Studies of impurity-induced turbulence stabilization and implications for breakeven in SPARC

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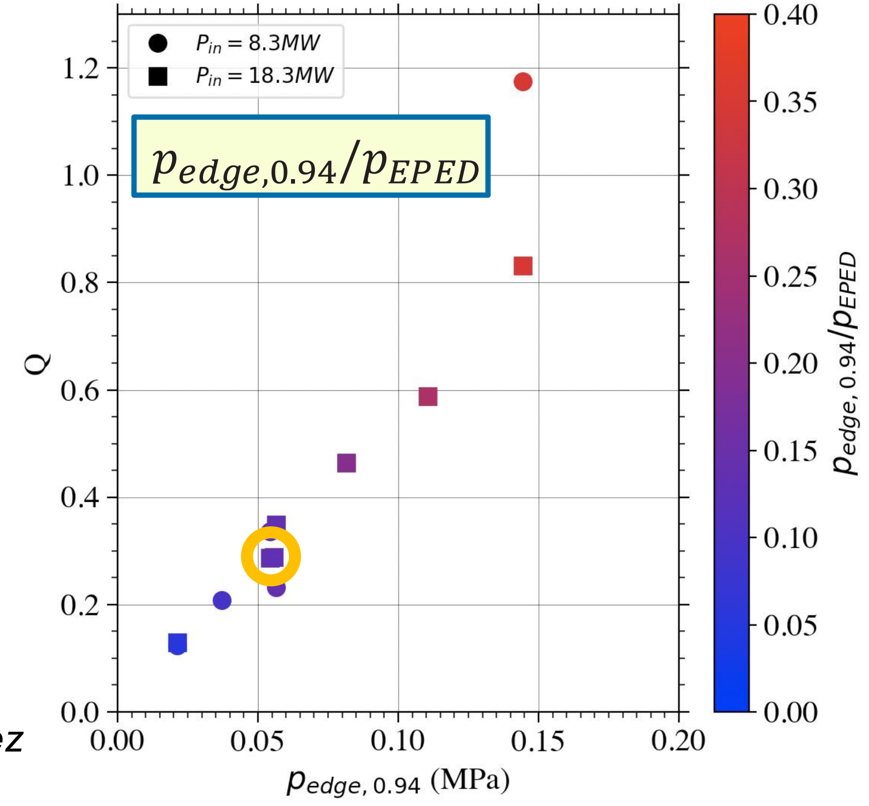
Study of L-mode *like* plasmas point to the need for high edge pressure

- Interest in $Q > 1$ in SPARC early campaigns led to the study of fusion performance in L-mode like scenarios.
- **PORTALS** is a transport solver that efficiently finds multi-channel flux-matched solutions directly with nonlinear gyrokinetics (CGYRO here).
- Variations of $n_{edge}, T_{edge}, P_{aux}$ investigated to evaluate performance.
- Study indicated the need for **moderate edge pressure** for breakeven.



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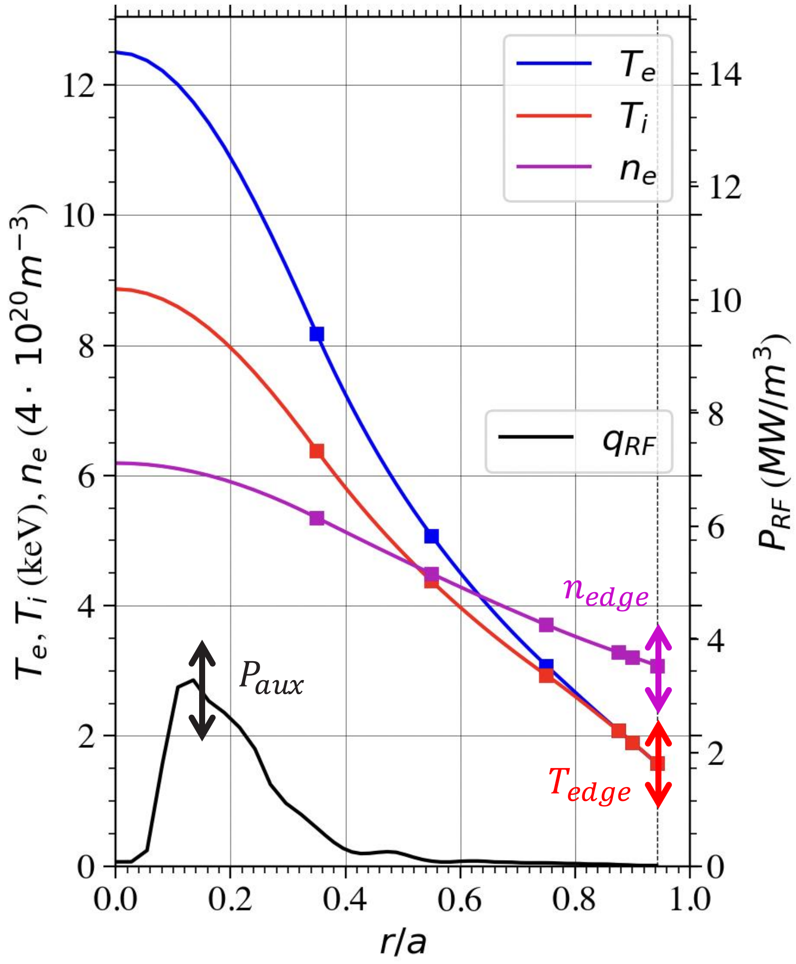
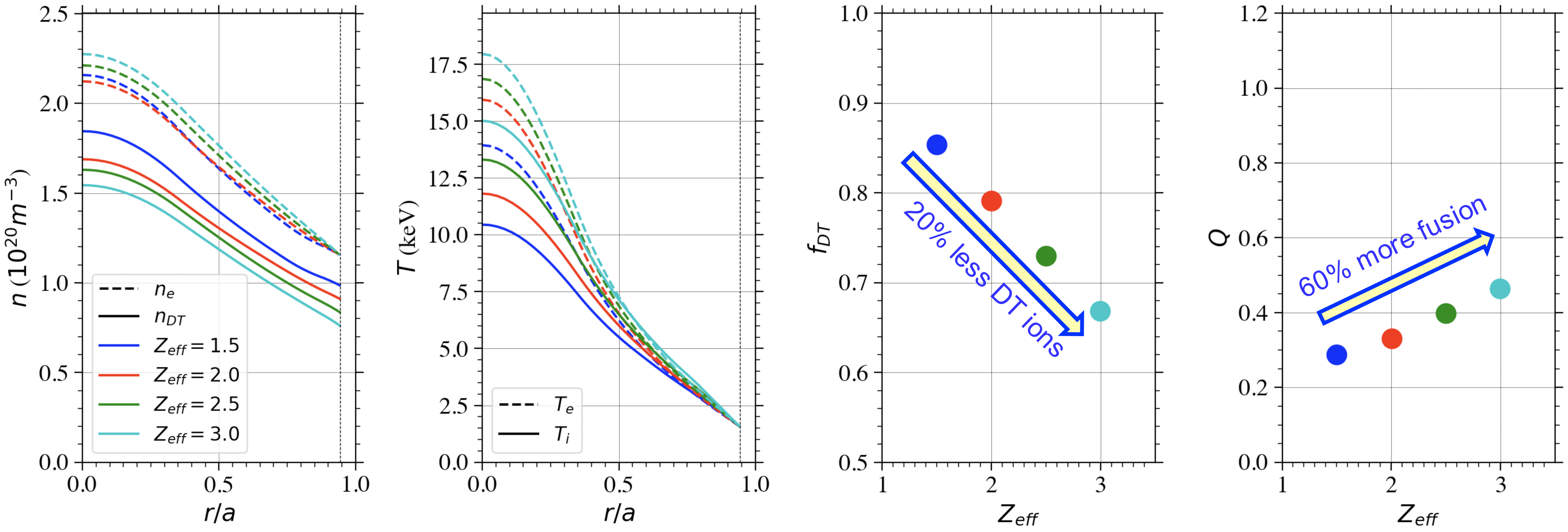
PoP 2024

PORTALS-CGYRO predictions



Impurity content scans show beneficial effects of higher Z_{eff}

- Increasing the low-Z impurity content from nominal assumptions ($f_{DT} = 0.85, Z_{eff} = 1.5$) leads to **more fusion power even with less DT ions**.



