EUROfusion

Turbulent transport of impurities in multispecies Wendelstein 7-X plasmas

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IPP

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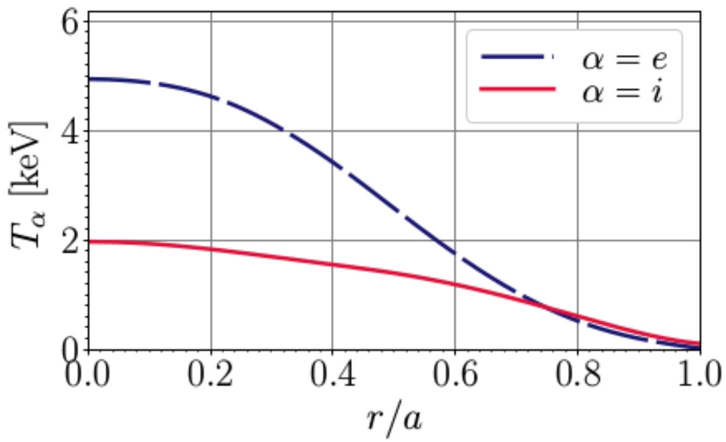
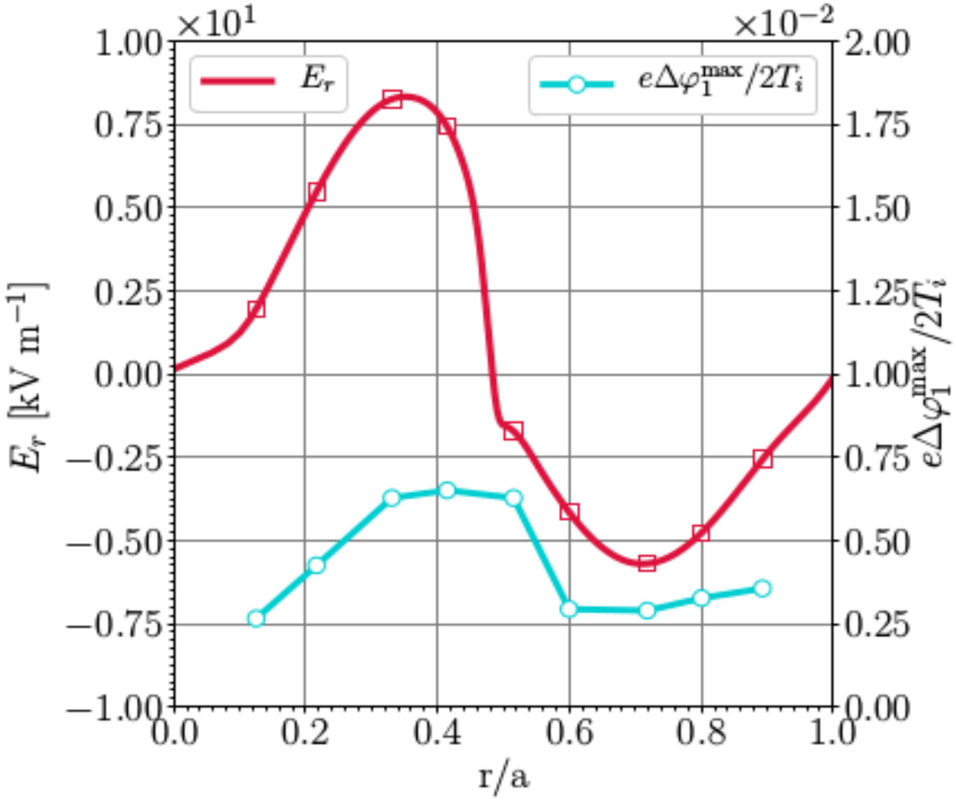
Motivation: neoclassical E_r and Γ_Z in stellarators

- Understanding impurity transport is crucial for the development and success of stellarators at a reactor scale.
- At reactor relevant conditions of $T_i \sim T_e$, neoclassical radial electric field E_r in stellarators is large and **negative** → impurity accumulation.





E_r typically drives the strongest contribution to the radial impurity flux Γ_Z.

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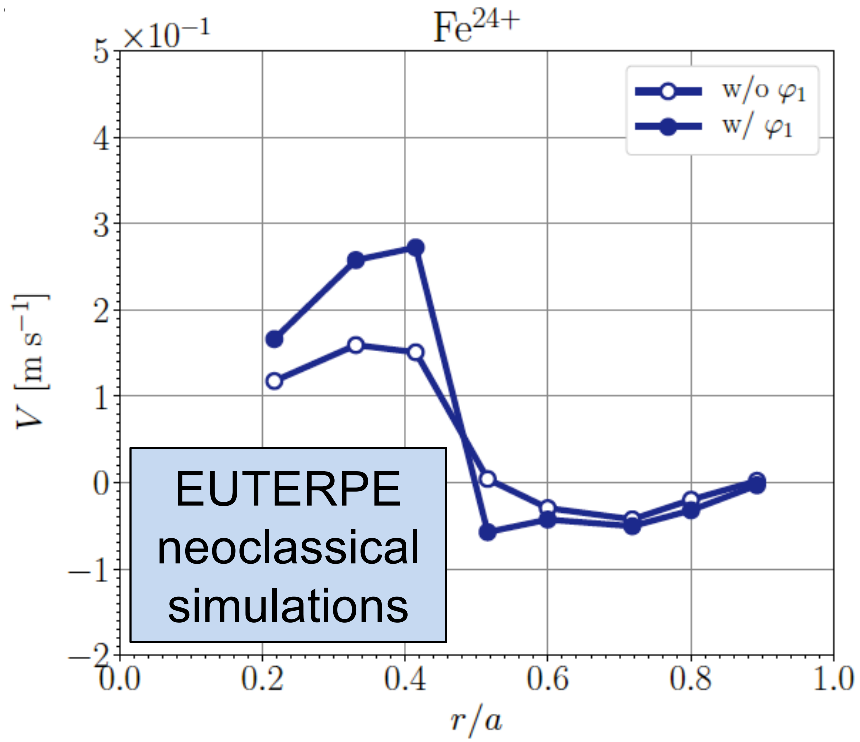

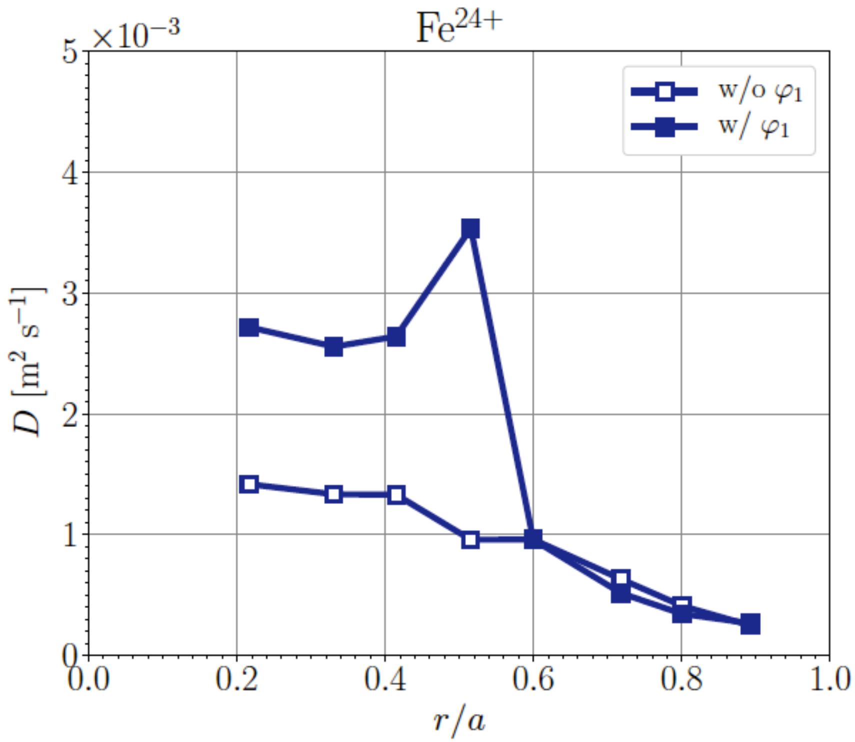

- Electron root (Er>0) ⟹ the **peaking factor V/D~O(10²)** ⟹ hollow impurity density.
- Ion root (Er<0) ⟹ the **peaking factor V/D~-O(10²)** ⟹ peaked impurity density.

