MAX-PLANCK-INSTITUT
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EUROfusion

Milestone and deliverable update

M.RM-W7XEXP and D.W7X-PART-TRANSP

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TSVV meeting, 14 September 2026

Items under review

M.RM-W7XEXP

Reduced models and scaling laws for heat and particle fluxes in W7-X using existing validated databases, validated against experiments.

Milestone 6, due December 2026
ABN, DF

D.W7X-PART-TRANSP

Quantify impurity and main ion transport during high-performance phases in W7-X with GENE simulations alone and with the GENE-KNOSOS-Tango framework.

Deliverable, due 2026
ABN, HCC

Milestone

M.RM-W7XEXP

Reduced models and scaling laws for heat and particle fluxes in W7-X

Reduced models by D. Fernando

Data-driven models for turbulent transport in W7-X

Fits and predictions from both families: **reduced models** and **surrogate models**

- A database of several hundred ion-scale kinetic-electron and electron-scale adiabatic-ion GENE simulations was assembled.
- Fitted to **prescribed model forms** using an active learning strategy: 4 fluxes × 10 radial positions.

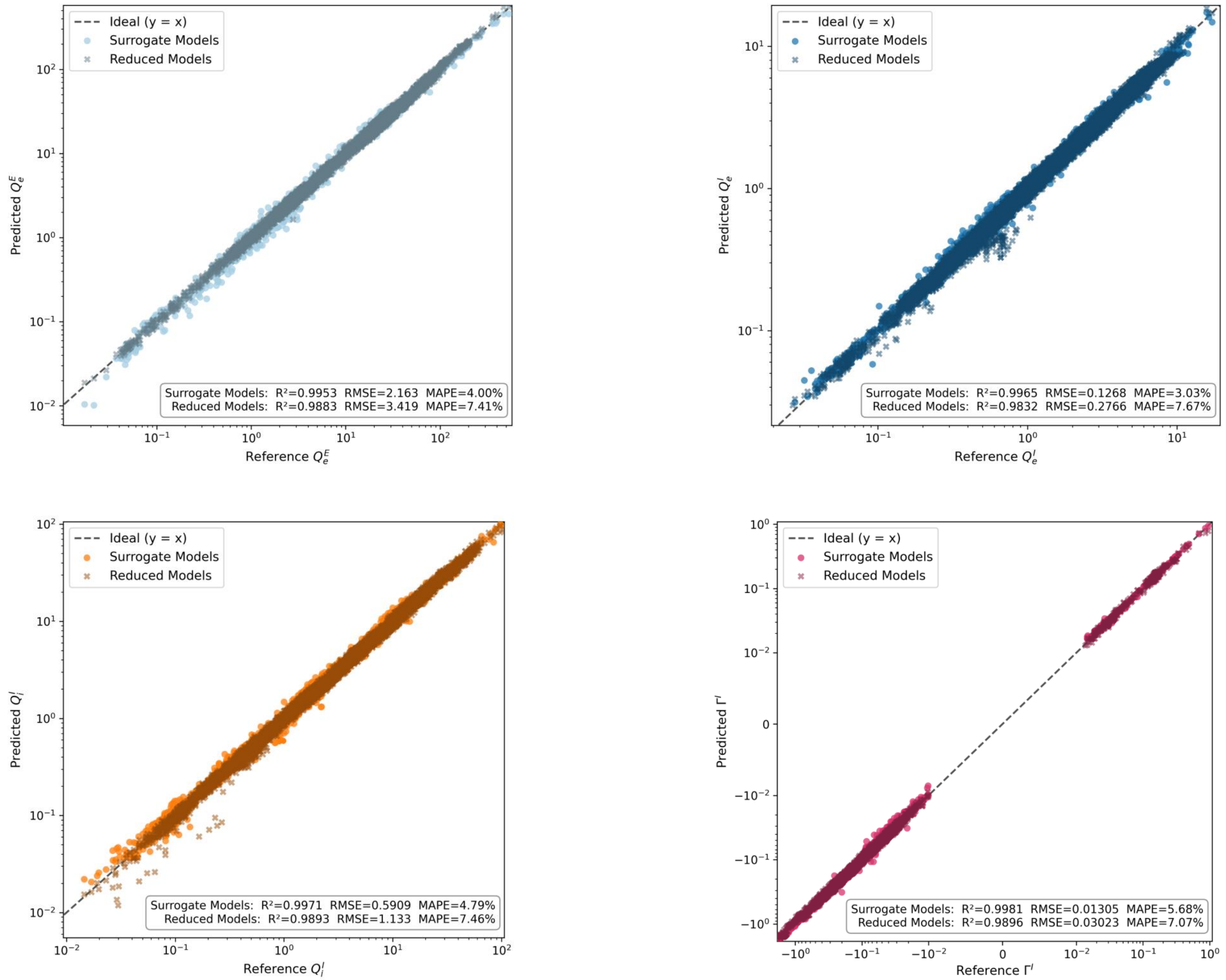
$$Q_{e,E}/Q_{gB}\ (\rho) = c_1 \omega_{Te}^{\ p_1} (\eta_e - 1)^{p_2} \tau^{-p_3}$$

$$Q_{e,I}/Q_{gB}\ (\rho) = c_1 \omega_{Ti}^{\ p_1} (\eta_i - 1)^{p_2} \beta^{-p_3} (1 + k_1 \gamma_E)^{-1}$$

$$Q_{i,I}/Q_{gB}\ (\rho) = c_1 \omega_{Ti}^{\ p_1} (\eta_i - 1)^{p_2} \beta^{-p_3} (1 + k_1 \gamma_E)^{-1}$$

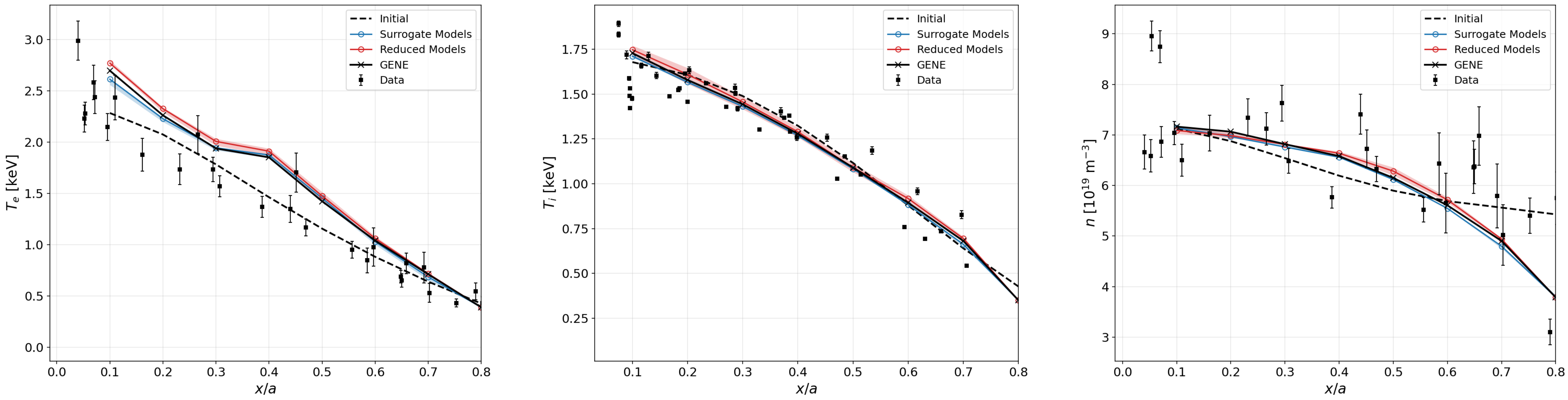
$$\Gamma_I/\Gamma_{gB}\ \ (\rho) = (c_1 \omega_n^{\ p_1} - c_2 \omega_{Te}^{\ p_2} - c_3 \nu)(1 + k_1 \gamma_E)^{-1}$$

- Used to train **surrogate models** for the same 4 fluxes.