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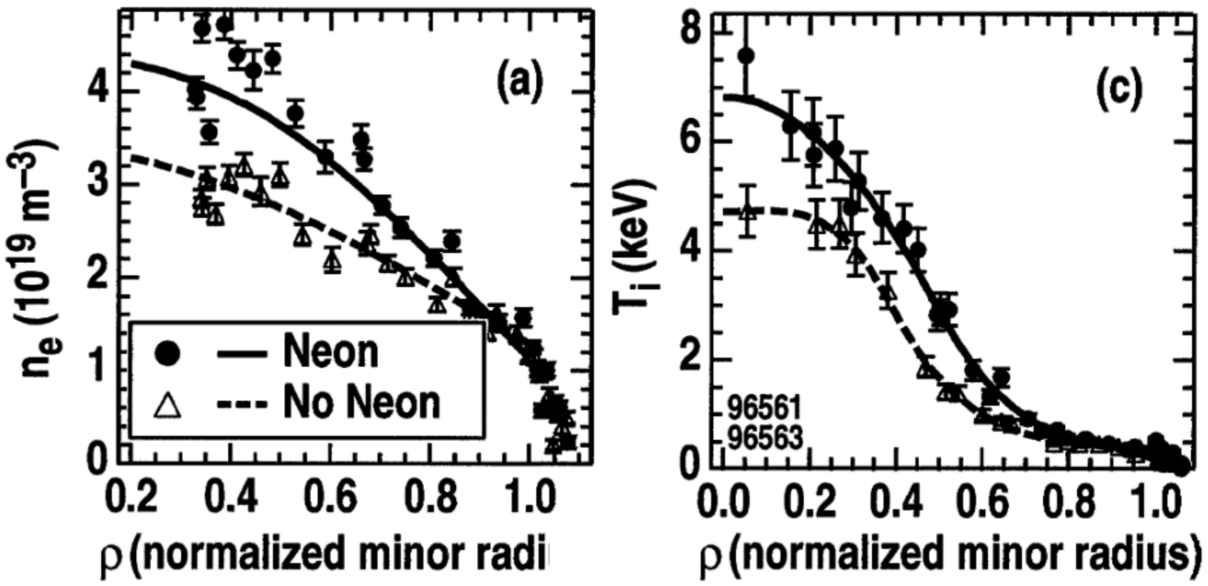
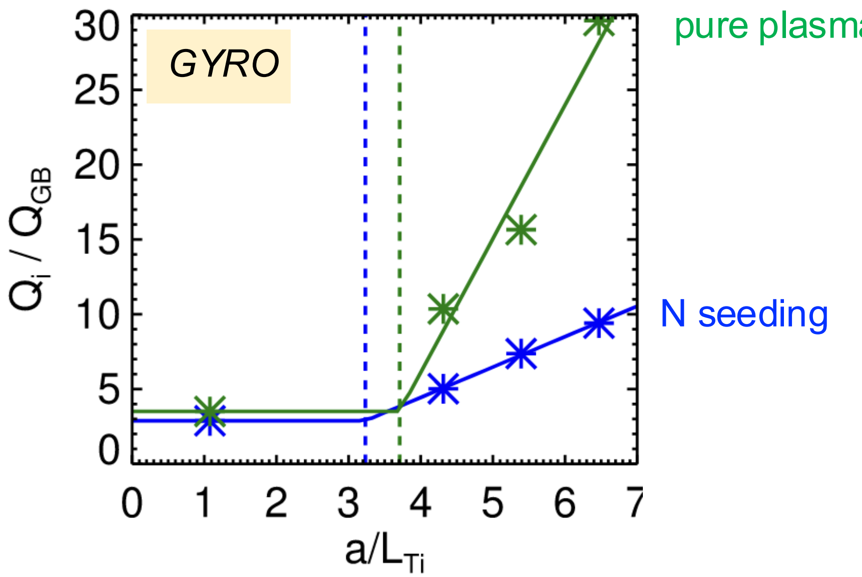
Impurity content scans show beneficial effects of higher Z_{eff}

- Increasing the low-Z impurity content from nominal assumptions ($f_{DT} = 0.85, Z_{eff} = 1.5$) leads to **more fusion power even with less DT ions**.
- Observed in some experiments and past simulation work → Turbulence stabilization by main ion dilution.

G. McKee PRL 2000 [DIII-D]

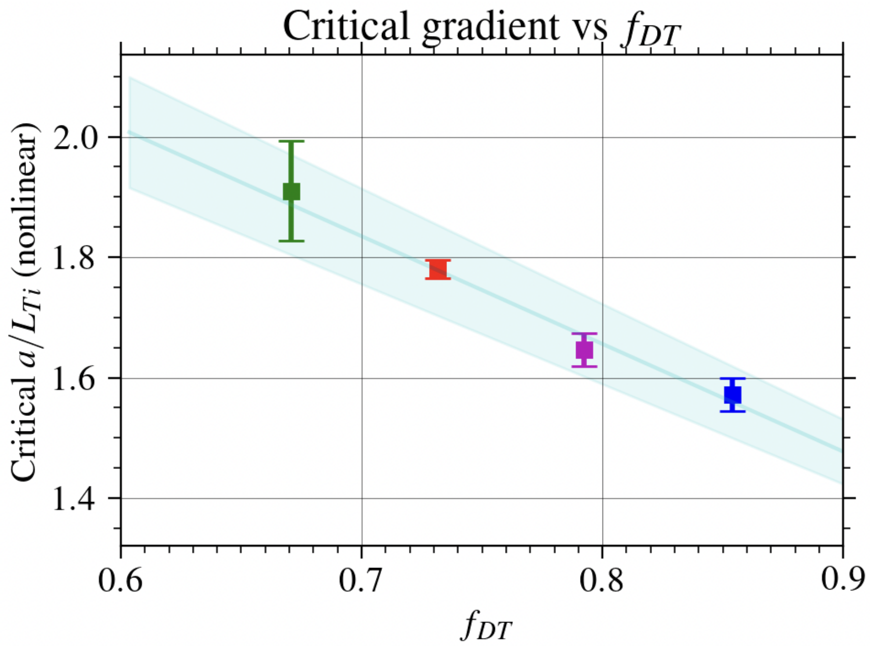


P. Ennever PoP 2015 [Alcator C-Mod]

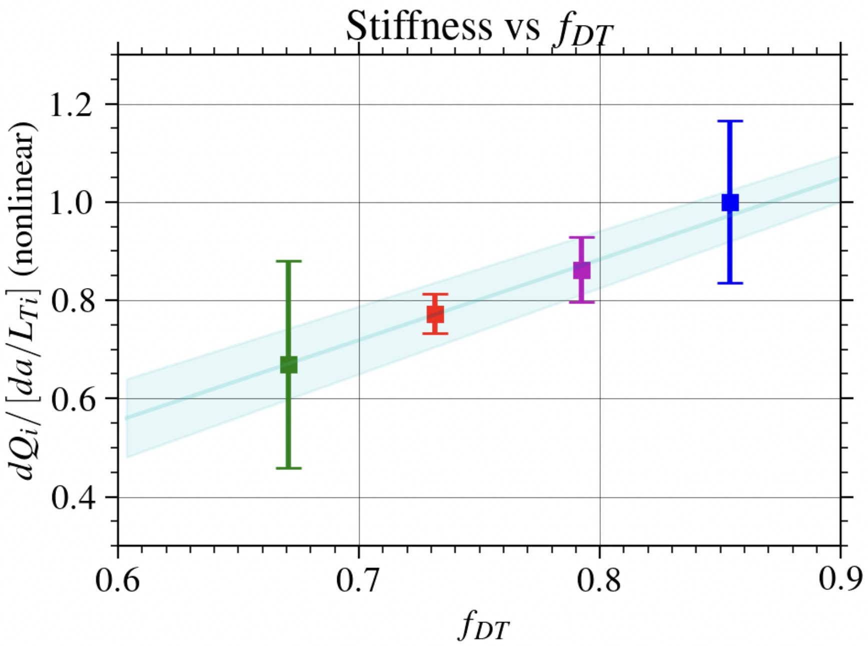


CGYRO standalone scans show increase critical gradient

- Scans of a/L_{Ti} with nonlinear CGYRO at the different impurity choices reveal **shift in critical gradient** and reduction in stiffness (example at $r/a = 0.55$).