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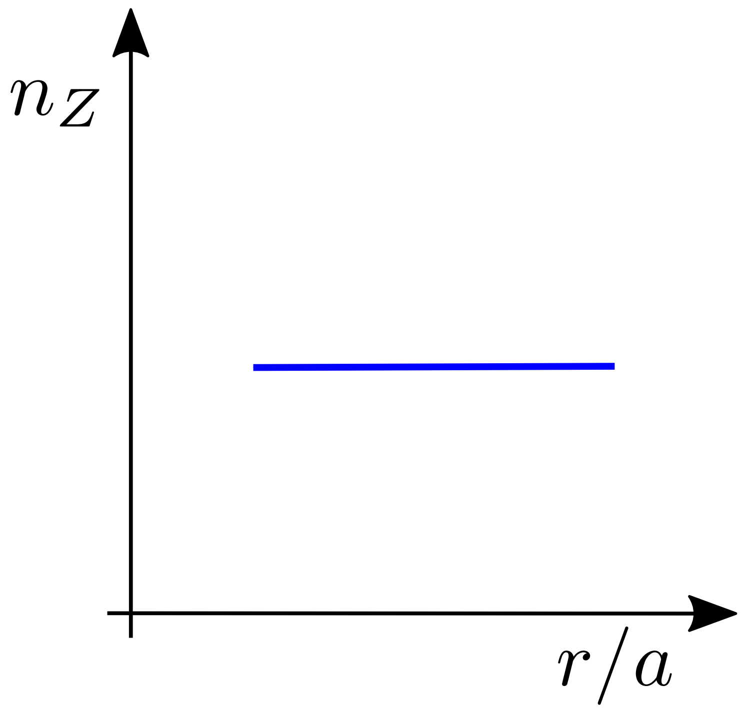

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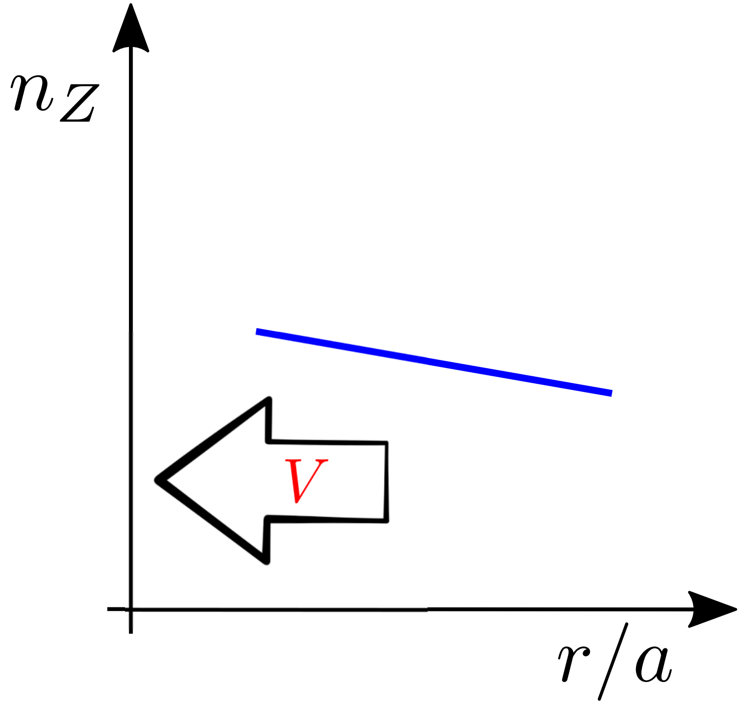

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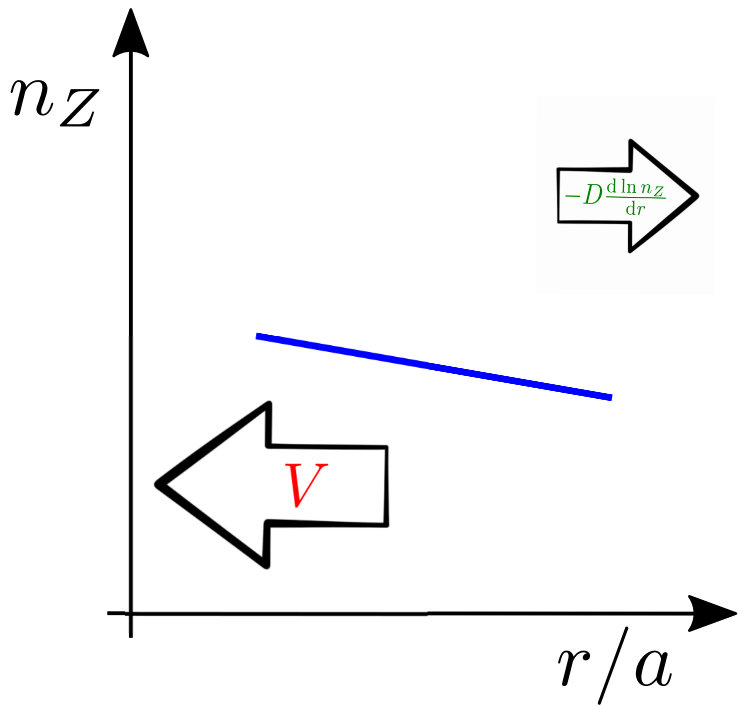

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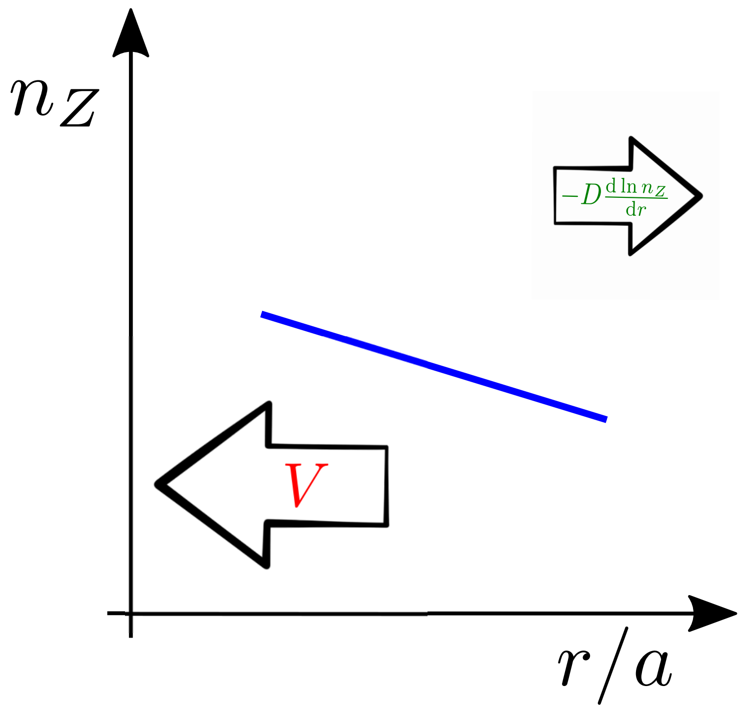

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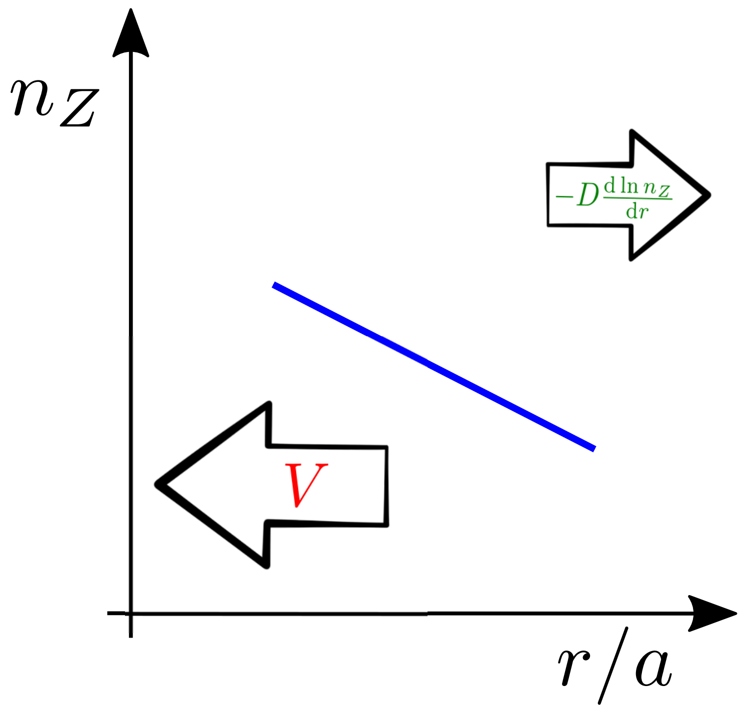

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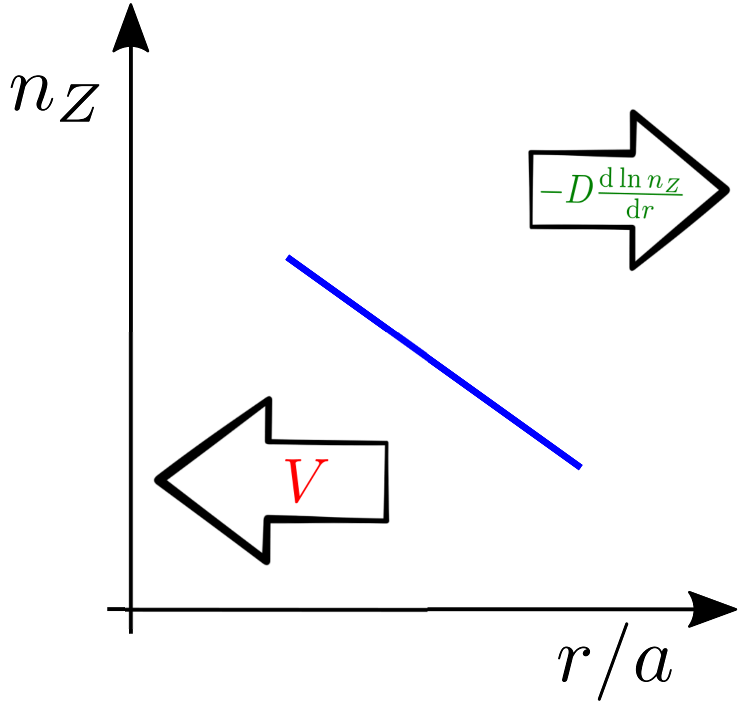