Reduced and surrogate models for profile prediction

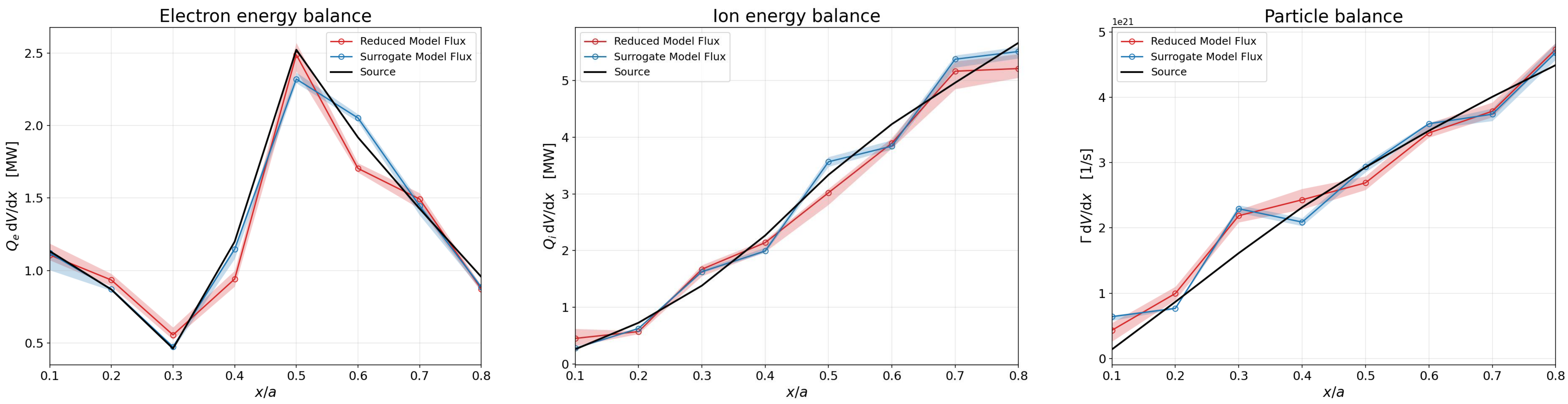
Tested within the GENE–KNOSOS–Tango framework. OP1.2b “NBI + ECRH” scenario.



- Initial guesses were sufficiently different from the converged profiles, especially at the boundary (ρ = 0.8).
- Very good agreement with the reference profiles.

Power and particle balances across scenarios

OP1.2b “NBI + ECRH” scenario.



– Very good agreement with the reference profiles and with the power and particle balances.

– Similar results for three other scenarios: high-density ECRH, low-density ECRH, and NBI.

– Extrapolation capability is currently under investigation.