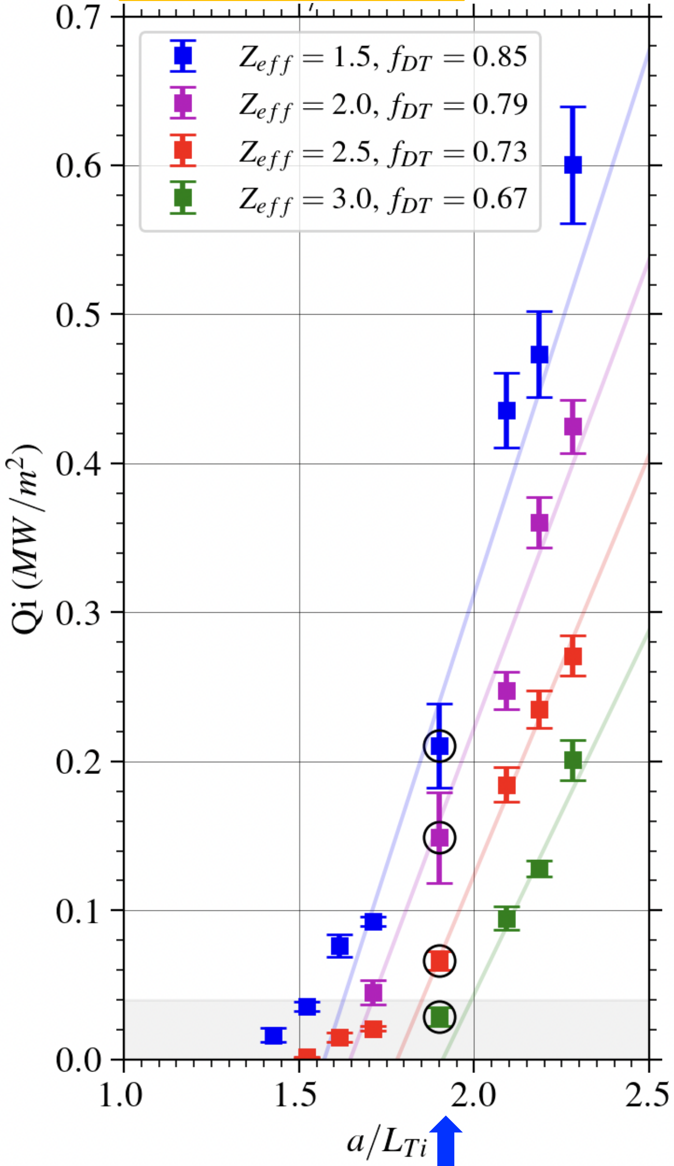


ITG **critical gradient** increases with more diluted DT ✓



Transport stiffness decreases with more diluted DT ✓

Nonlinear CGYRO

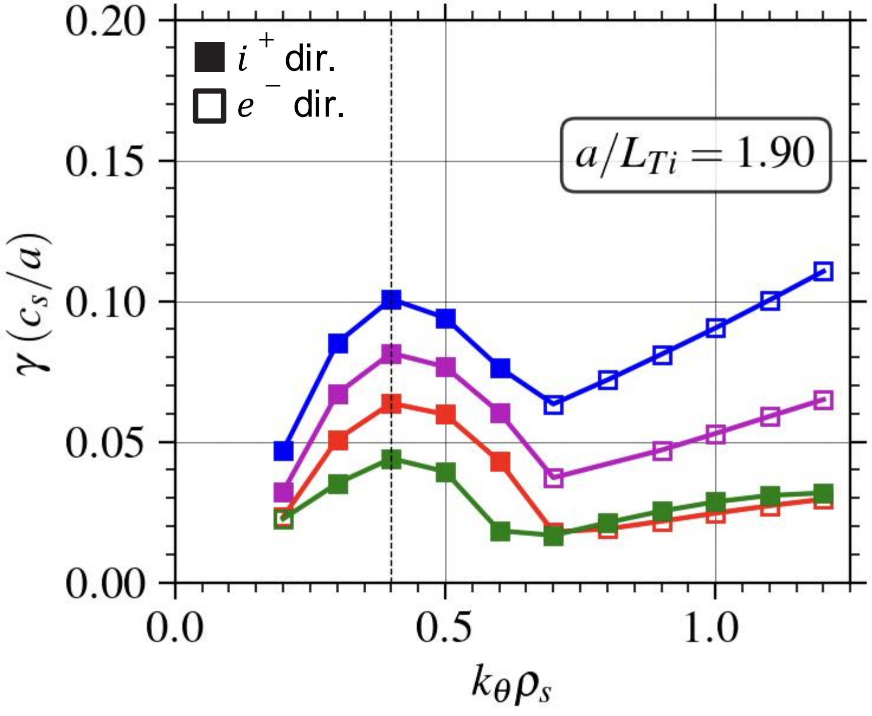


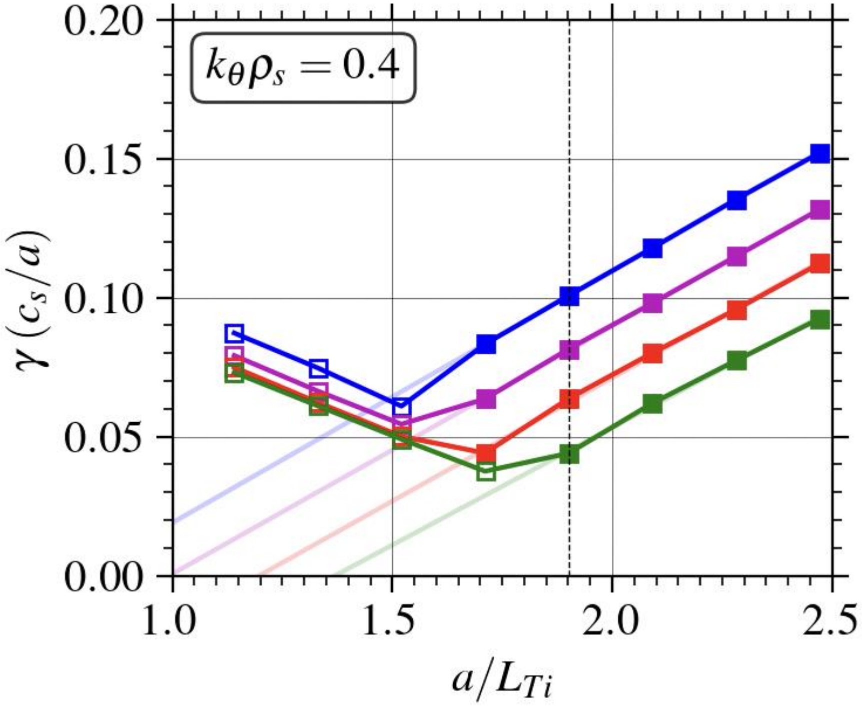
Flux-matched a/L_{Ti} ○

CGYRO standalone scans show increase critical gradient

- Scans of a/L_{Ti} with nonlinear CGYRO at the different impurity choices reveal **shift in critical gradient** and reduction in stiffness (example at $r/a = 0.55$).
- Consistent with **reduction in linear growth rates** of ITG.

Linear CGYRO





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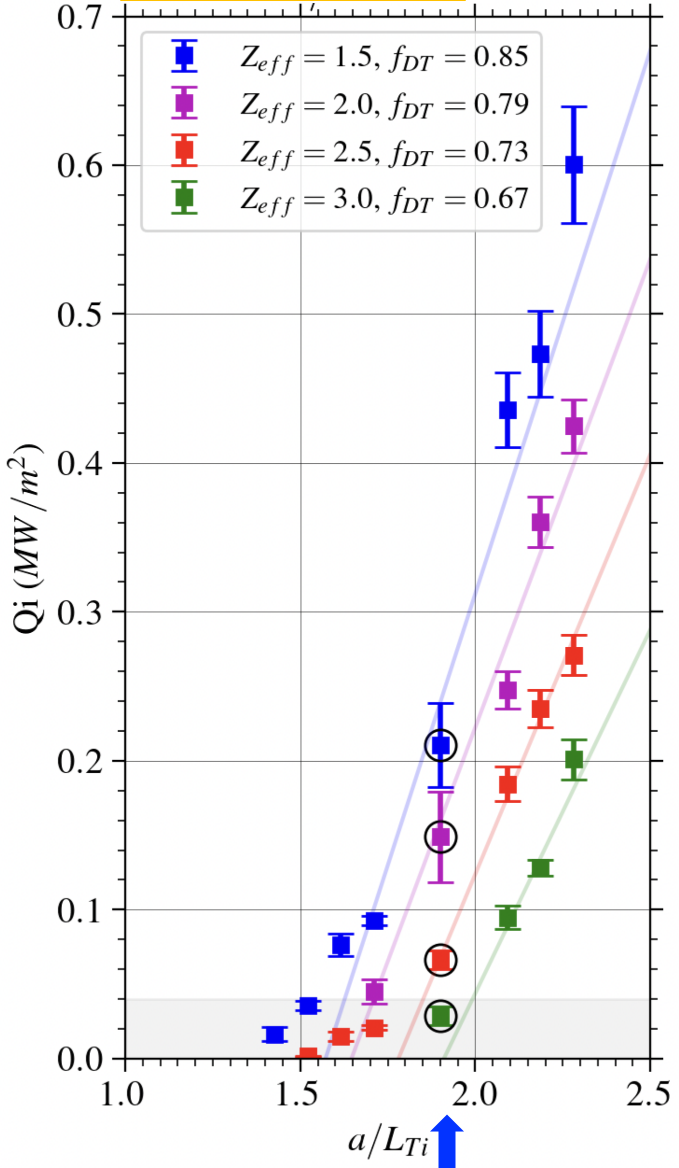

Flux-matched a/L_{Ti}

Increasing Z_{eff} or f_{DT} alone is not enough for turbulence stabilization

- Simulations so far scanned mix by increasing low-Z ($f_{Z=9} = 0.005$) impurity, resulting in $[Z, f_Z]$ **moving together** when lumping He3 & W.

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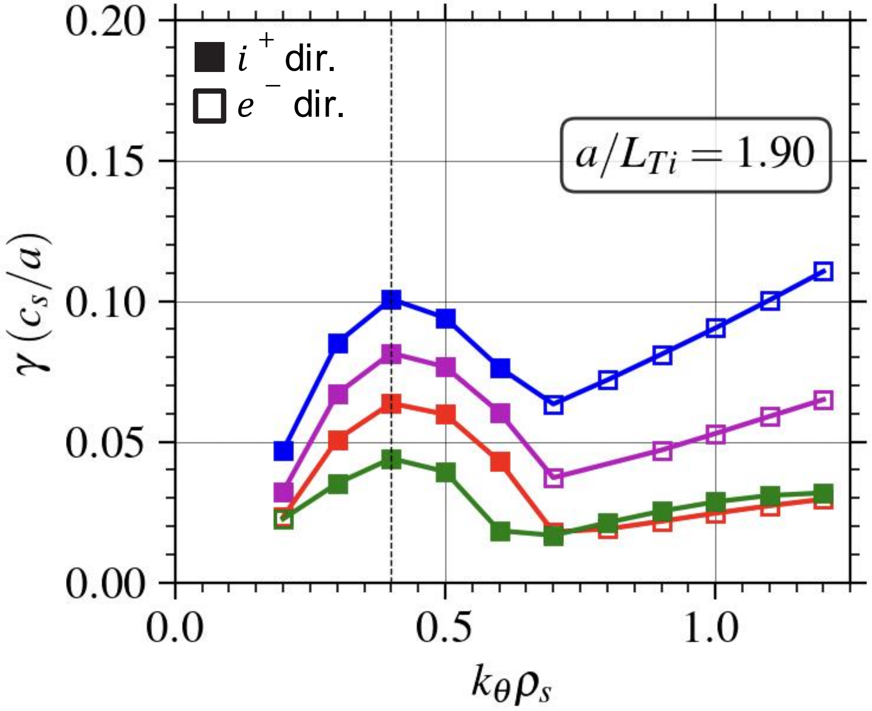