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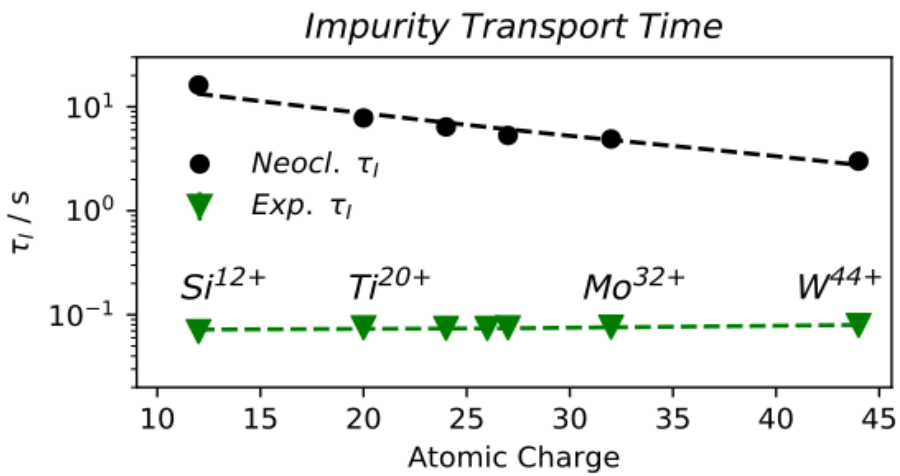
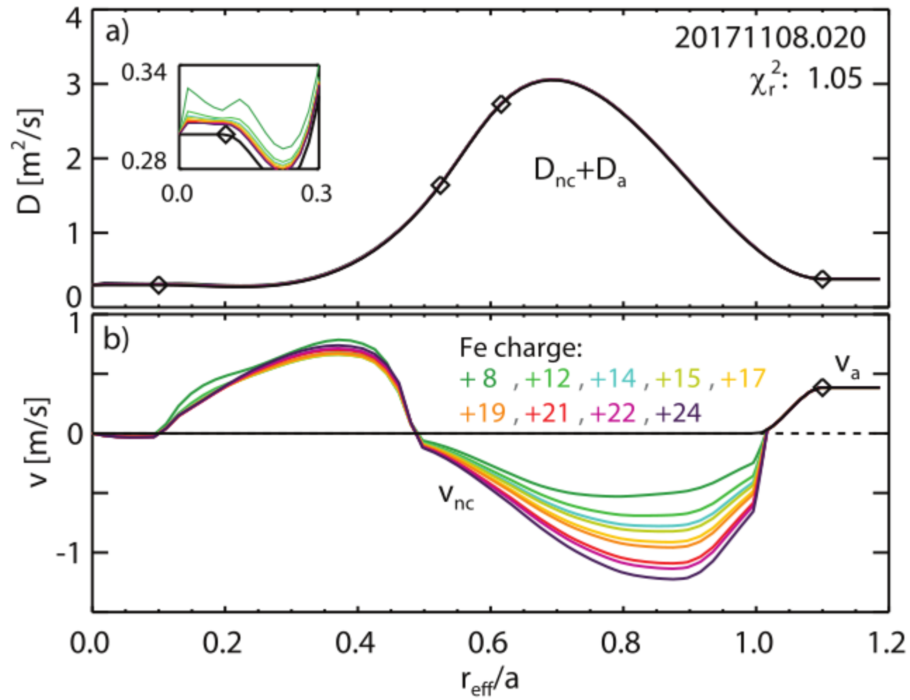
The size of D and τ_I in experiments

- Experimental diffusion coefficient (D_Z) and confinement time (τ_I) in W7-X are orders of magnitude above neoclassical predictions.
- **Absence of impurity accumulation** in most OP1* scenarios [Klinger NF'19].

[Langenberg PoP'20]



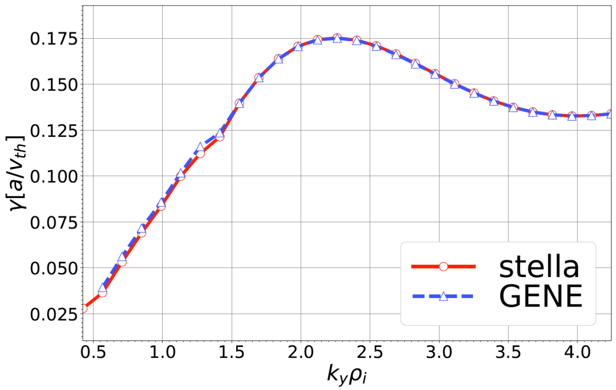
[Geiger NF'19]



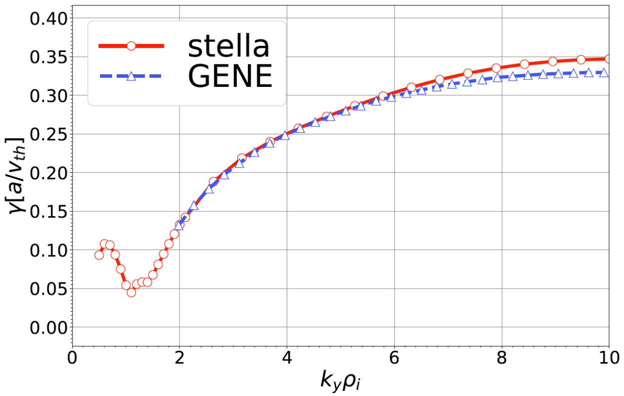
Strong indication of **turbulence-driven transport** but simulations are **anecdotal.**

The code `stella` [Barnes JCP'19].

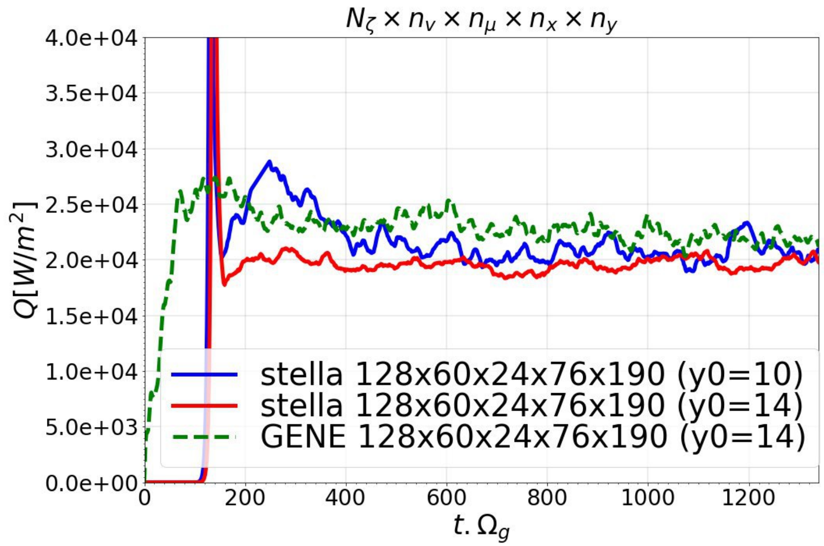
- δf flux tube electrostatic gyrokinetic stellarator code of recent development at U. Oxford
- Operator splitting and implicit treatment of parallel streaming and acceleration terms $\Rightarrow$ **efficient treatment of kinetic electrons (larger time-step allowed)** in **multispecies simulations**.
- Recently benchmarked against GENE [A. González-Jerez, in progress].



(←) For the ***bean* flux tube** (α=0), **growth rate** as a function of $\mathbf{k_y\rho_i}$ for $\mathbf{k_x\rho_i=0}$ for an **ITG** case with a/L_{Ti}=3.0.



(←) For the ***bean* flux tube** (α=0), **growth rate** as a function of $\mathbf{k_y\rho_i}$ for $\mathbf{k_x\rho_i=0.0}$ for a **TEM** case with a/L_{ne}=3.0.