Deliverable

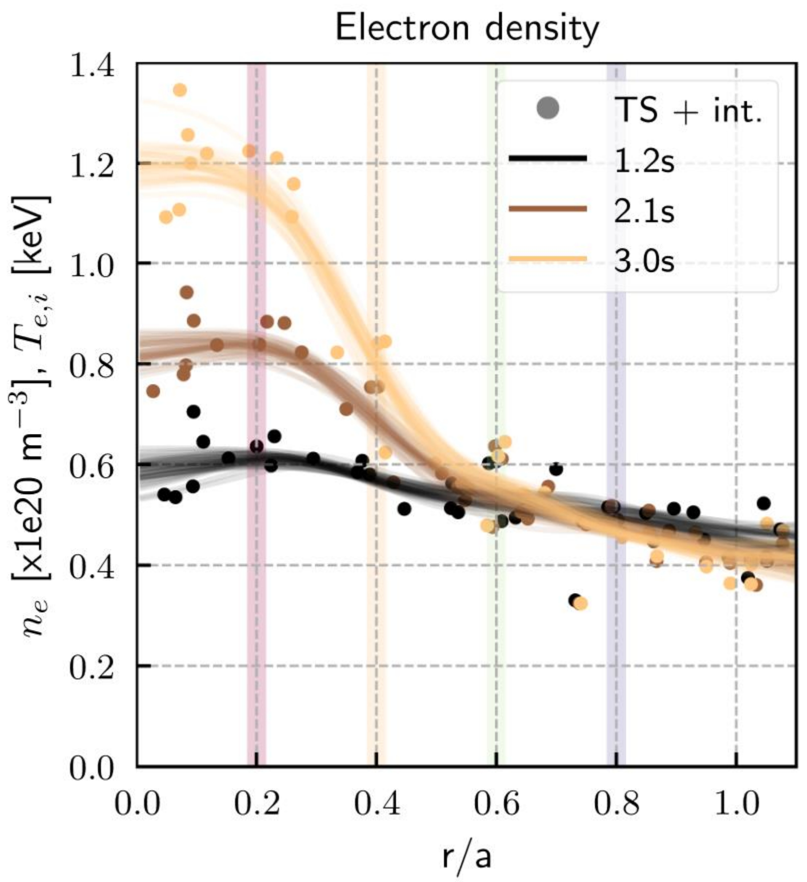
D.W7X-PART-TRANSP

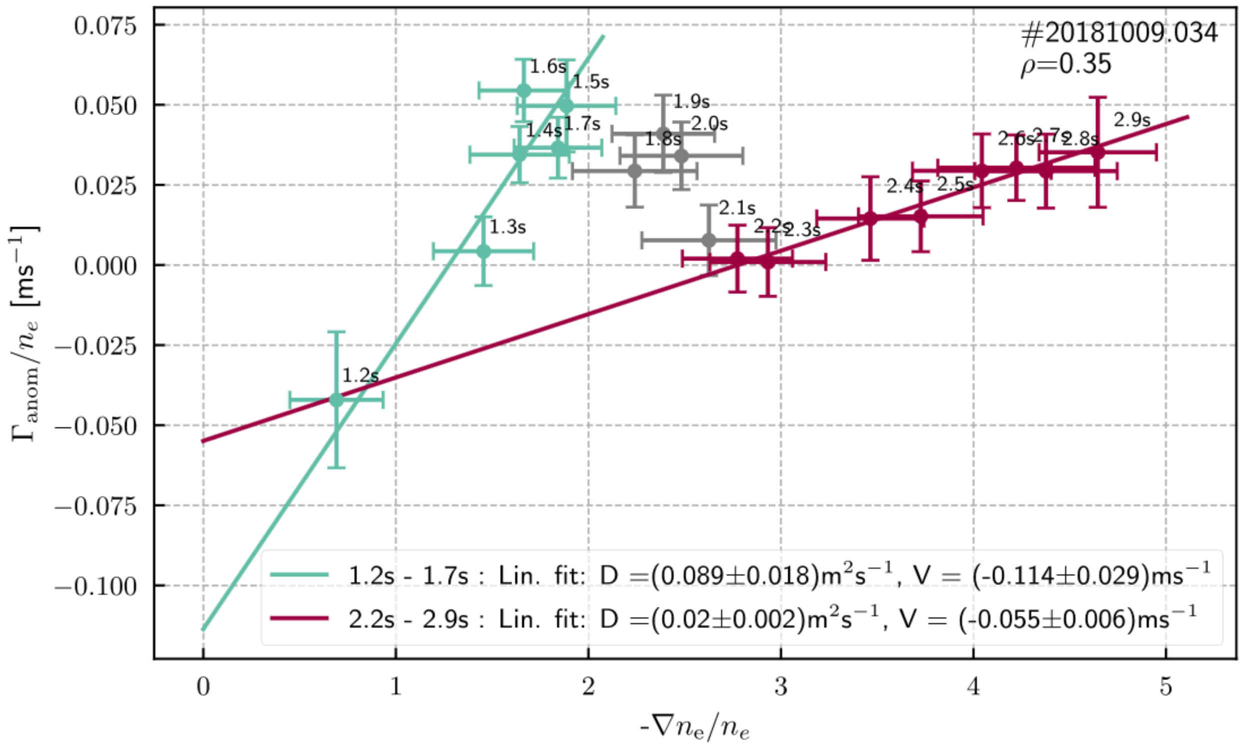
Impurity and main ion transport in high-performance W7-X plasmas

Main ion transport and MTM by H. Cu-Castillo. GENE–Tango simulations by A. Di Siena.

Motivation: improved particle confinement

- W7-X experimental regime with improved particle confinement.
- The particle source (NBI) overcomes the outward turbulent particle flux, leading to density peaking.





[1] S. Bannmann et al 2024 Nucl. Fusion 64 106015

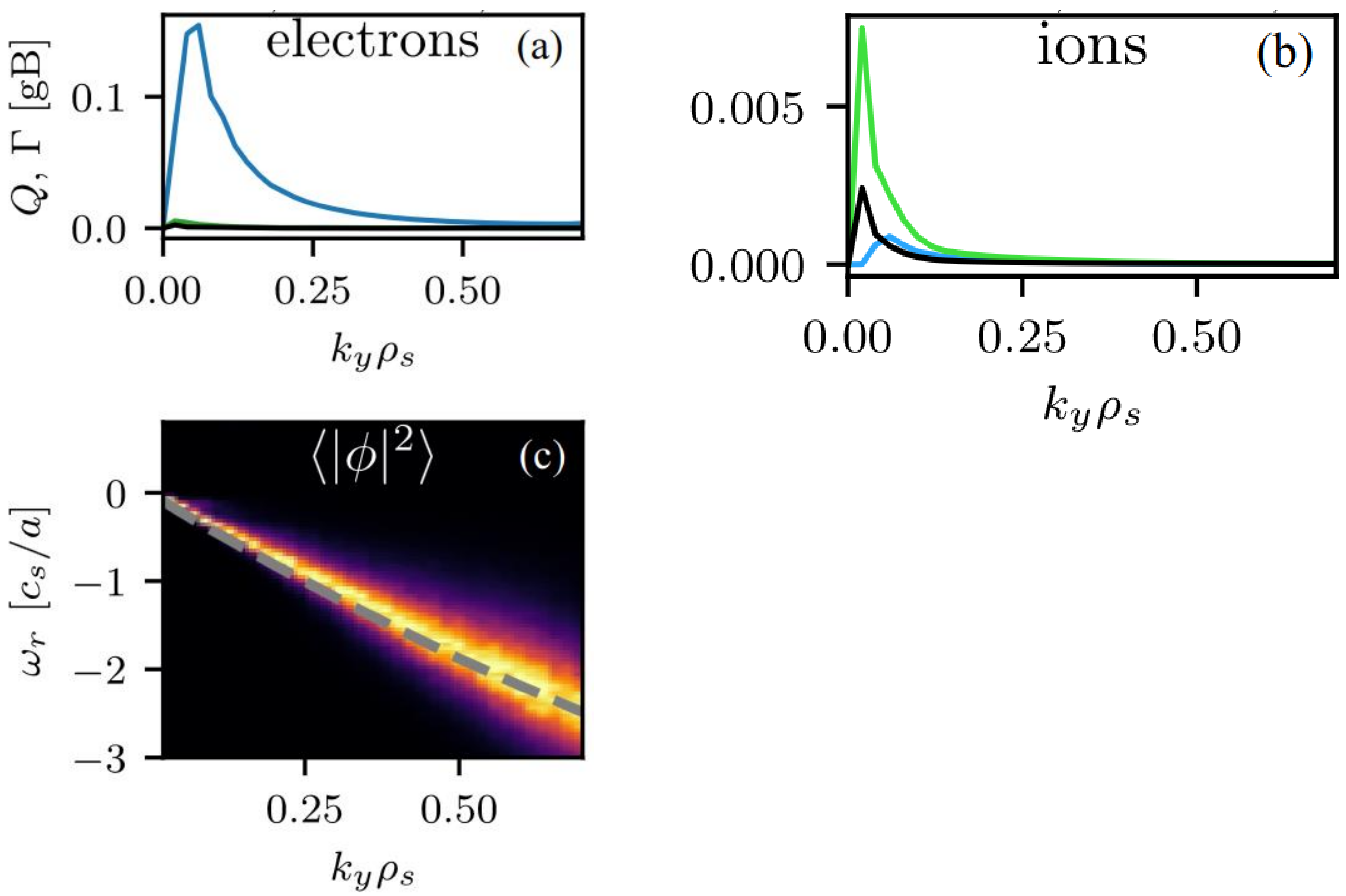
Local model reproduces the experimental fluxes

Local model (GENE) captures the most essential physics in the turbulence-reduced regime. ρ = 0.4, t = 2.8 s.

- Experimental heat flux and particle flux are reproduced.
- Transport is mainly driven by microtearing mode (MTM) turbulence: electron-driven and electromagnetic.