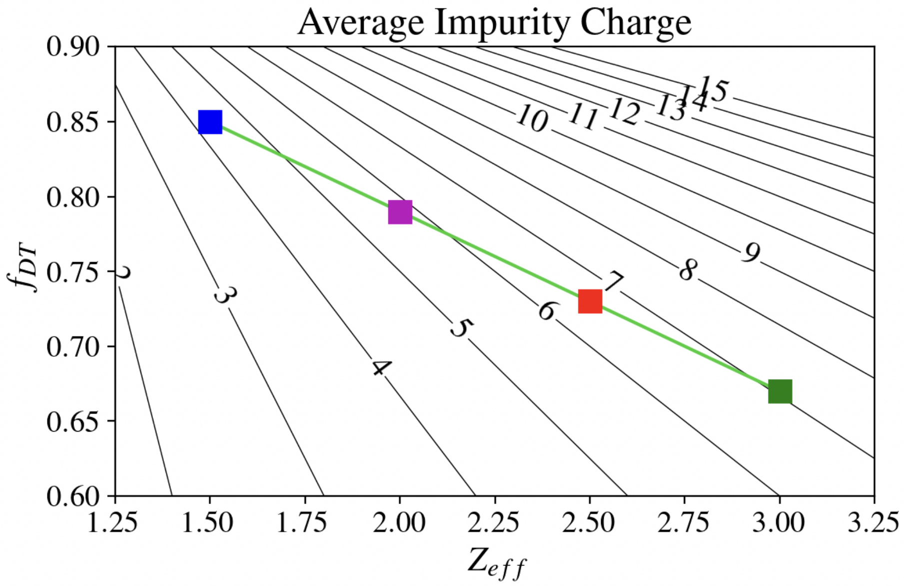

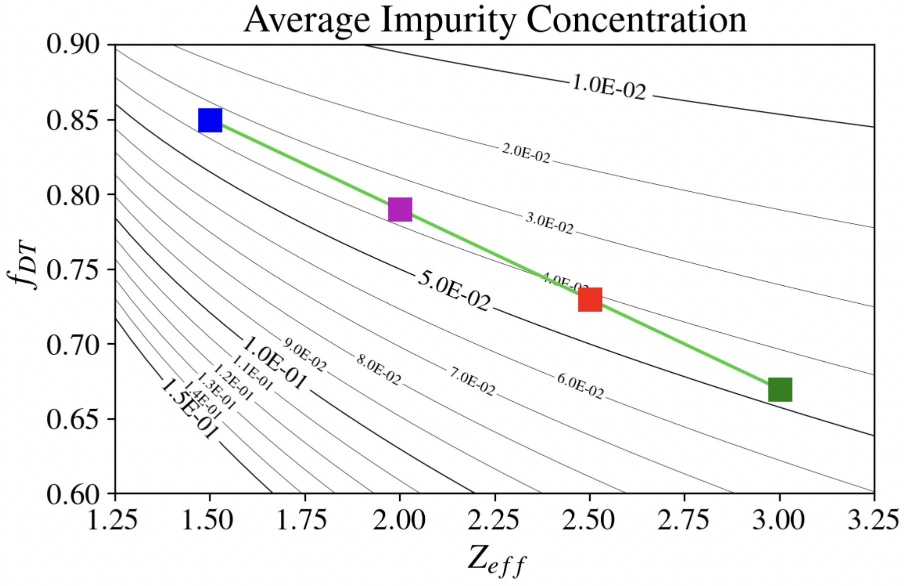

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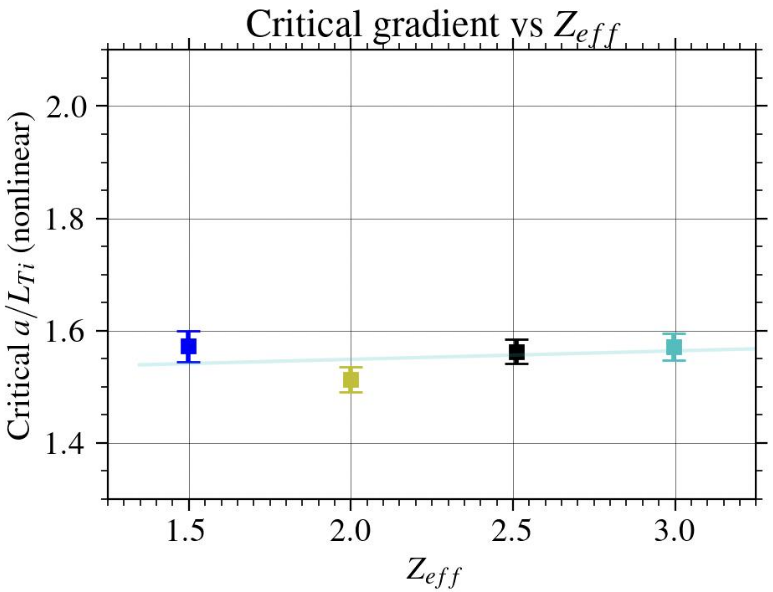