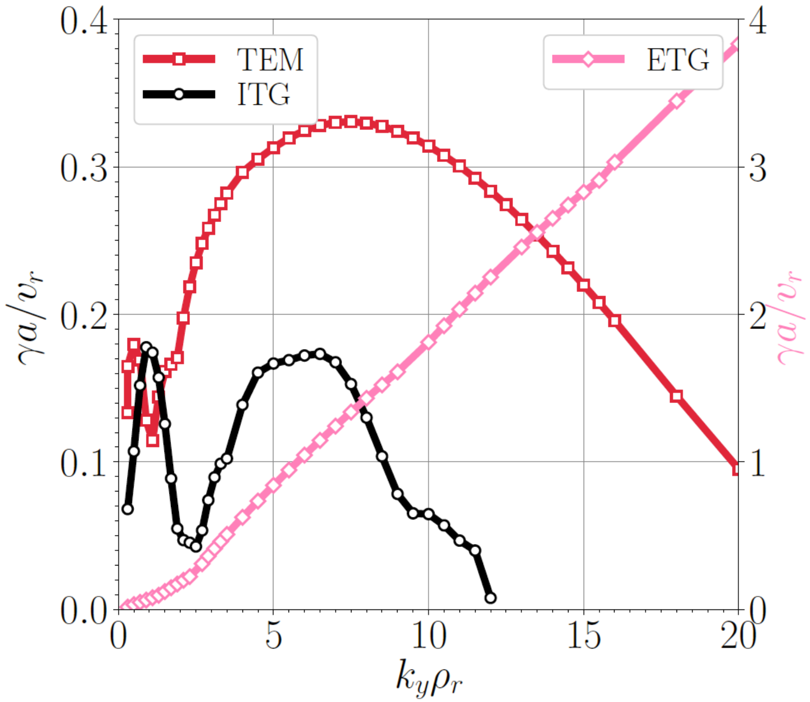


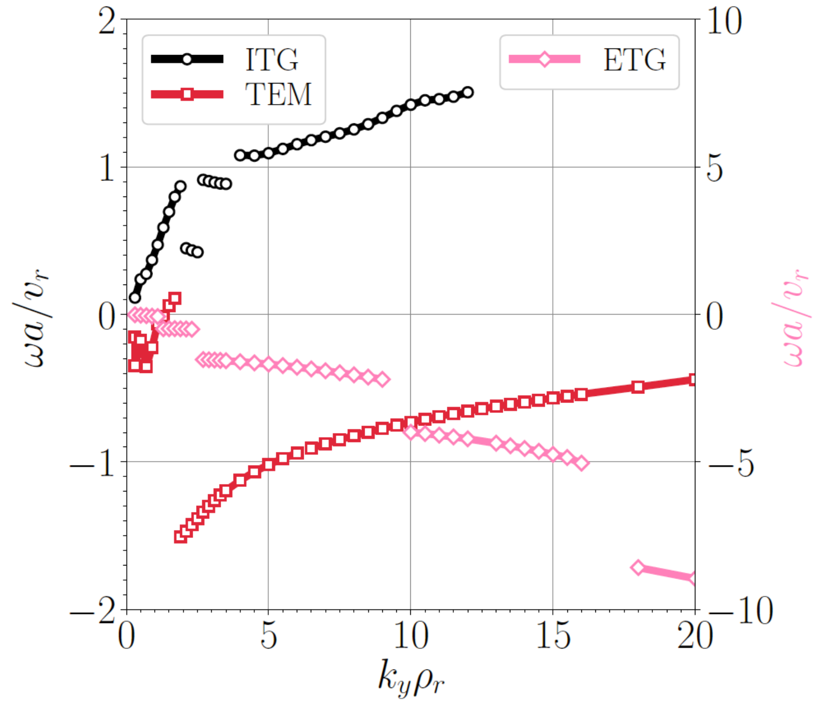
(↑) For the ***bean* flux tube** (α=0), **ion heat flux** evolution for an **ITG** case with a/L_{Ti}=3.0.

Linear properties of background instabilities

- Gradients are set such that representative **ITG**, **TEM** and **ETG** instabilities are isolated.
- W7-X (EIM) @ r/a=0.8.
- **Trace n_z** level content of impurities.

	a/L_{T_i}	a/L_{T_e}	$a/L_{n_i} = a/L_{n_e}$	T_e/T_i
ITG	4.0	0.0	0.0	1.0
TEM	0.0	0.0	4.0	1.0
Species	Ar^{16+}, W^{16+}, W^{44+}			



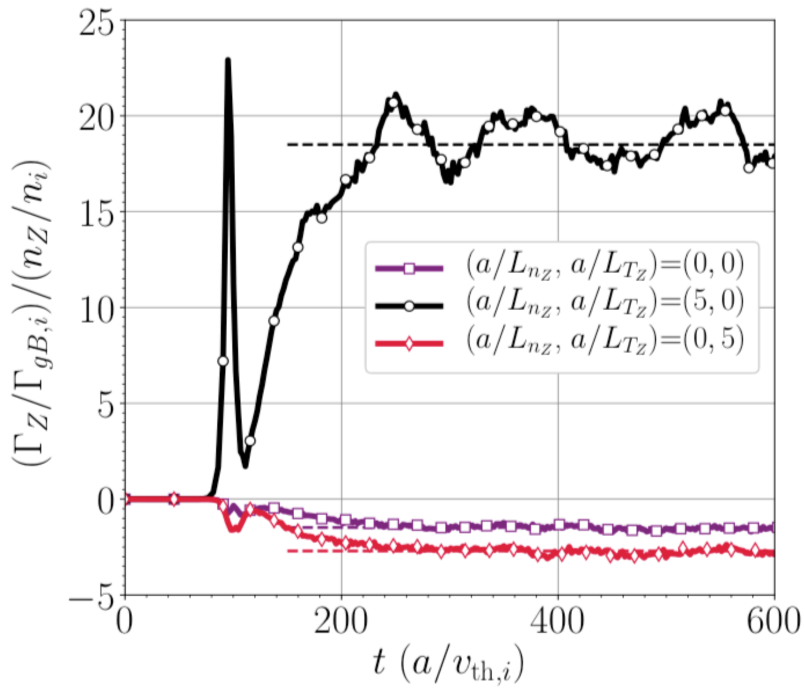


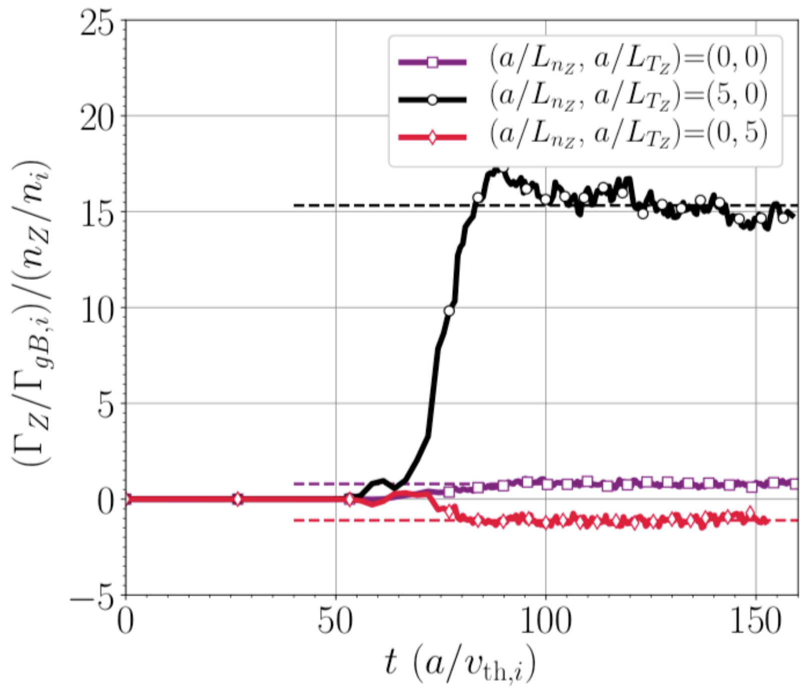
- **Broad γ-spectrum of ITG** mode with various changes of eigenmode structure.
- **More unstable TEM** than ITG mode. More unstable ETG than TEM.

D_{Z1}, D_{Z2} and C_Z for trace Ar^{16+}, W^{16+}, W^{44+}

- Impurity **transport coefficients independent on impurity parameters**, like gradients. Impurities do not *participate* in quasi-neutrality when they are trace.

$$\Gamma_Z = -n_Z \left(D_{Z1} \frac{\mathrm{d} \ln n_Z}{\mathrm{d}r} + \boxed{D_{Z2} \frac{\mathrm{d} \ln T_Z}{\mathrm{d}r} + \underbrace{C_Z}_{-V}} \right)$$