	⟨A·Q⟩ [MW]	⟨A·Γ⟩ [1/s]
experiment	0.6	9.9×10^{19}
simulation	0.84	4.3×10^{19}

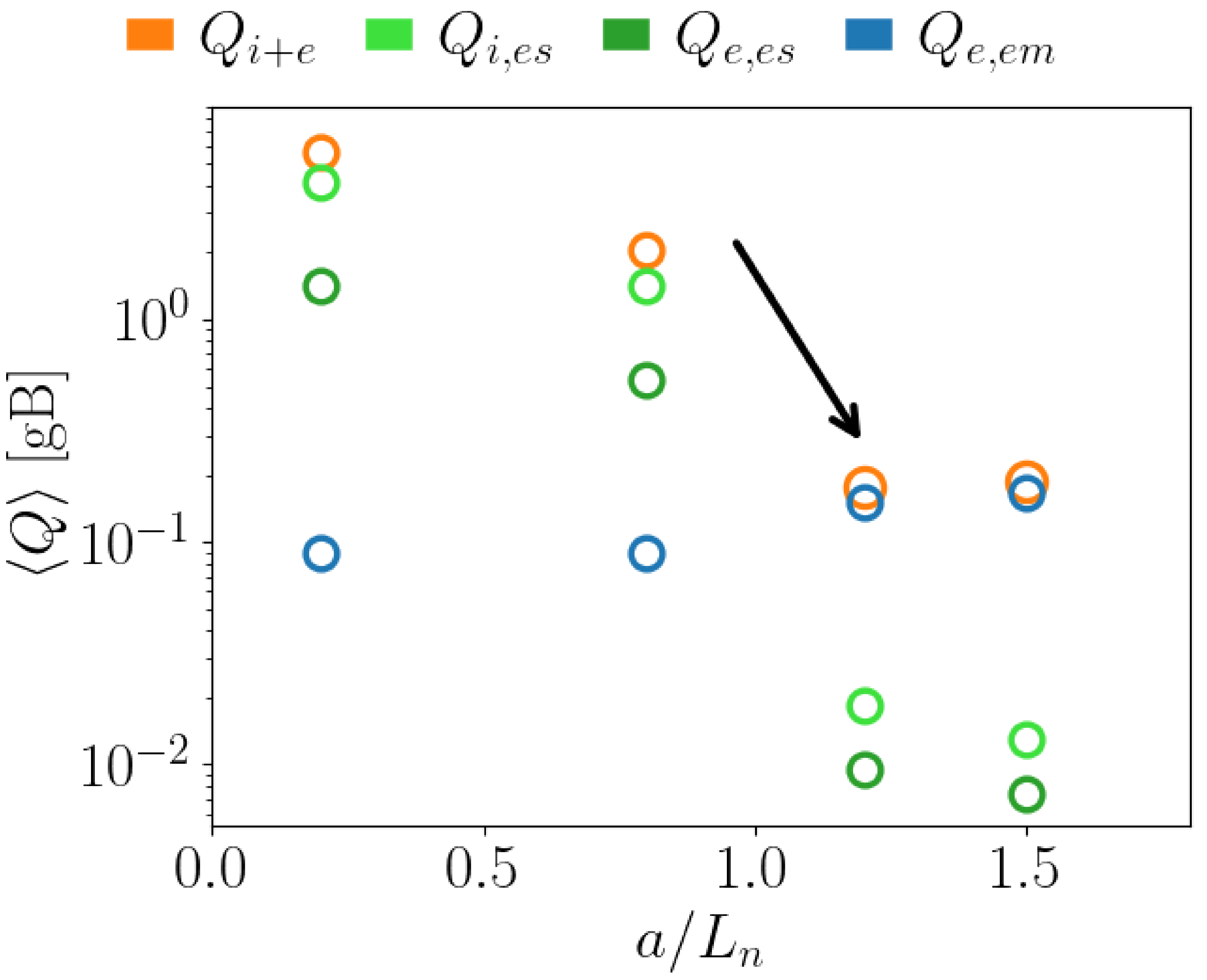
H. Cu-Castillo, Phys. Rev. Lett. 137, 035102 (2026)



Dashed grey line: linear simulation, MTM instability

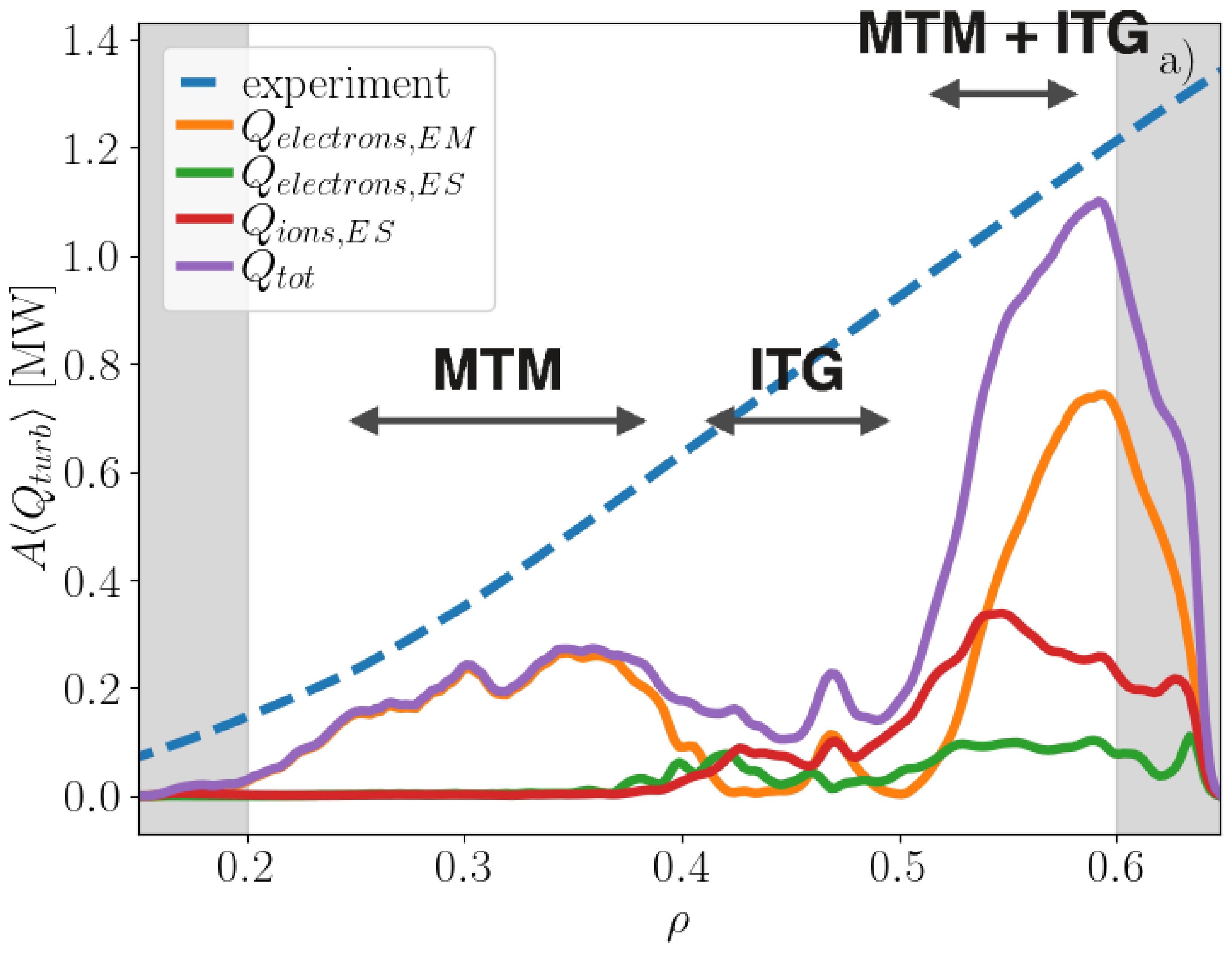
Microtearing turbulence survives ITG/TEM suppression