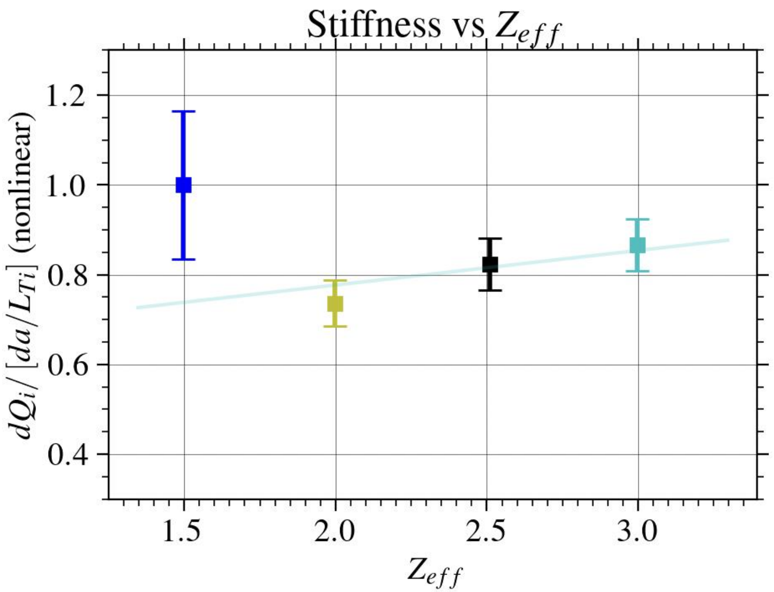

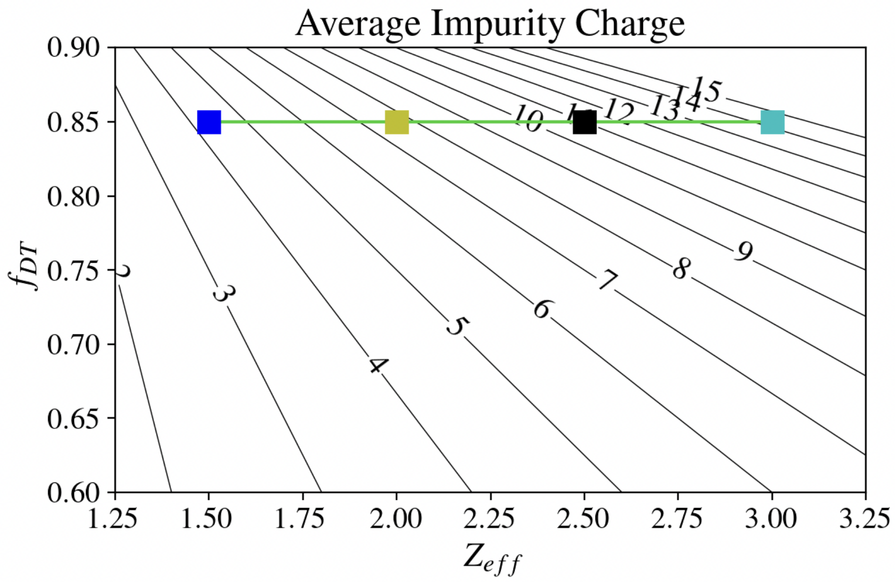

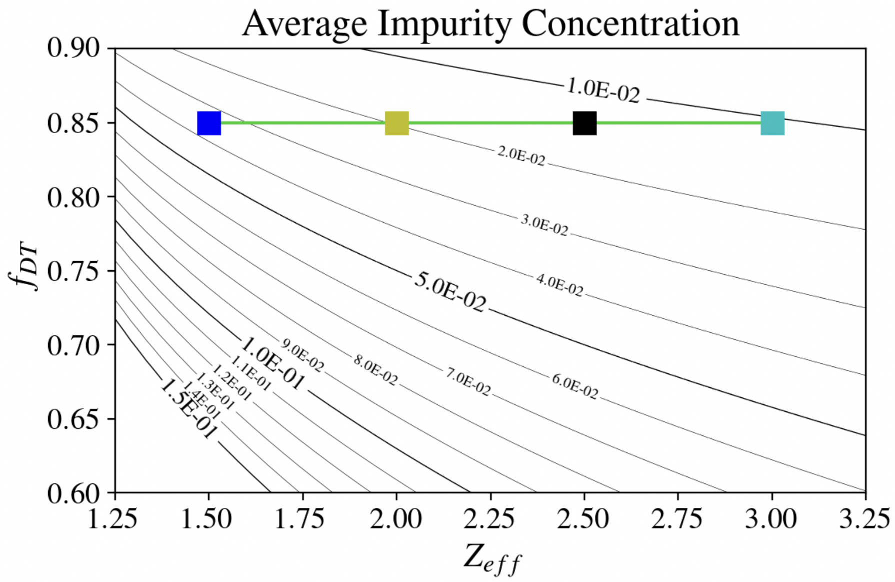

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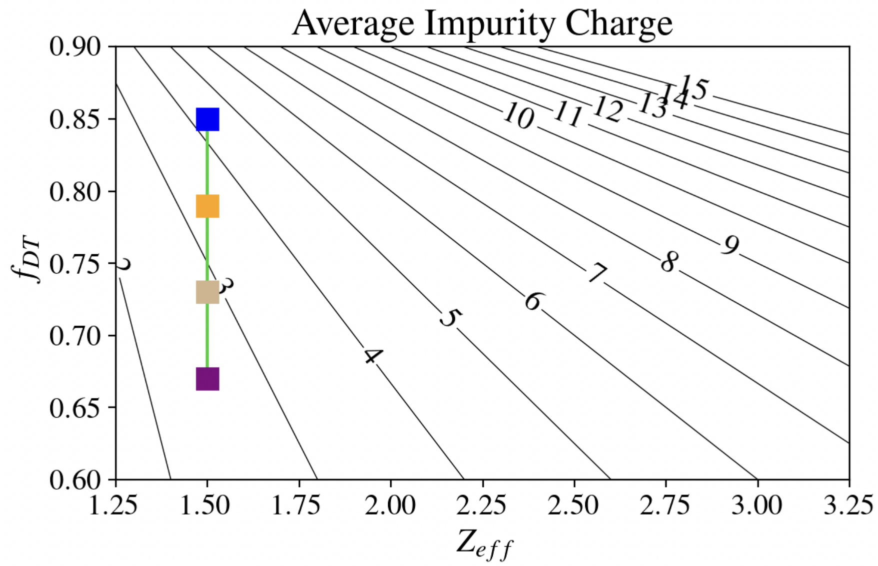
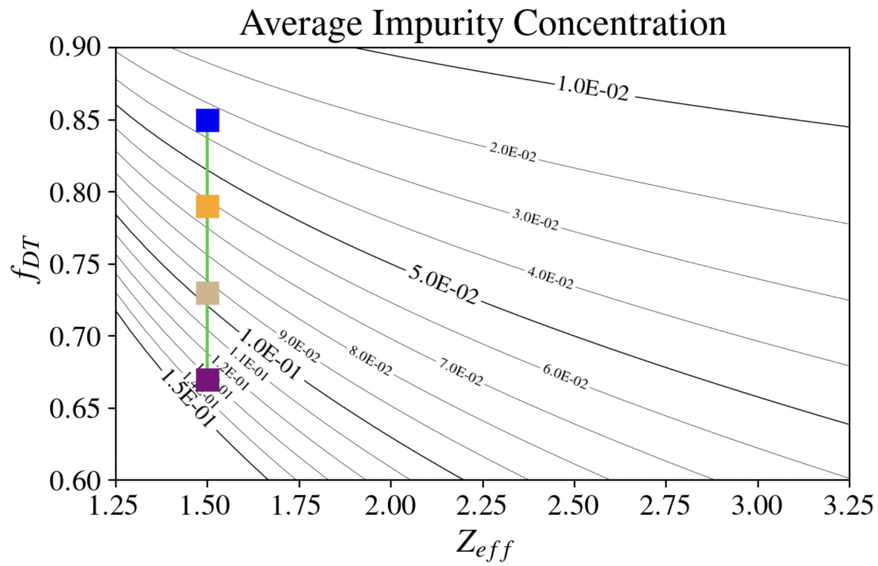
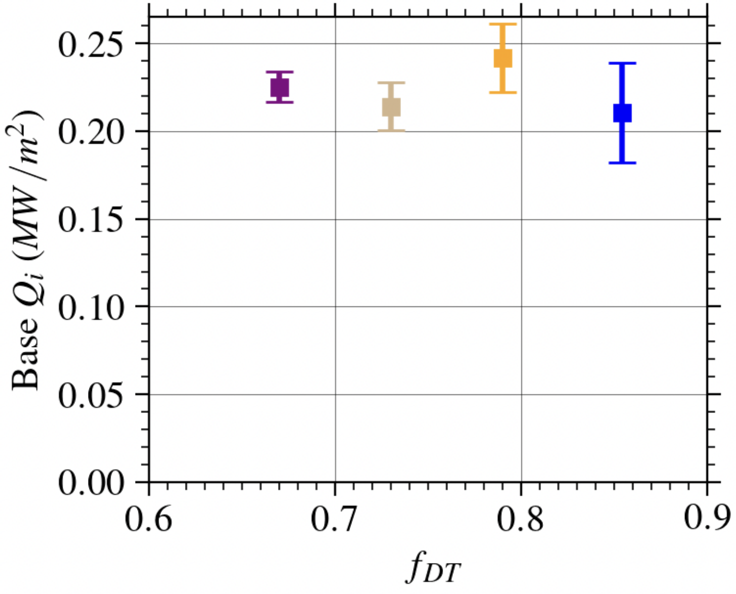
- If Z_{eff} constant → **weak effect of decreasing f_{DT}** (via low-Z impurity).





Nonlinear CGYRO



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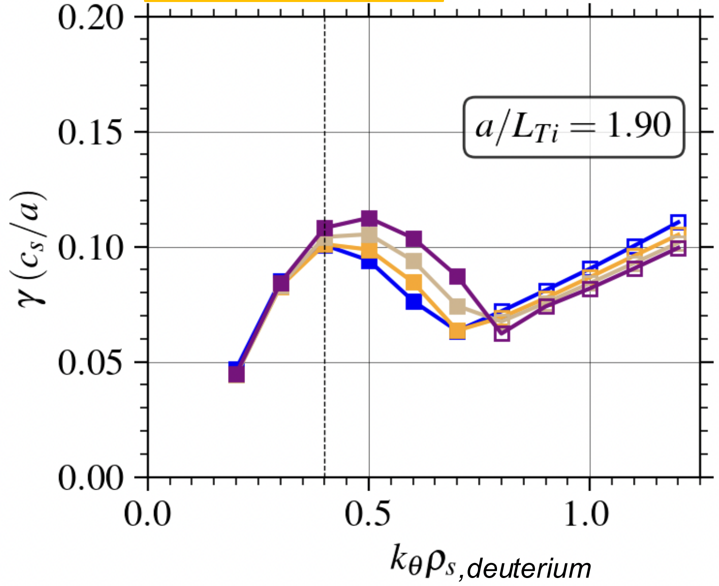
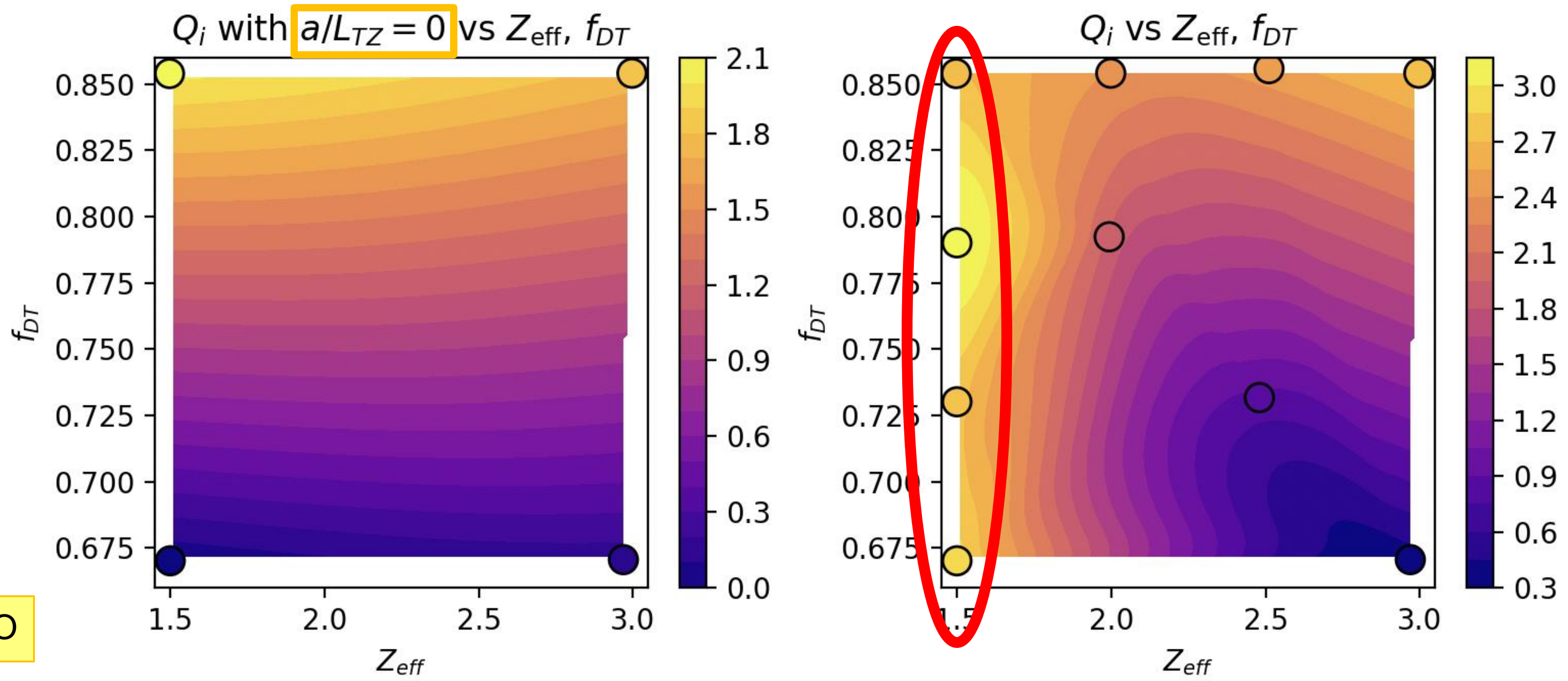


Increasing Z_{eff} or f_{DT} alone is not enough for turbulence stabilization

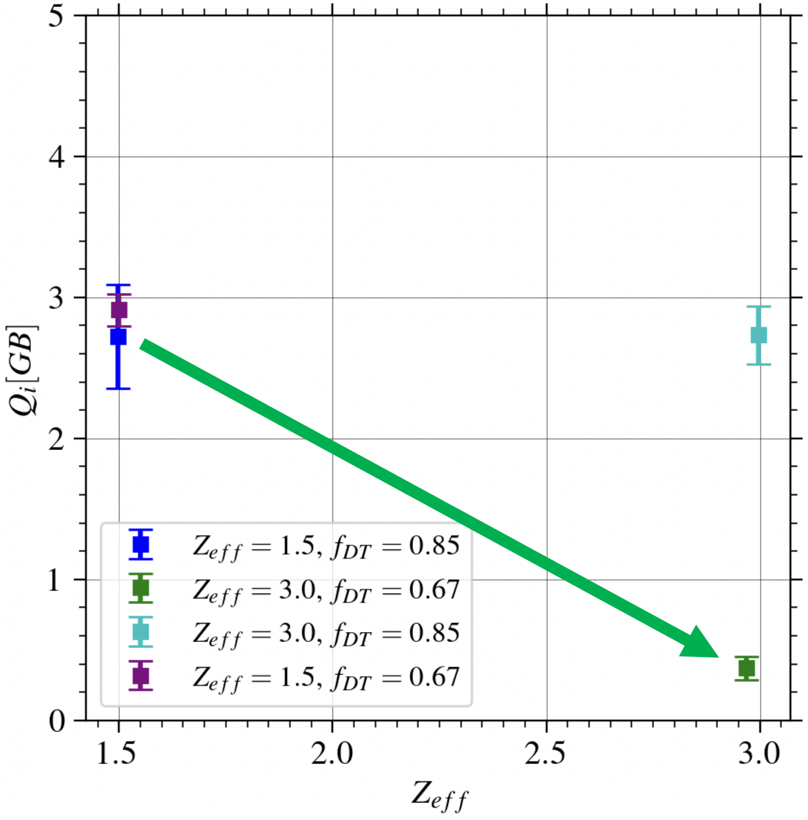
- Simulations so far scanned mix by increasing low-Z ($f_{Z=9} = 0.005$) impurity, resulting in $[Z, f_Z]$ **moving together** when lumping He3 & W.
- If f_{DT} constant → **weak effect of increasing Z_{eff}** (via high-Z impurity).
- If Z_{eff} constant → **weak effect of decreasing f_{DT}** (via low-Z impurity).
  - ➢ Only when $\boldsymbol{a/L_{TZ} = 0}$, turbulence is stabilized at lower f_{DT}.