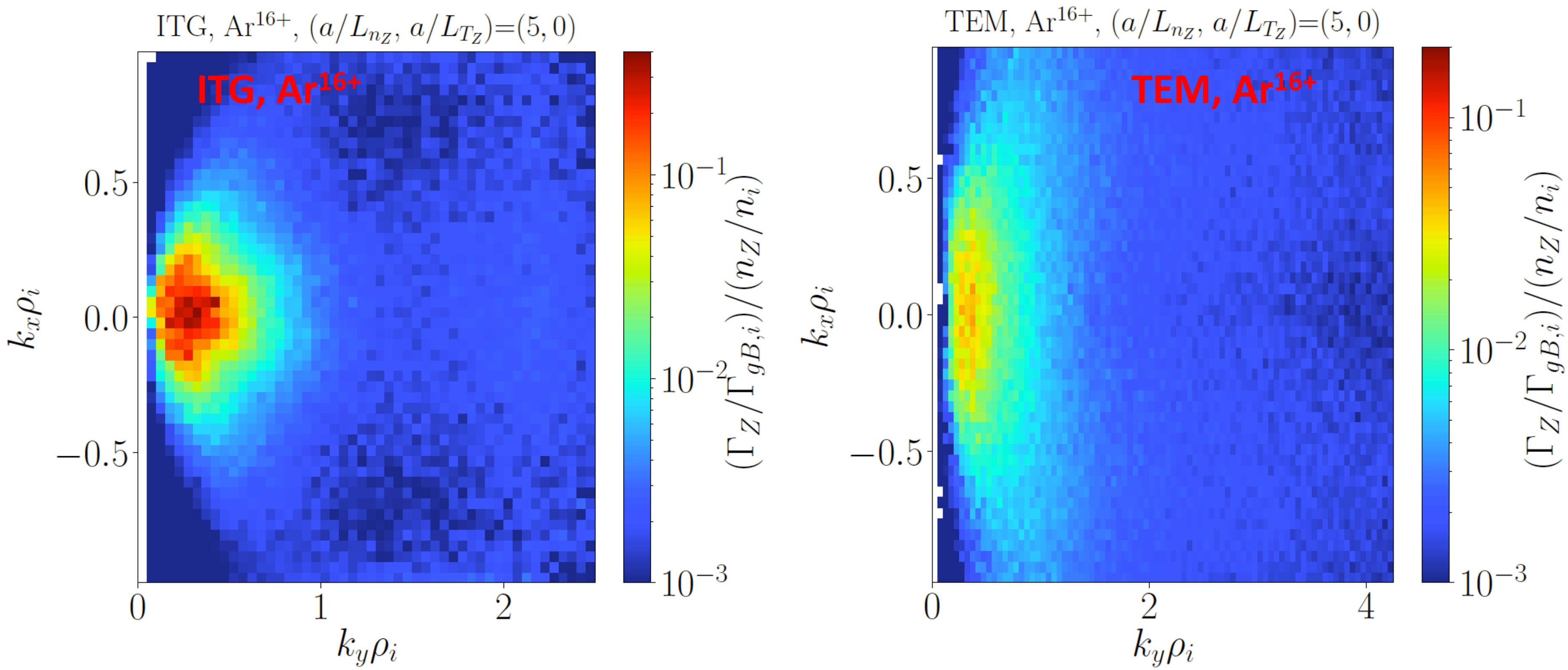




- **ITG** turbulence drives outward diffusive transport **more efficiently than TEM**.
- **Thermo-diffusion** drives, for both turbulence types, **inward** impurity flux.
- **ITG** ⇒ **pinch** contribution , **TEM** ⇒ **anti-pinch** contribution [Alcusón in progress ‘20].

Flux spectra and background turbulence

- **ITG**-driven turbulent impurity flux has **stronger localization along k_x and k_y than TEM**-driven impurity flux.



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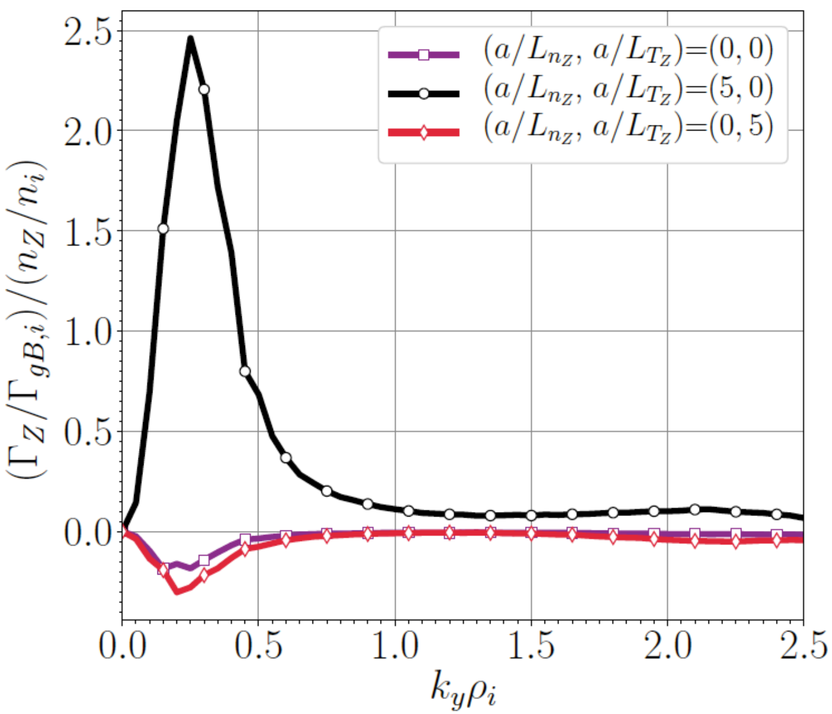

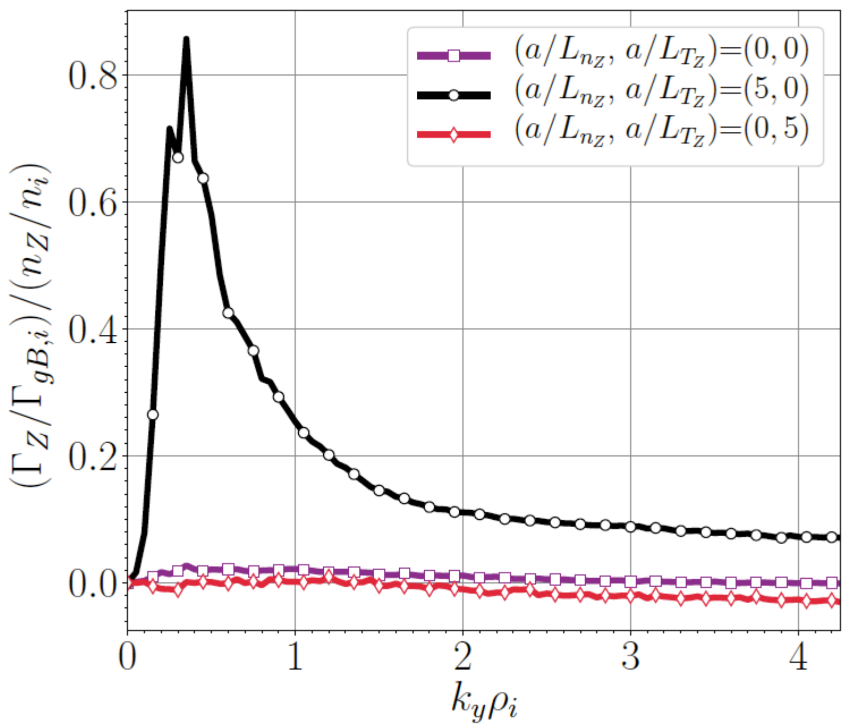

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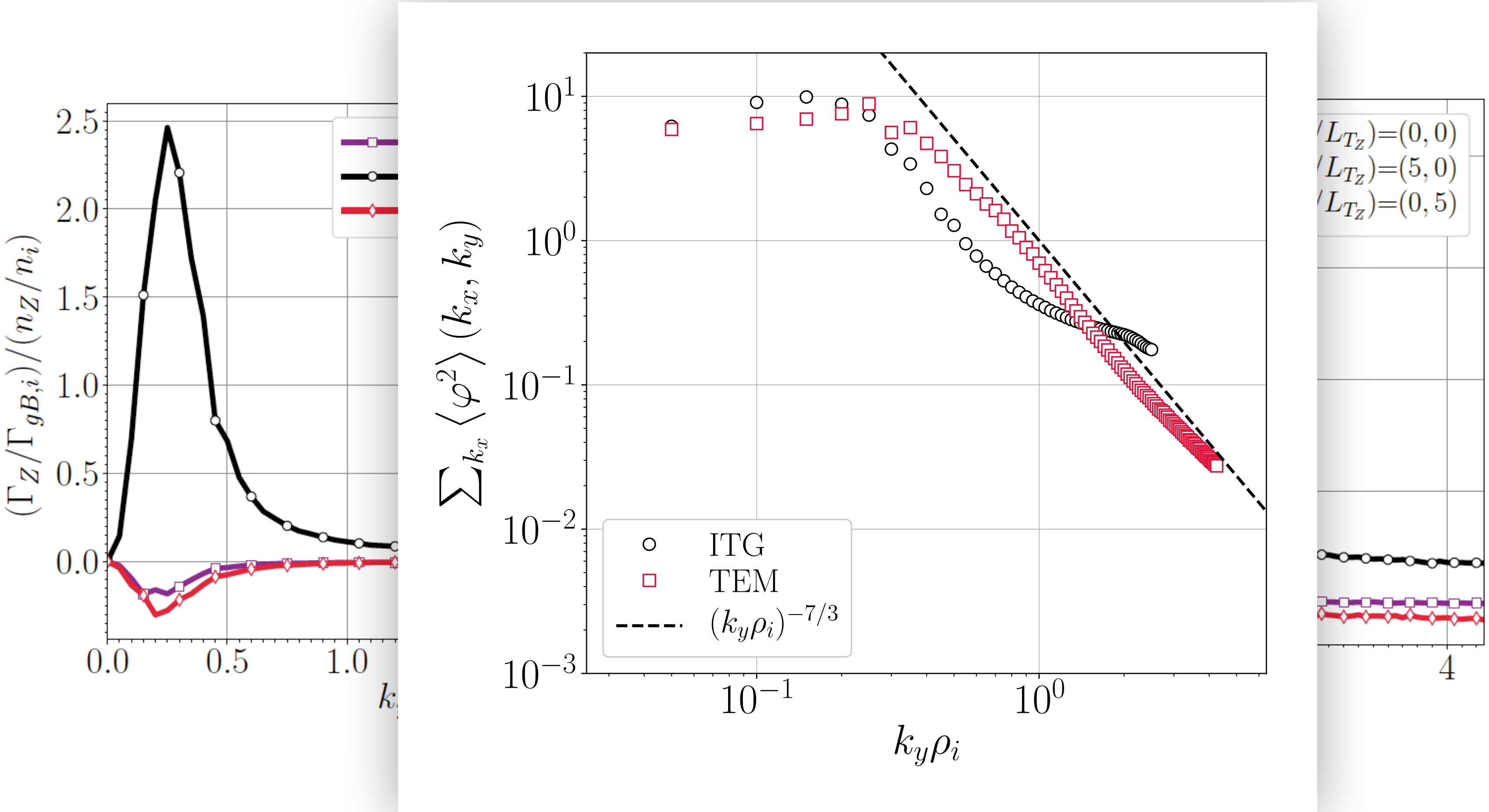