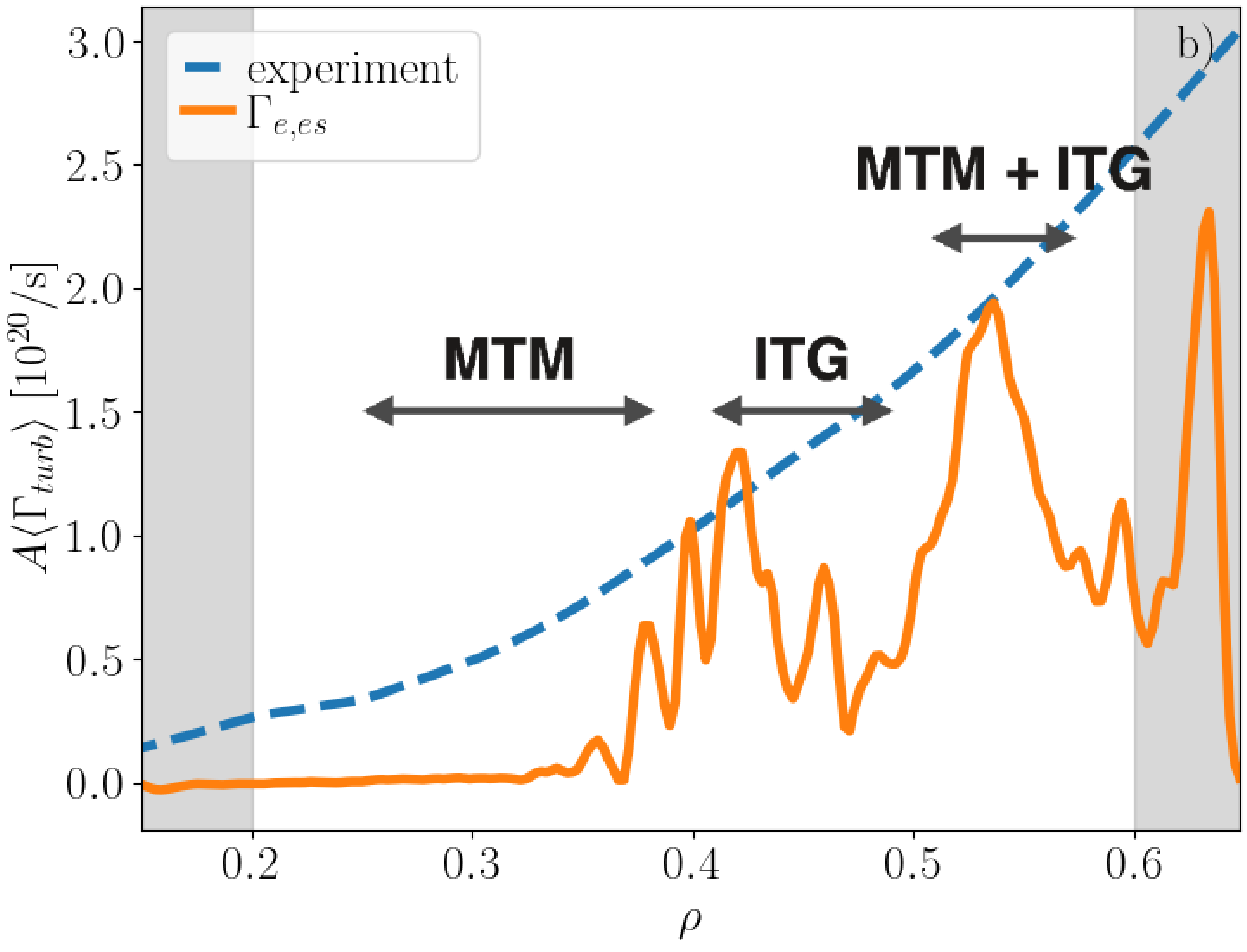
- Microtearing turbulence survives after ITG/TEM is suppressed by large a/L_n.
- MTM is dominant in the experimental scenario with large a/L_n.
- No ∇n-driven TEM, due to the quasi-isodynamic and Max-J properties of W7-X.
- MTM turbulence reproduces the observations for a/L_n > 1: negligible ion heat flux, and heat flux independent of a/L_n.



GENE-3D: turbulence regimes vary with radius

Global simulations show various turbulence regimes at different radial positions. t = 1.7 s.