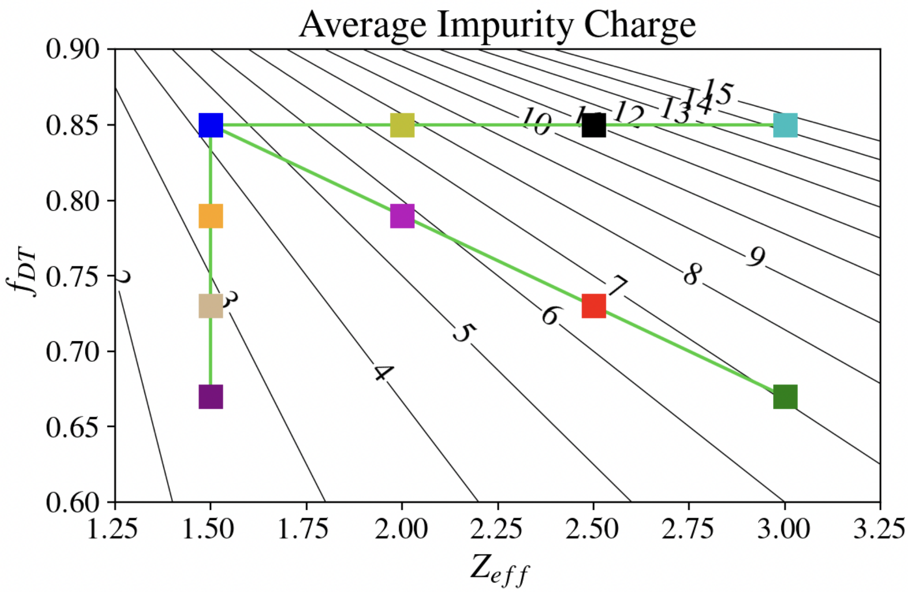


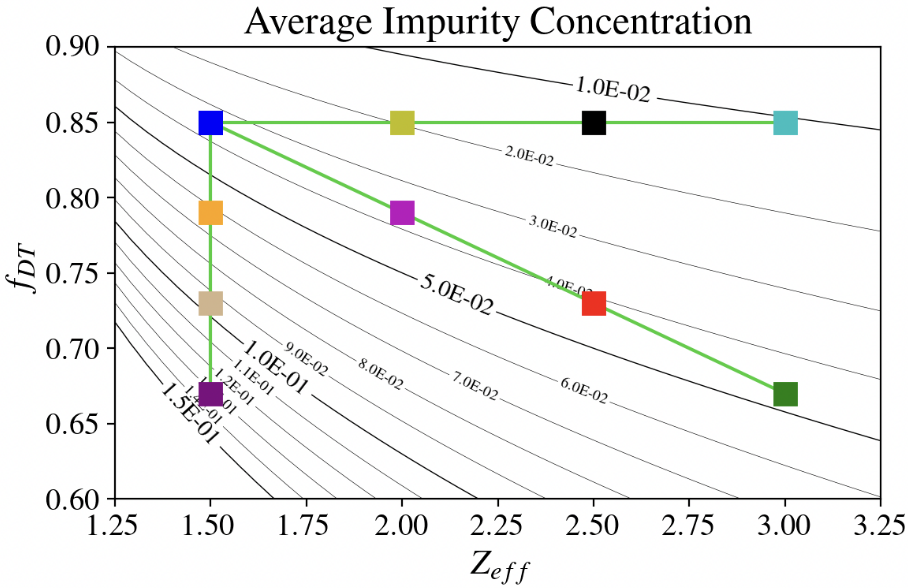
Nonlinear CGYRO

Careful choice of impurity mix can result in higher performance

- The **trajectory in $f_{DT} - Z_{eff}$** is critical to enhance performance.

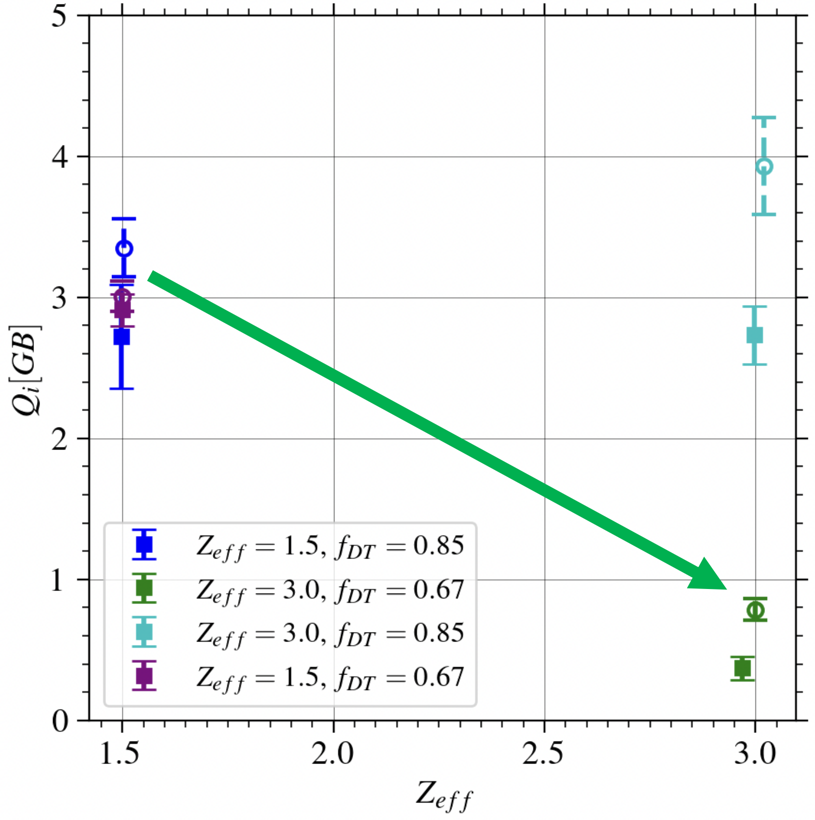






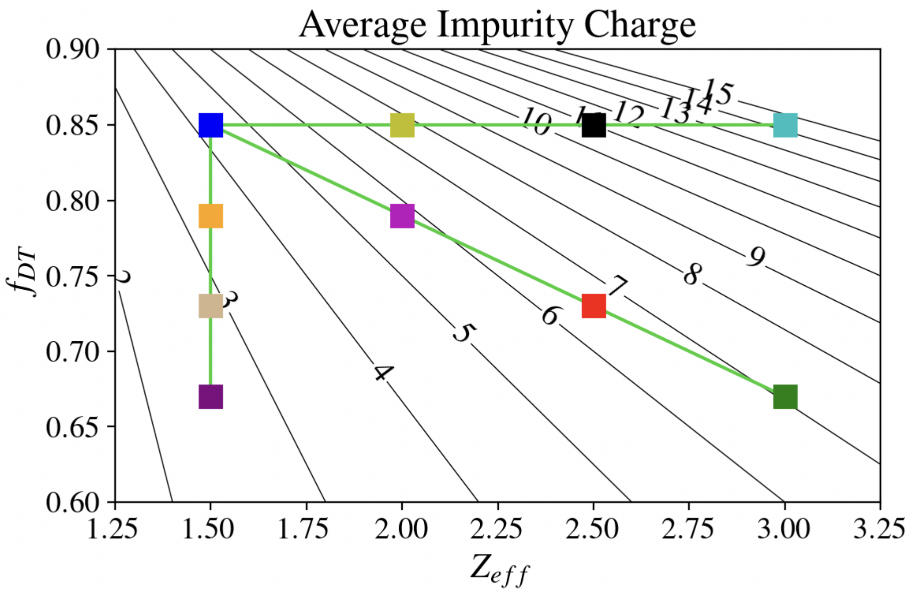
Careful choice of impurity mix can result in higher performance

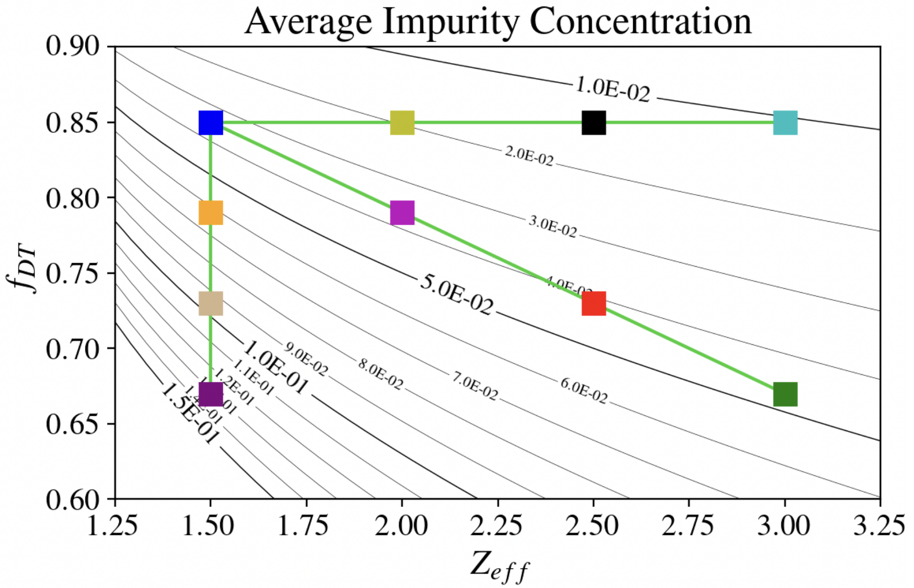
- The **trajectory in $f_{DT} - Z_{eff}$** is critical to enhance performance.
- **Lumping of impurities** has a weak effect on stabilization results.
  - Quantitative differences at high Z_{eff} for base case, but qualitative picture holds