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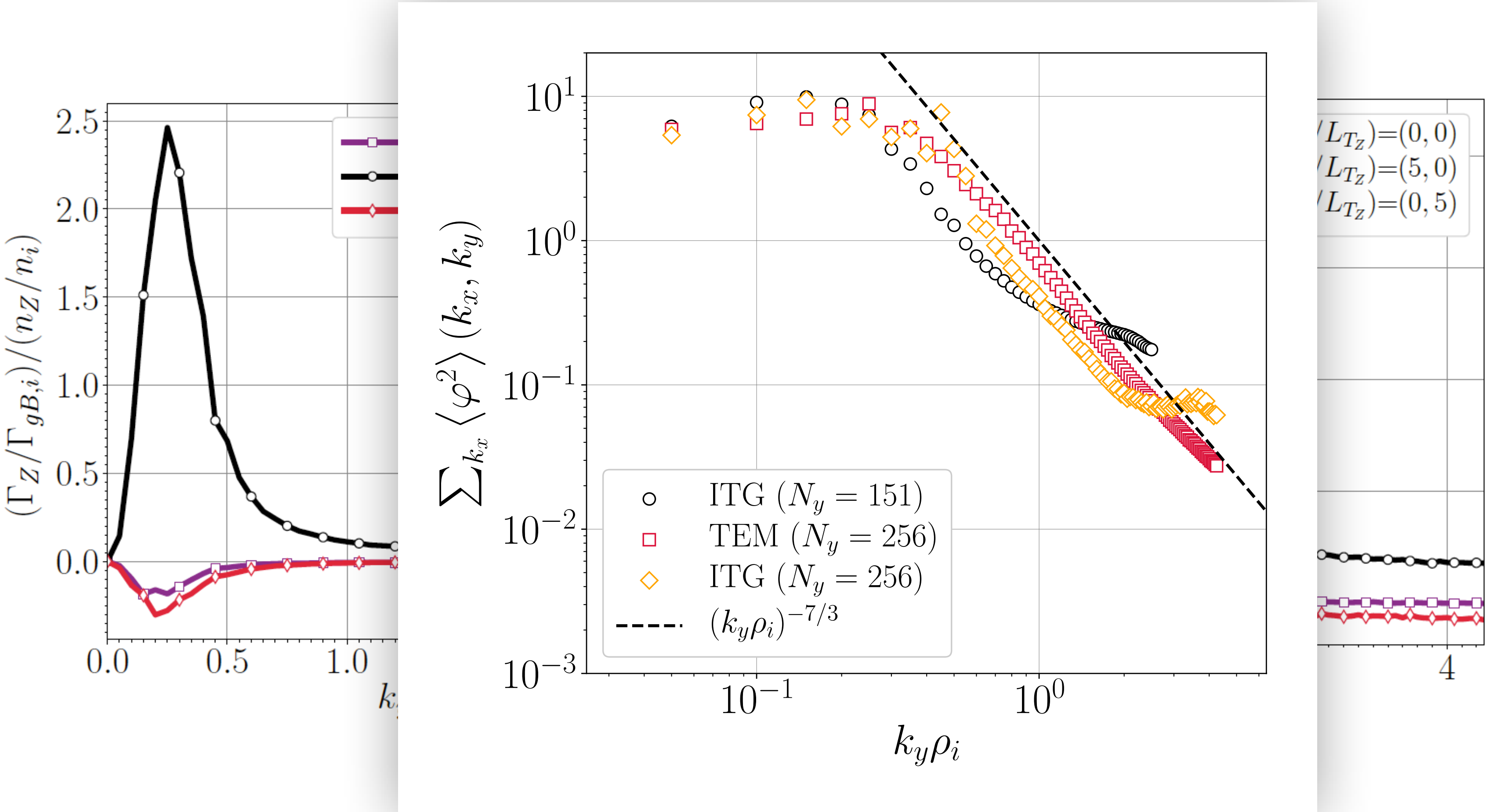
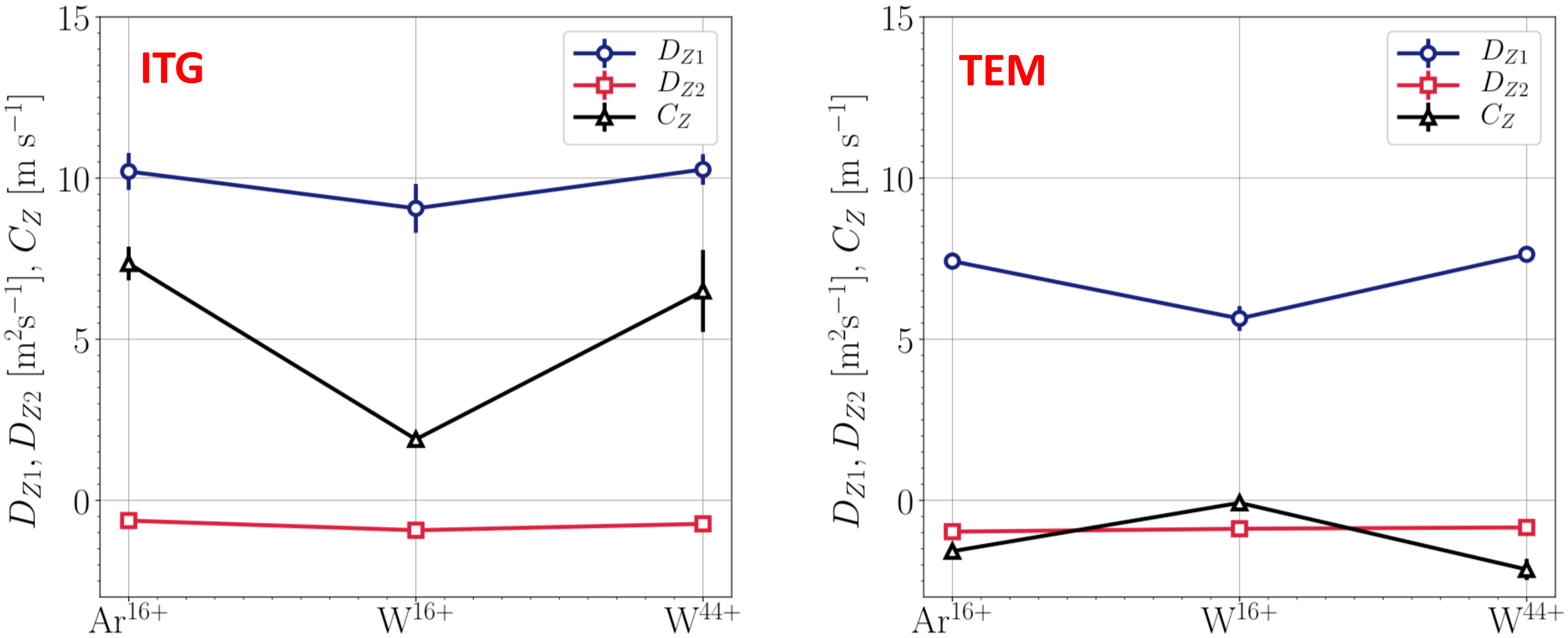


