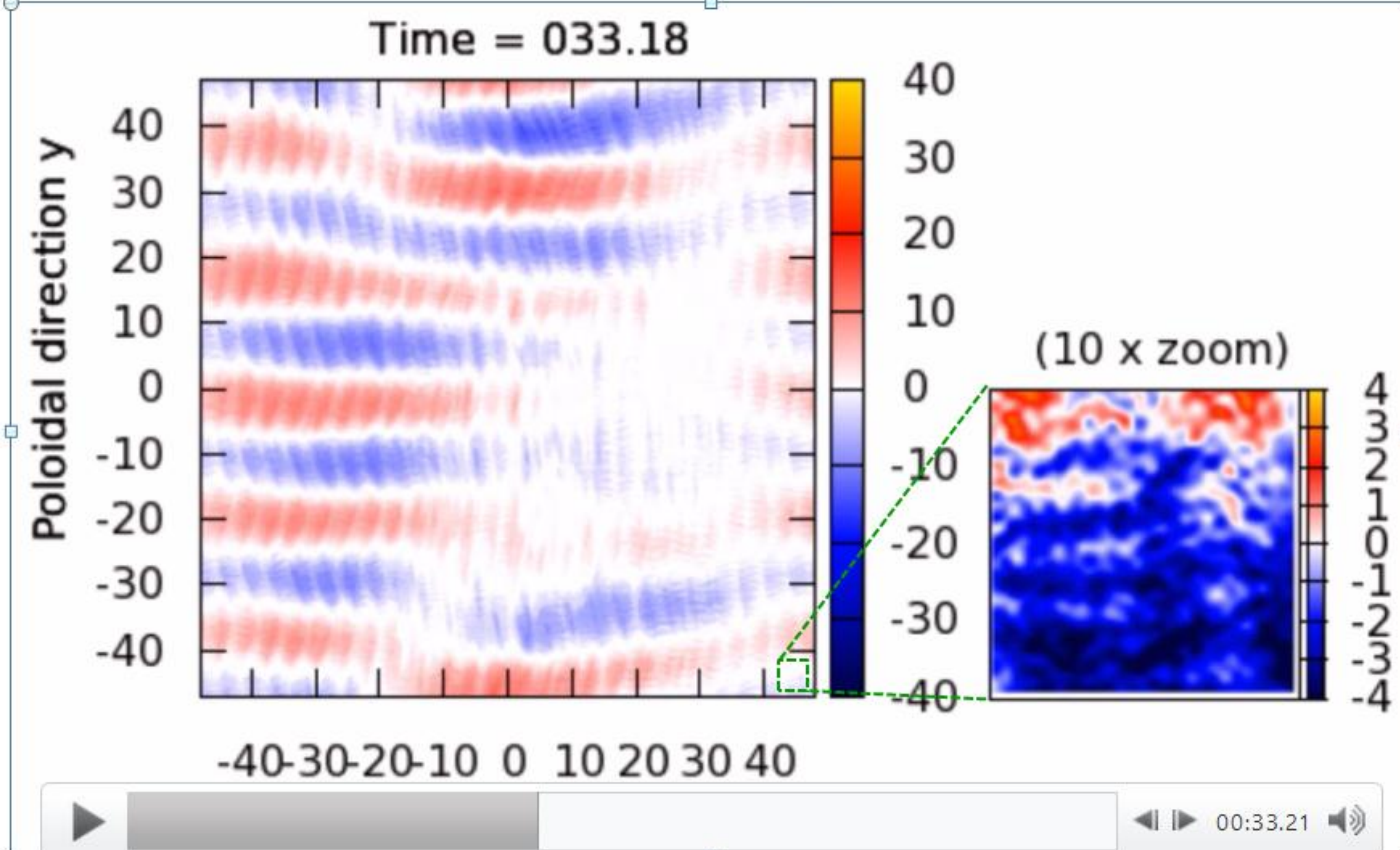

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