4 gyrokinetic species: e^-, D, T, Z_{lump}

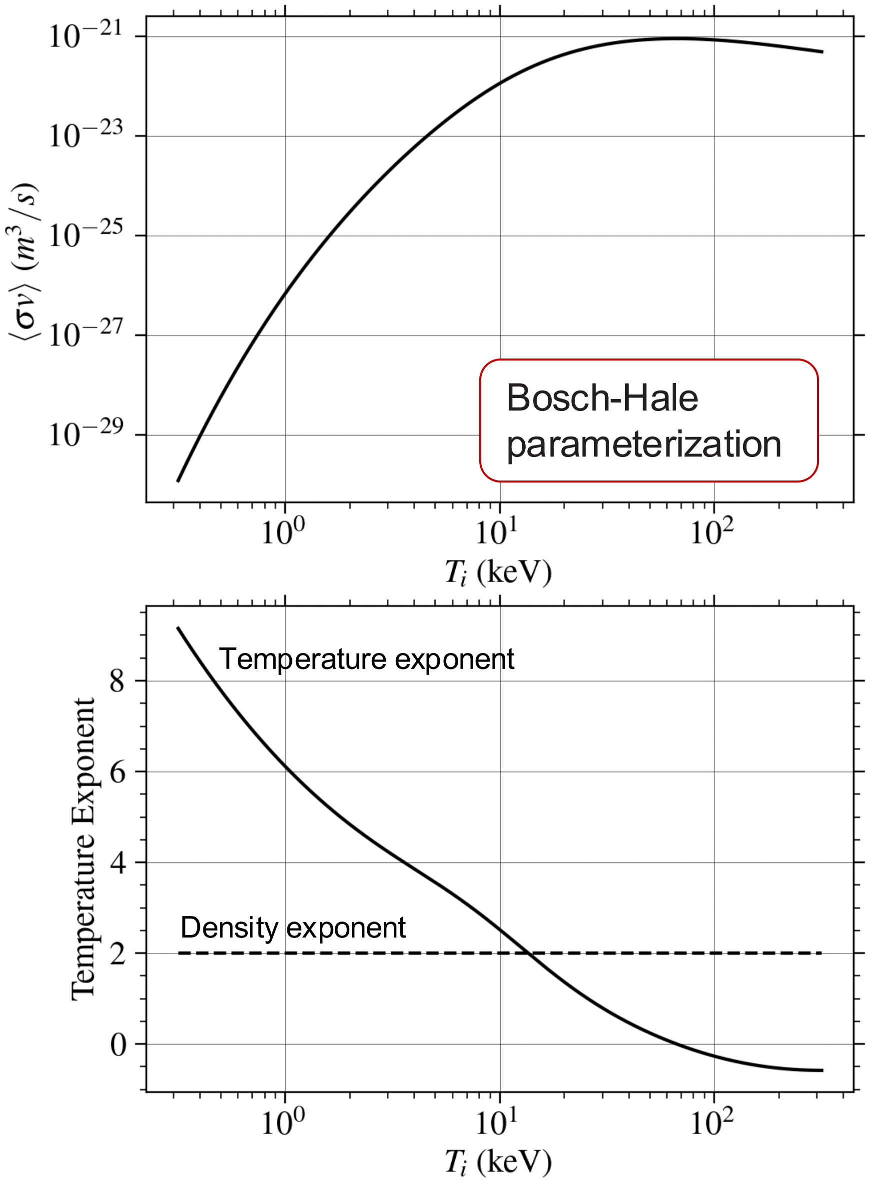
6 gyrokinetic species: $e^-, D, T, W, He3, Z_{low}$





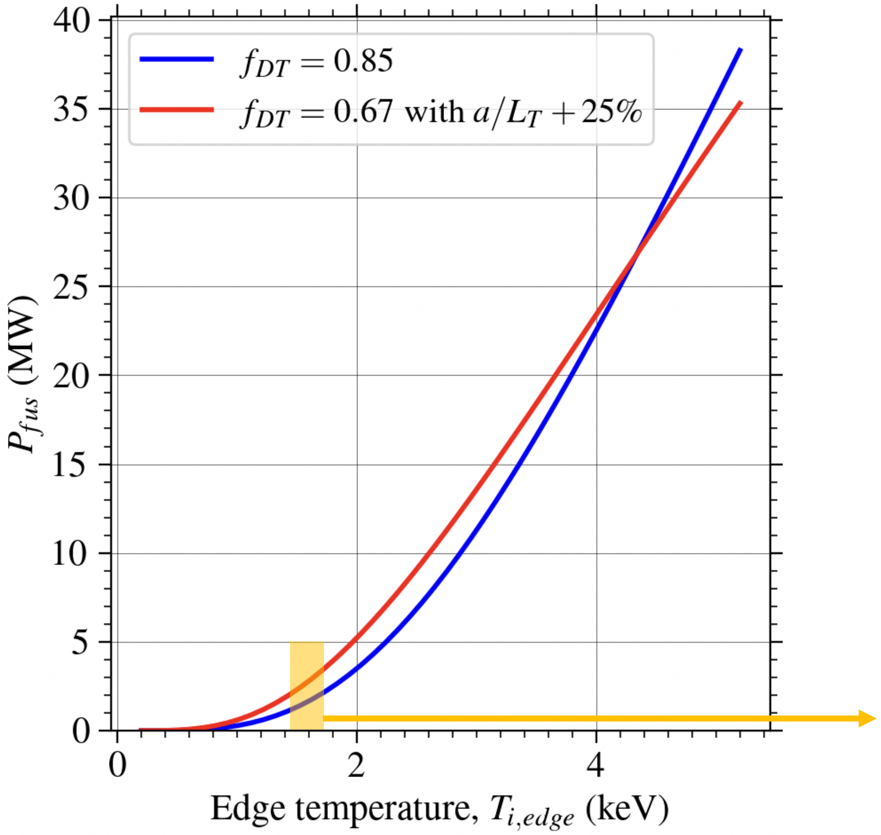
Effect expected to be important at low temperatures

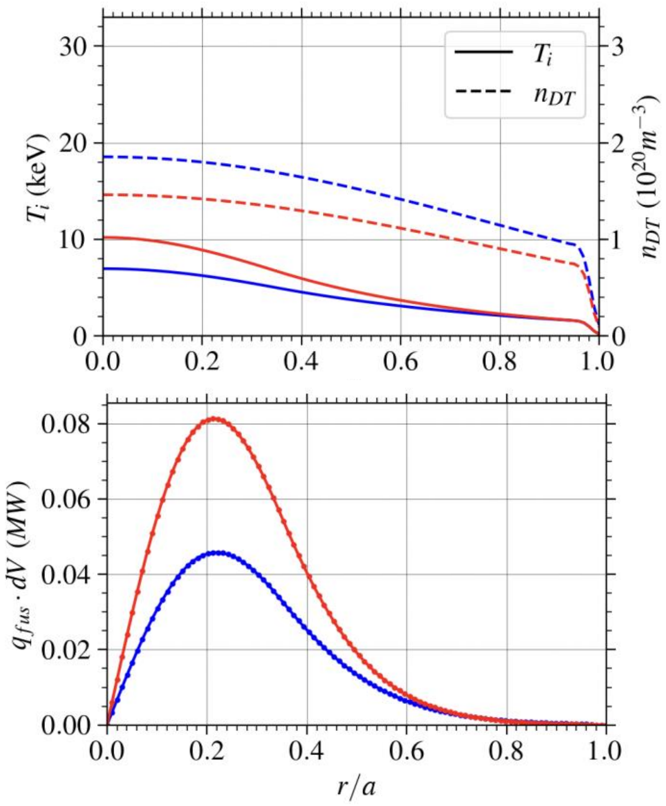
- Fusion reaction rate coefficient has a stronger temperature exponent below 10 keV.

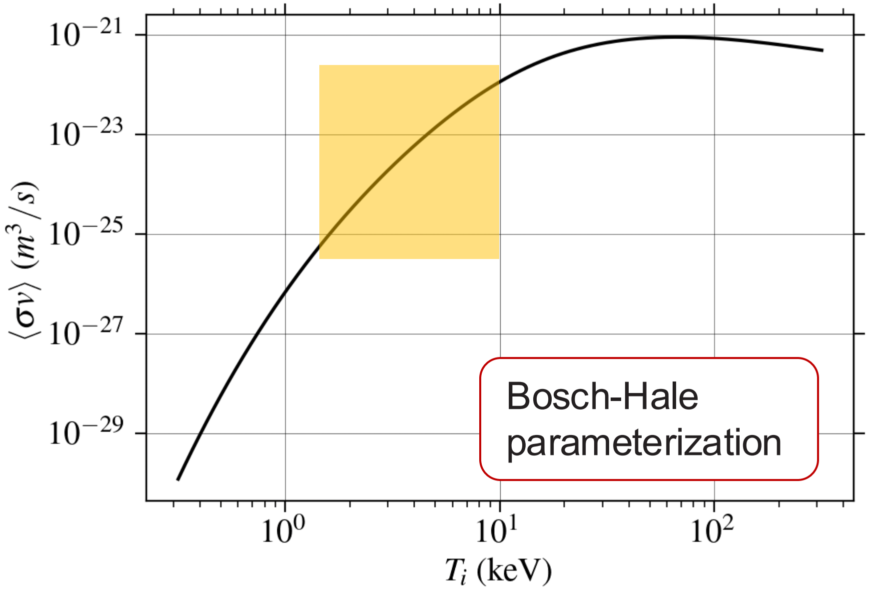


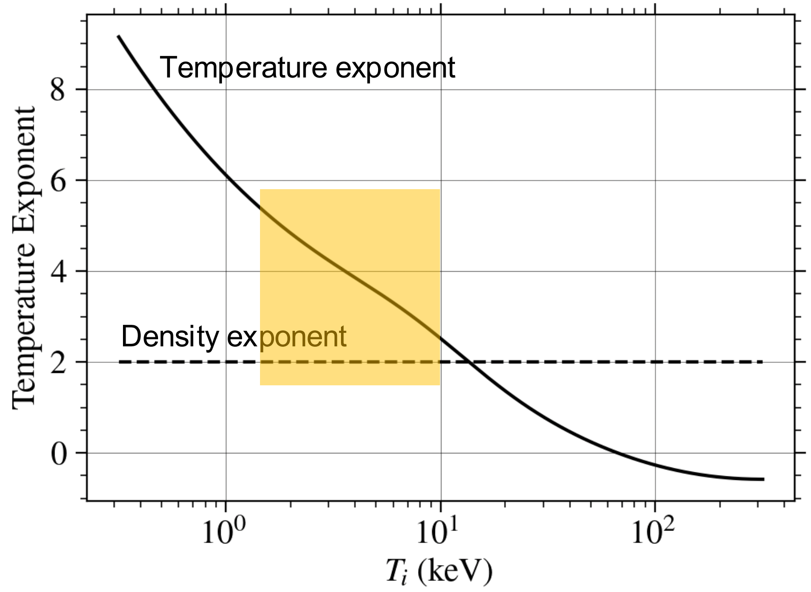
Effect expected to be important at low temperatures

- Fusion reaction rate coefficient has a stronger temperature exponent below 10 keV.
- Effect **higher $a/L_T|_{crit}$** with the trade off of **lower n_{DT}** (at same $\langle n_e \rangle$) may only be beneficial at low temperatures.