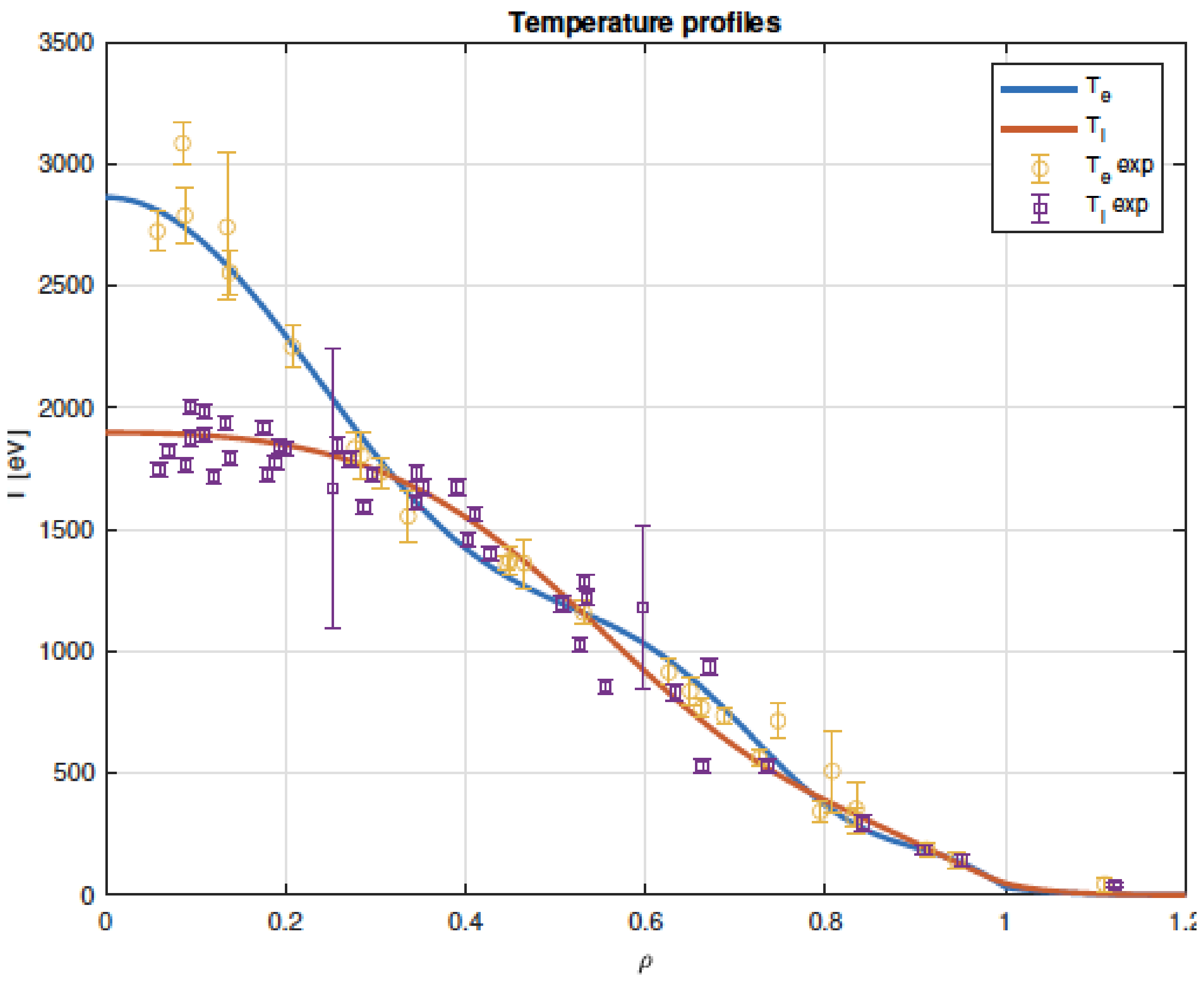


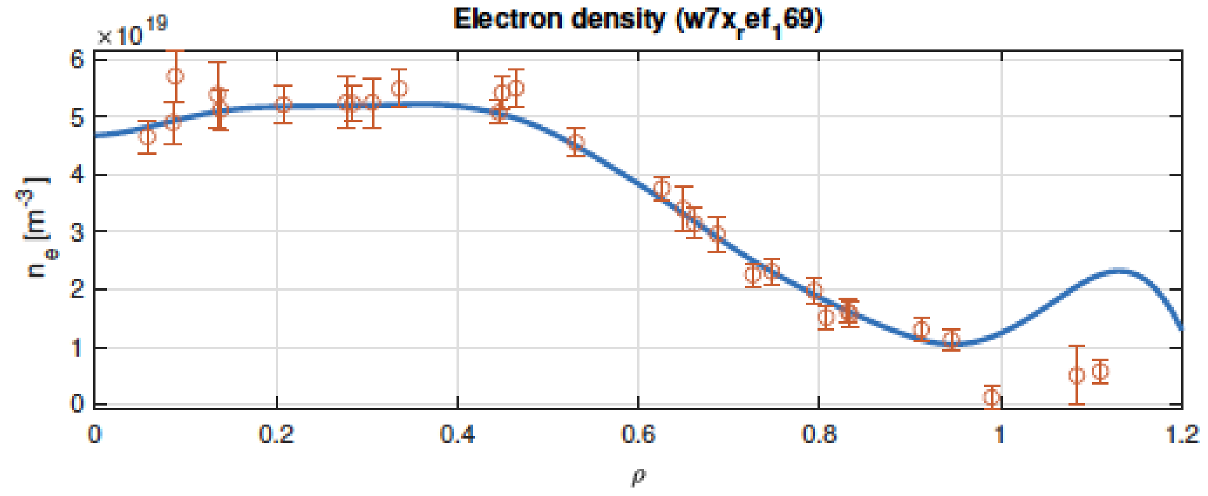
- Dominant instability by radius: MTM, then ITG, then mixed MTM + ITG towards the edge.

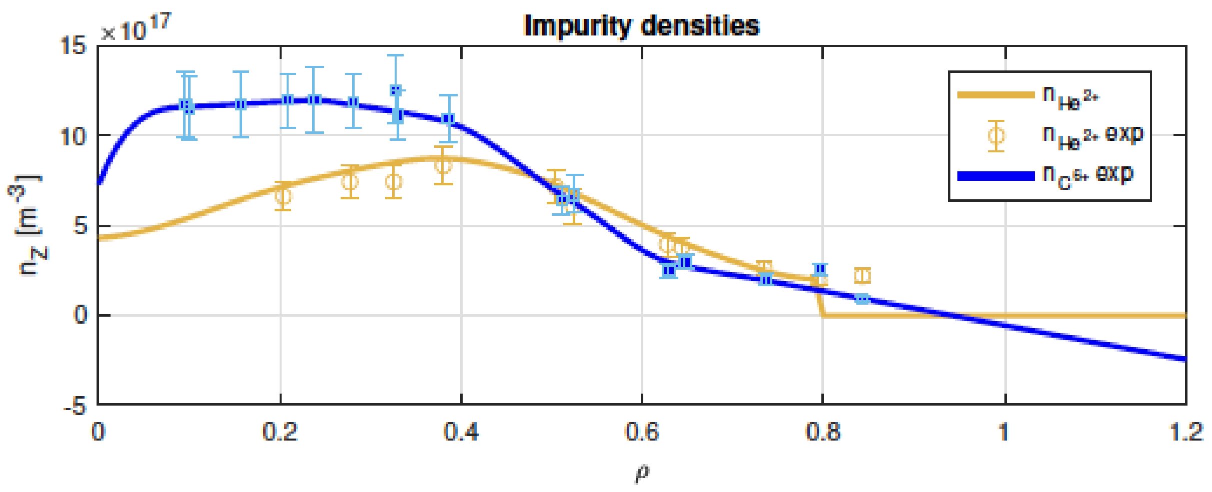
Discharge and input profiles

W7-X 20250513.032, t ≈ 7 s

Experimental temperature and density profiles used as input; impurity densities for carbon and helium.







Goal: reproduce these profiles self-consistently with GENE–Tango.