D_{Z1}, D_{Z2} and C_Z for trace Ar^{16+}, W^{16+}, W^{44+}

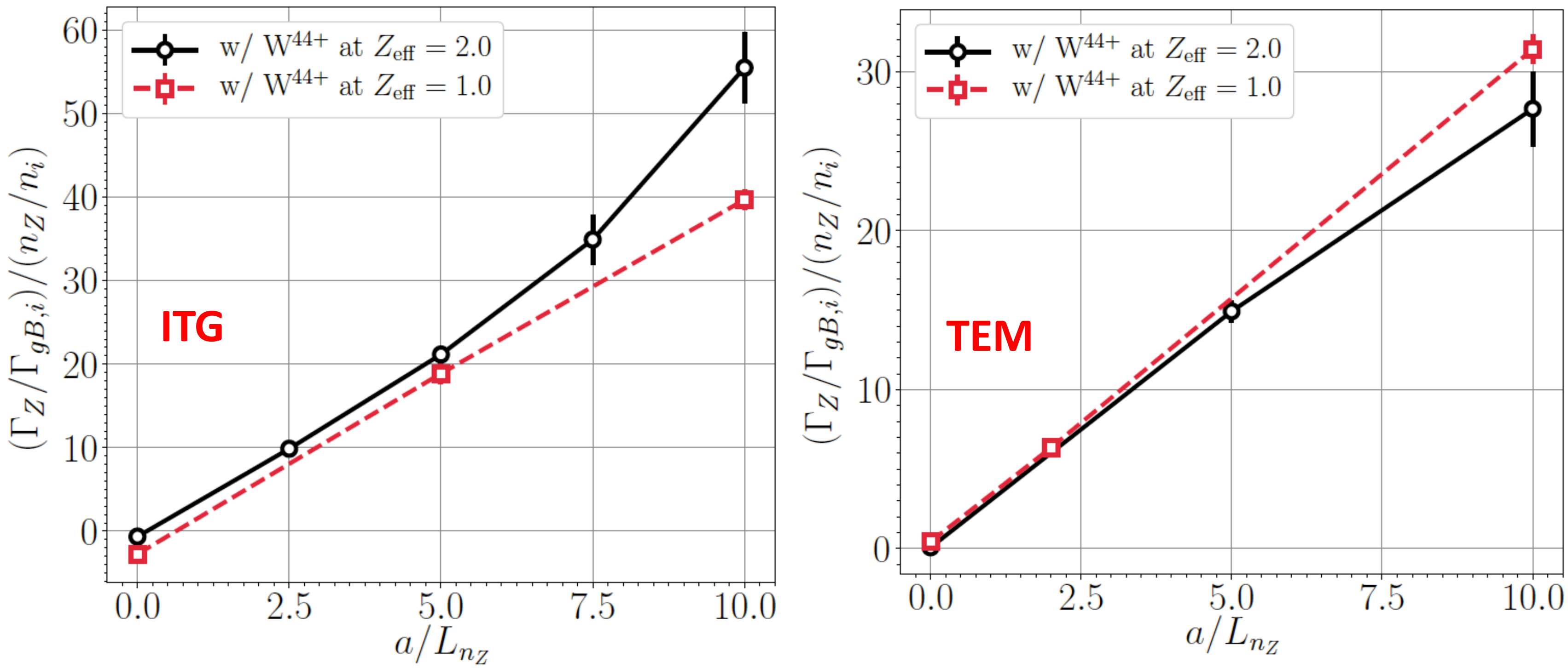
- The experimental value of D_{Z1} is reasonably close to ITG and TEM simulations.
- **ITG turbulent** driven Γ_Z produces **larger D_{Z1} than TEM** turbulence.
- **Convection** (V) gets negative contribution from both D_{Z2} and C_Z in the ITG case, and opposite contributions from D_{Z2} and C_Z in TEM case.
- The **large D_{Z1} supports** a low value of the peaking factor (V/D) $\Rightarrow$ **nearly flat n_Z profiles, at worst!**

$$\frac{V}{D} = -\frac{D_{Z2} \mathrm{d} \ln T_Z / \mathrm{d}r + C_Z}{D_{Z1}}.$$



What if impurities are non-trace?

- Trace concentration allows to **assume impurity transport coefficients independent on impurity parameters**, like gradients. Impurities do not *participate* in quasi-neutrality.
- How far from linear does, for instance, Z_{eff}=2 make $\Gamma_Z(n_Z)$? **Not far.**
- The flux deviates from linear trend in opposite directions for ITG than for TEM.



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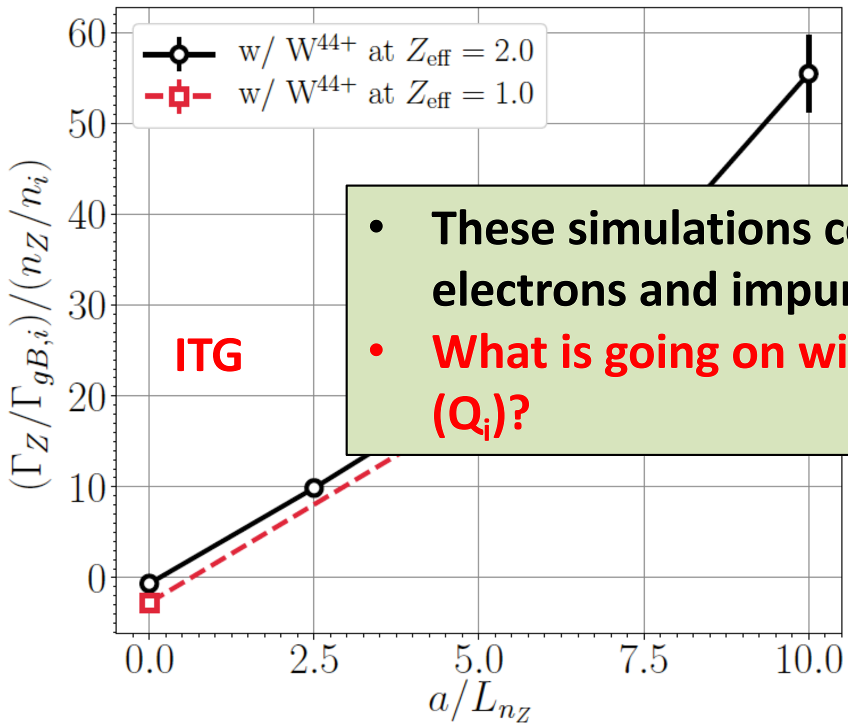
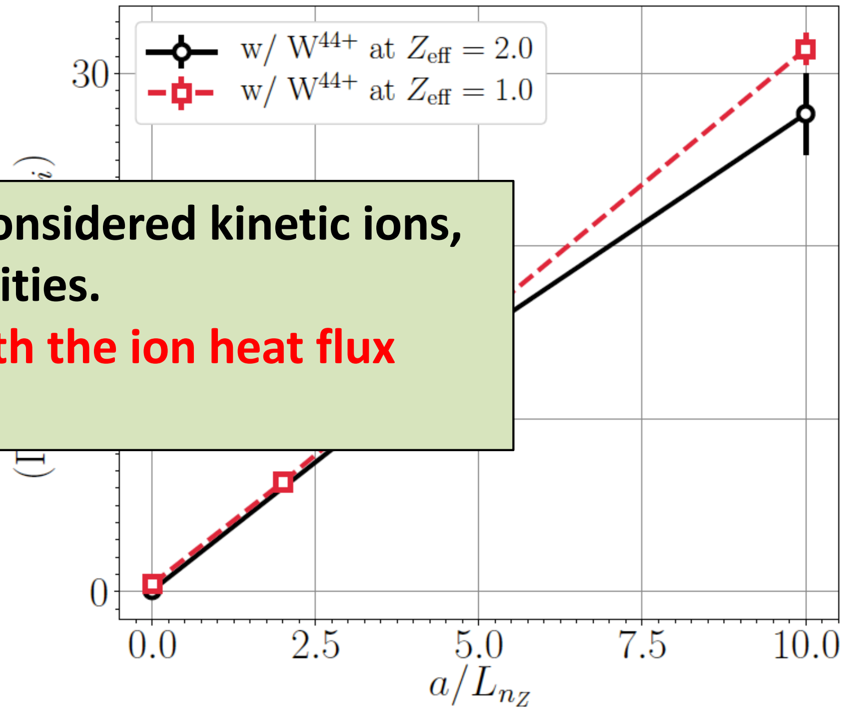
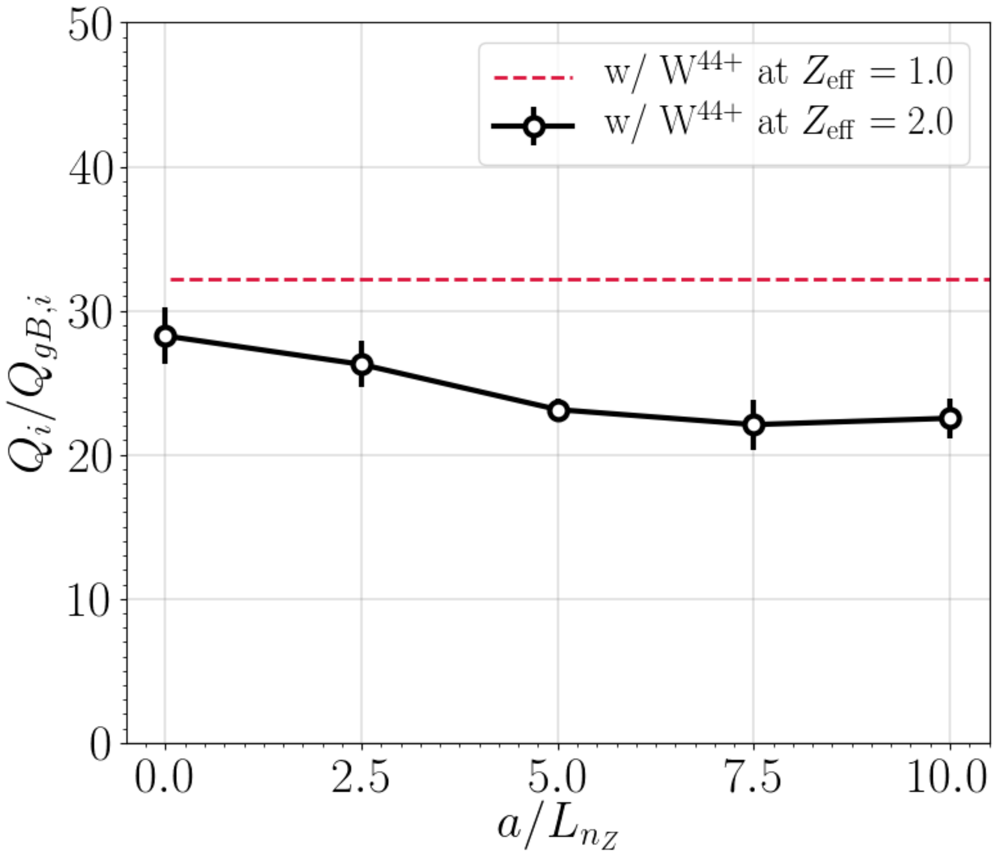