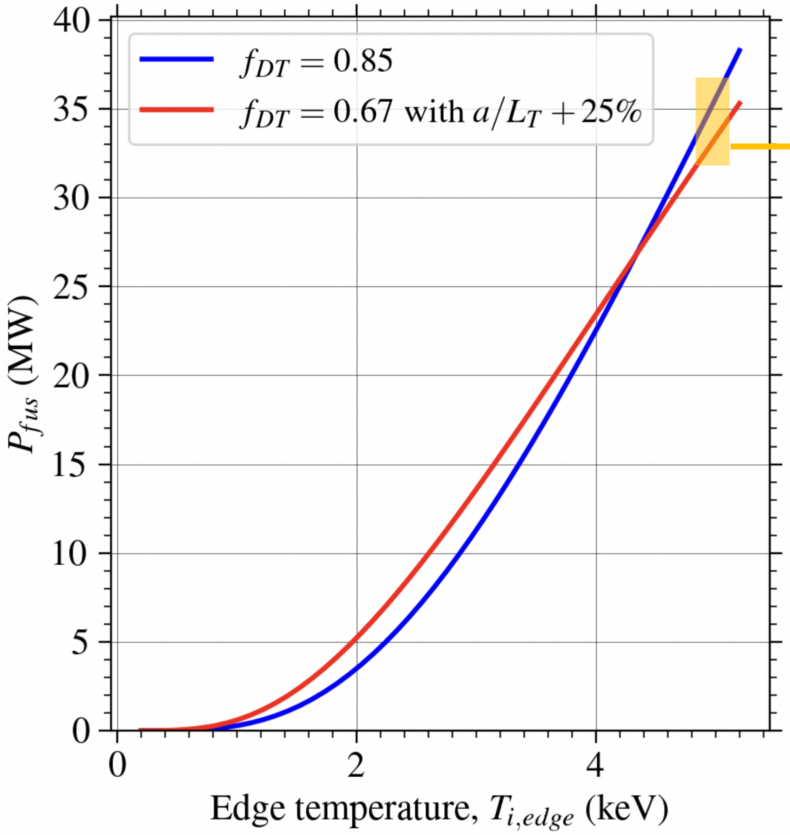


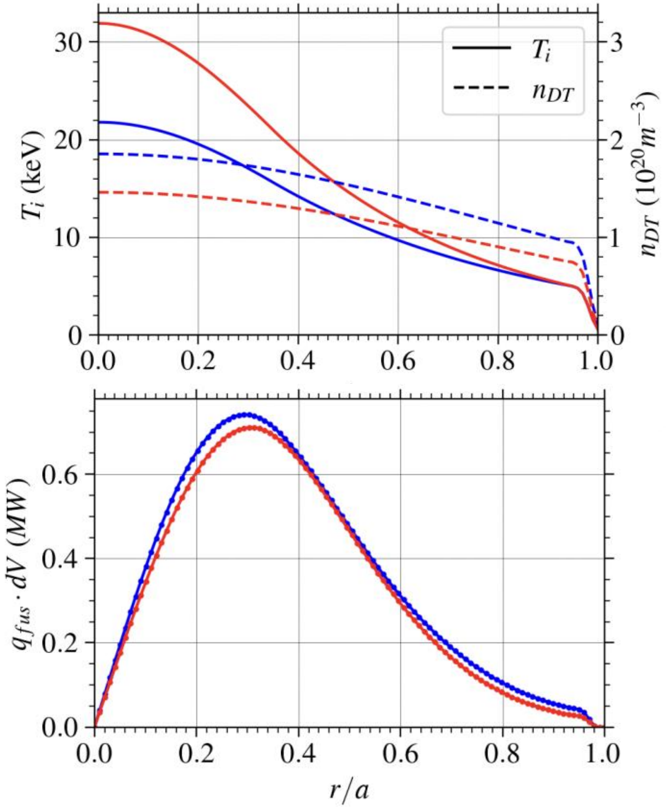


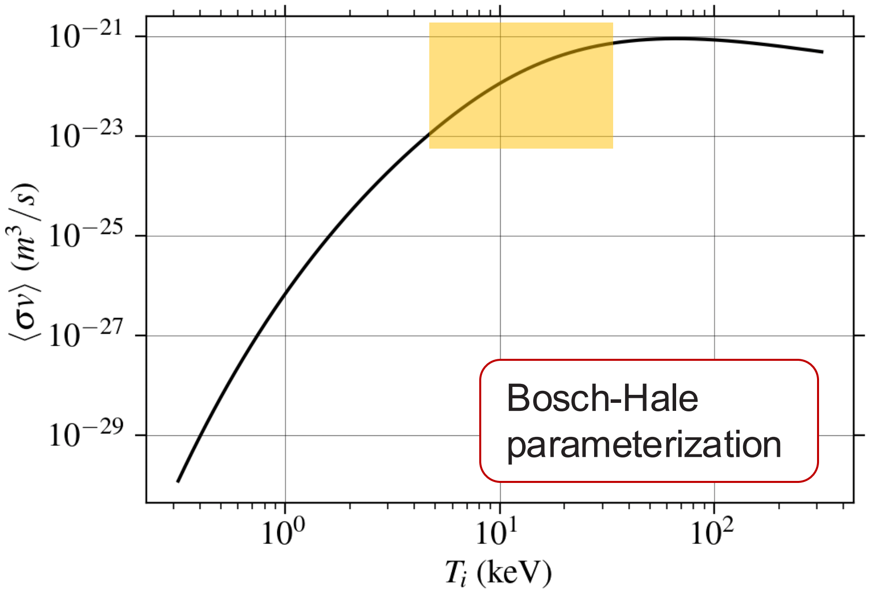


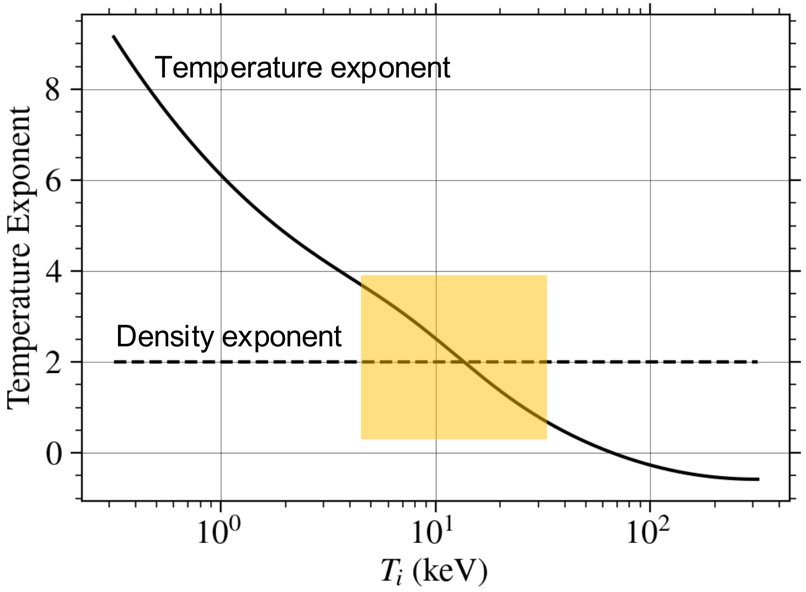
Effect expected to be weaker in reactor-like, high-temperature plasmas

- Fusion reaction rate coefficient has a stronger temperature exponent below 10 keV.
- Effect **higher $a/L_T|_{crit}$** with the trade off of **lower n_{DT}** (at same $\langle n_e \rangle$) may only be beneficial at low temperatures.



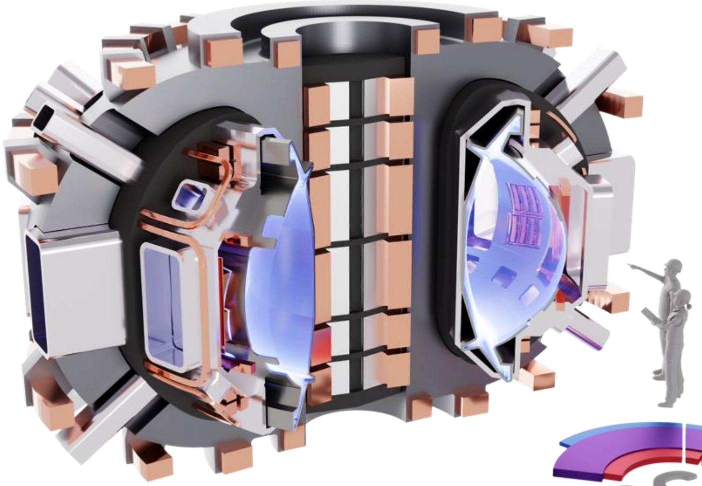






Conclusions and future work

- **PORTALS-CGYRO** is now a tool that can be used to investigate core plasma physics at high turbulence fidelity.
- Core **dilution stabilization** of ITG can be an attractive mechanism to increase performance towards $Q > 1$ with an L-mode like edge.
- Experimental planning & reactor design activities can benefit from **physics-based modeling** if applied early on.
- Not discussed but important:
  - **Edge** may also be affected by impurities (e.g., Z_{eff} effect on PB)
  - Line **radiation** from impurity mix may change the trade-off: Lower Q .
  - **Operational** considerations: pulse length at high Z_{eff}, capabilities for puff impurity mixes, compatibility with edge/divertor solutions.



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Some relevant presentations on impurity effects from group members:

M. Muraca, JO04.6 (next talk) → Impurity transport in SPARC
A. Saltzman, NP13.148 → Impurity + shaping optimization in ARC