Numerical tool: GENE-Tango

i SFINCS computes neoclassical fluxes and E_r for a given pressure profile.

ii GENE evaluates turbulence levels for the given pressure profile and E_r.

iii Tango evaluates new plasma profiles consistent with the given turbulent, neoclassical and classical levels and sources.

iv New profiles are transferred back to SFINCS and GENE, and the process is repeated.

$$Q_s(\rho_{tor}) = Q_s^{neo} + Q_s^{turb}$$

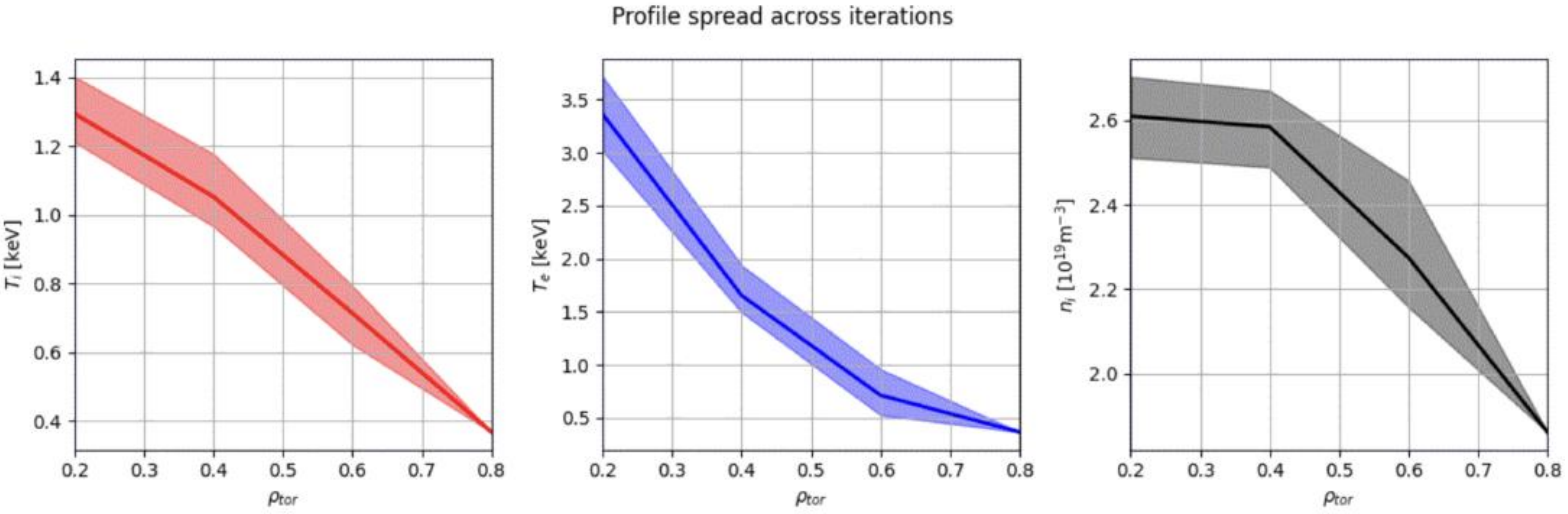
$$\Gamma_s(\rho_{tor}) = \Gamma_s^{neo} + \Gamma_s^{class} + \Gamma_s^{turb}$$

hydrogen	T_i
electrons	T_e, n_e
carbon	n_C
helium	n_{He}

Steady-state profiles without impurities

– Almost converged profiles as a function of ρ_{tor} . Shaded areas show the spread across the last four iterations.

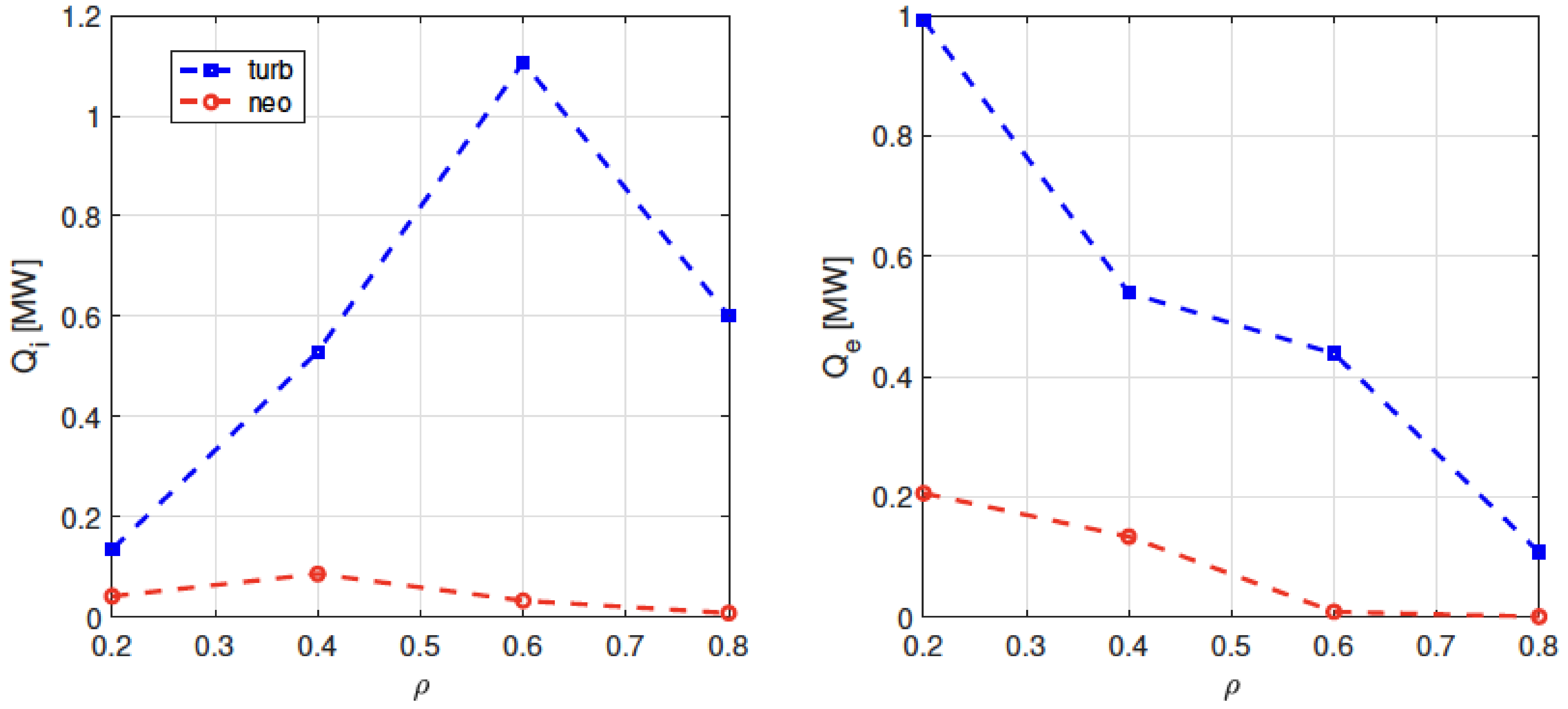
– T_e is well matched.



Neglecting impurities strongly underestimates the profiles: on-axis T_i about 30% lower (1.3 vs 1.9 keV), density about 50% lower (2.6 vs 5×10^{19} m^{-3}).

Turbulent vs neoclassical heat flux

Heat flux splitting at the final iteration.

