ISOTOPE MIX EFFECT ON EDGE TURBULENT TRANSPORT IN PRE-L-H TRANSITION CONDITIONS IN JET-ILW

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CONTEXT – JET-ILW EXPERIMENTAL DATA

- L-mode pre-LH transition with **ICRH heating only**
- Low impurity content: **no ion/rotation measurements**
- 6 Pulses with similar profiles and magnetic configuration (Favourable x-point)
- $B = 1.8$ T | $I_P = 1.65$ MA | $q_{95} = 3.65$

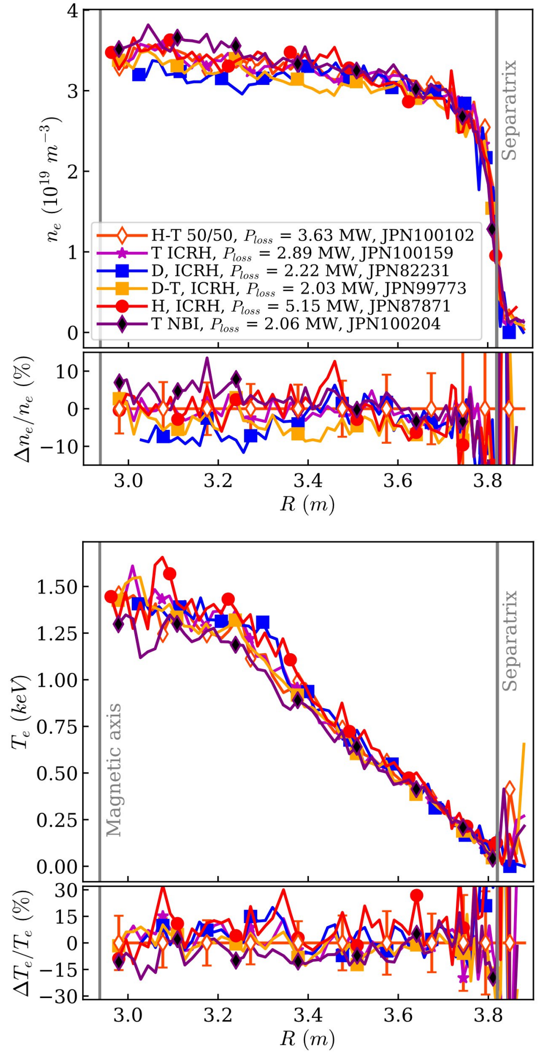
$$P_{loss} - P_{rad} = P_{sep} \xrightarrow{\text{at } t_{LH}} P_{LH}$$

Pulse #	Species	P_{LH} (MW)	P_{rad} (MW)	A_{eff}
87871	H	4.55	0.75	1.01
82231	D	1.81	0.52	2
100102	53% H + 47% T	2.97	0.85	1.96
100102	26% H + 74% T	2.42	0.69	2.5
99773	49% D + 51% T	1.66	0.57	2.5
100159	T	1.68	1.22	2.92

Isotope effect

$$P_{LH} \propto 1/A_{eff}$$

$$P_{LH}(H) > P_{LH}(D) > P_{LH}(T)$$



[Birkenmeier et al. *PPCF*, 2023]

CONTEXT – ISOTOPE EFFECT

- **Isotope effect in pure plasma explained by passing electron dynamics** [Bonanomi et al. *PoP*, 2021]
- In JET-ILW is observed

$$P_{LH} \propto \chi_{eff}$$

- Transport is observed to be higher in lower isotope mass plasmas !
- Identical profiles but higher input power leads to **stronger heat fluxes (turbulent)**