- **These simulations considered kinetic ions, electrons and impurities.**
- **What is going on with the ion heat flux (Q_i)?**

How Q_i is affected by the presence of impurities?

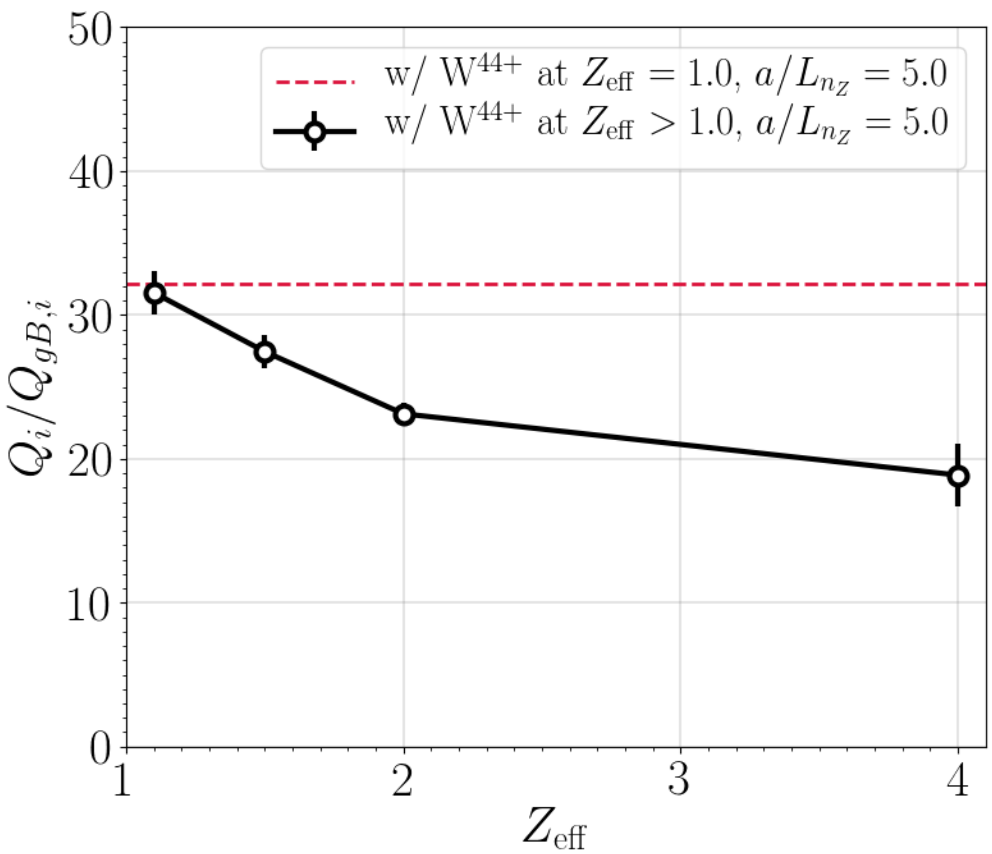
- For the ITG case, including W^{44+} at Z_{eff}=2 yields a **reduction of the ion heat flux of approximately 30%.**



- The mere presence of the impurity produces a modest fall of Q_i even if the profile is flat.
- **Q_i decreases further** with the strength of the impurity density gradient up to a constant value.
- **In equilibrium:** the turbulence will determine V/D, and this will, in turn set the reduction of Q_i.

How Q_i is affected by the presence of impurities?

- For the ITG case, including W^{44+} and scanning Z_{eff} yield a reduction of **the ion heat flux of up to approximately 40% for** Z_{eff}=4.



- **Q_i dependence on Z_{eff}** is strong at low to moderate values of **Z_{eff}** a leads to a noticiable Q_i reduction.
- **As in the n'_Z scan, as Z_{eff}** increases Q_i monotonically falls, although at a more moderate rate at higher values of **Z_{eff} .**

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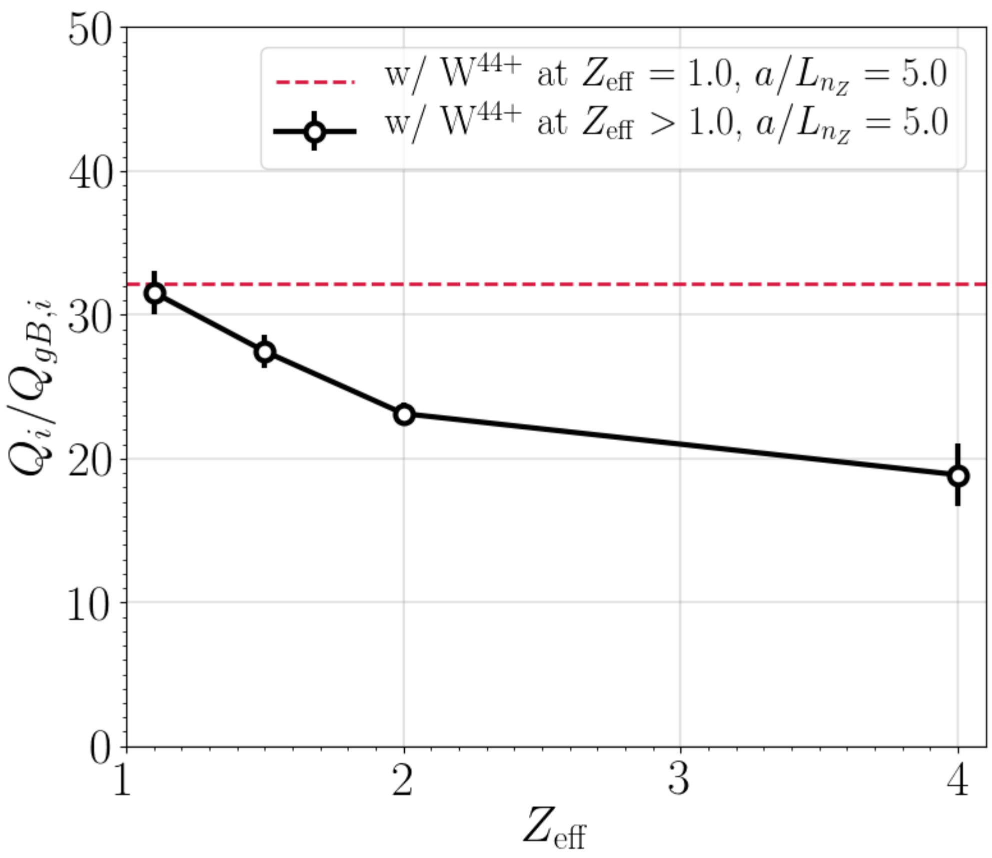

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- Does the deliberate injection of impurities, which may introduce **transiently stronger density gradients and larger Z_{eff}** , lead to a stronger Q_i reduction too? Experiments indicate so [Lunsford APS-DPP 2020]

How Q_i is affected by the presence of impurities?

SUMMARY

- **`stella`** mixed implicit-explicit treatment of the GK eqs. has allowed us to address with **several multispecies simulations** the question about the **turbulent transport** of impurities **in stellarators**.
- D_{Z1} carries the largest contribution to the total impurity flux.
- **The values of D_{Z1}** numerically obtained are reasonably close to those reported in W7-X experiments [Geiger NF'19].
- **ITG/TEM** turbulence drives **inward/outward impurity convection** via $C_Z \Rightarrow$ **peaked/hollow** n_Z
- For impurity concentrations **at moderate Z_{eff}**, the **dependence** of the impurity flux on the impurity density gradient is **close to linear.**
- We have found numerically that a highly charged heavy **impurity**, like W^{44+}, **at non-trace concentration** provokes a substantial **reduction of the turbulent ion heat flux.**

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THANKS FOR YOUR ATTENTION!