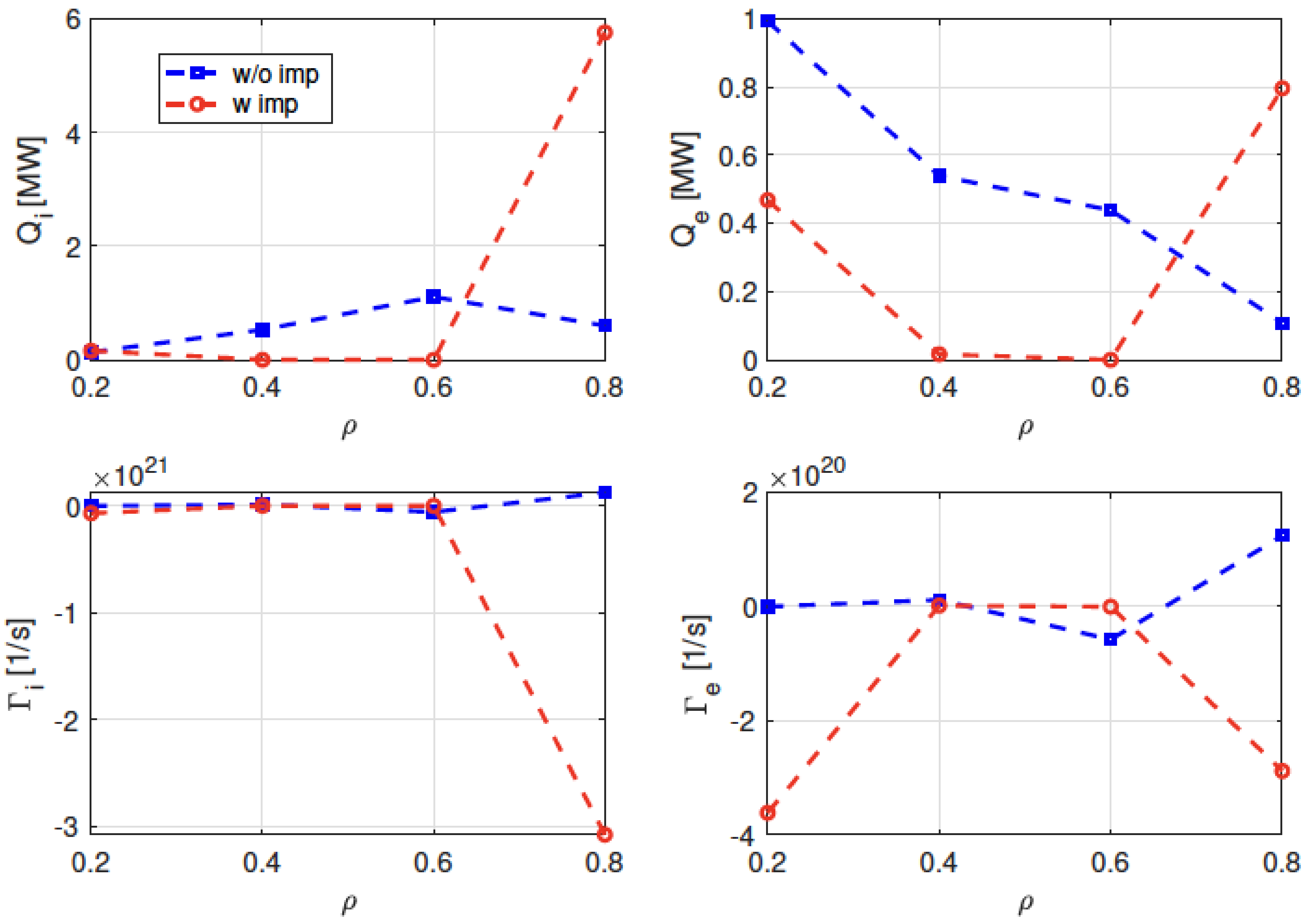


Turbulence sets the heat transport level. Neoclassical contributions reach about 20%, mostly in the electron channel.

Effect of impurities on turbulent transport

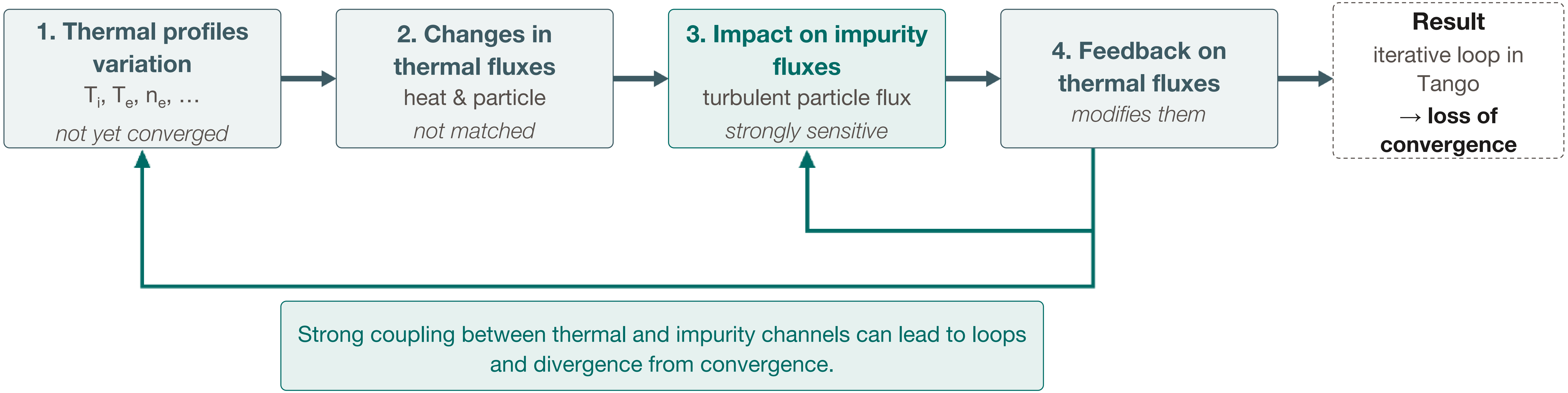
From iteration 25 without impurities: introduce He^{2+} and C^{6+}, adjust n_e for quasineutrality, then perform a single GENE-Tango step.

Impurities induce a strong stabilization of the turbulence.



Convergence with impurities

GENE–Tango convergence with impurities is challenging: impurity turbulent particle fluxes are highly sensitive to variations in thermal profiles.



Current approach

Limit variations in impurity densities to stabilize the system, allow the thermal profiles including impurities to approach convergence, then gradually relax the impurity constraints.

What remains before the end-of-year report

Milestone · M.RM-W7XEXP

- ✓ Validated W7-X database assembled for the fits.
- ✓ Reduced models and scaling laws fitted for heat and particle fluxes.
- ✓ Predictions validated against experimental discharges.

- Check extrapolation to different scenarios and magnetic configurations.

D. Fernando

Deliverable · D.W7X-PART-TRANSP

GENE-3D, density-peaking phases

- Investigate particle fluxes at time points with higher density and compare with previous times at lower peaking.
- Add impurities in both scenarios and study the influence of turbulence reduction on turbulent impurity transport.

GENE–Tango, discharge 20250513.032

- Converge the self-consistent runs with impurities under the constrained-density approach.
- Compare the converged fluxes and profiles with the experimental targets.

H. Cu-Castillo, A. Di Siena