Pulse #	Species	P_{LH} (MW)	P_{rad} (MW)	A_{eff}
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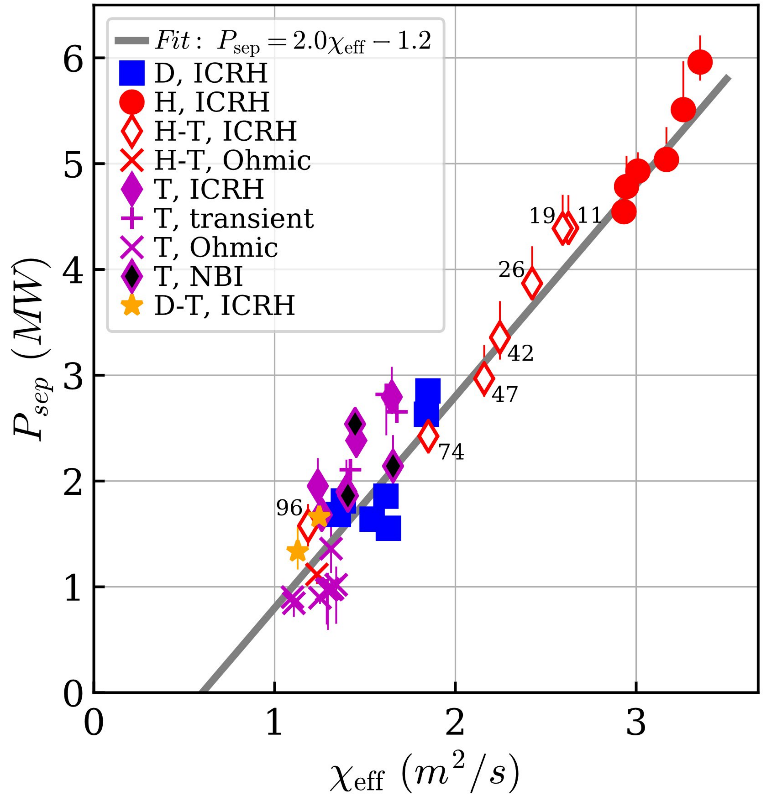
Isotope effect

$$P_{LH} \propto 1/A_{eff}$$

$$P_{LH}(H) > P_{LH}(D) > P_{LH}(T)$$

But at same A_{eff} …

$$P_{LH}(H+T) > P_{LH}(D)$$



[Birkenmeier et al. *PPCF*, 2023]

APPROACH OF THIS STUDY

Models - TGLF/GENE

$Q_{turb}(\rho_{tor})$

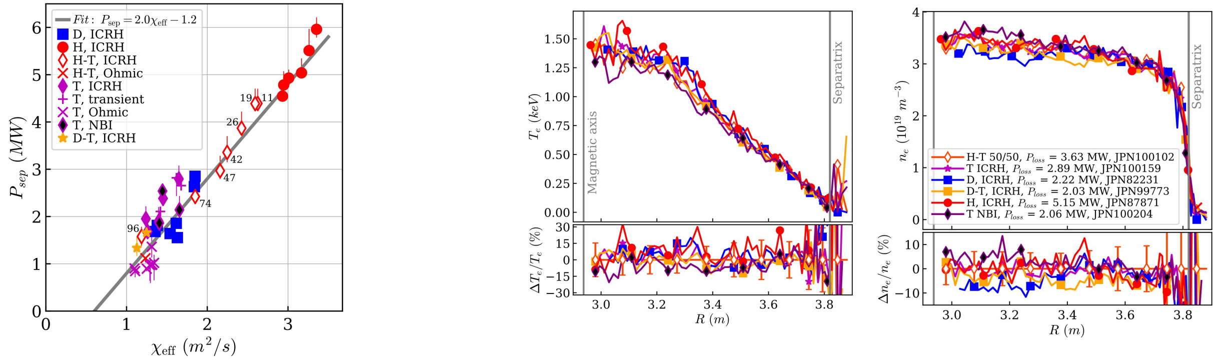
Main hypothesis

$P_{LH} \propto \chi_{eff}$

$\chi_{eff} \propto Q_{tot}$

+

Experimental measurements



[Birkenmeier et al. *PPCF*, 2023]

$Q_{turb}(\rho_{tor}) \propto P_{LH}$

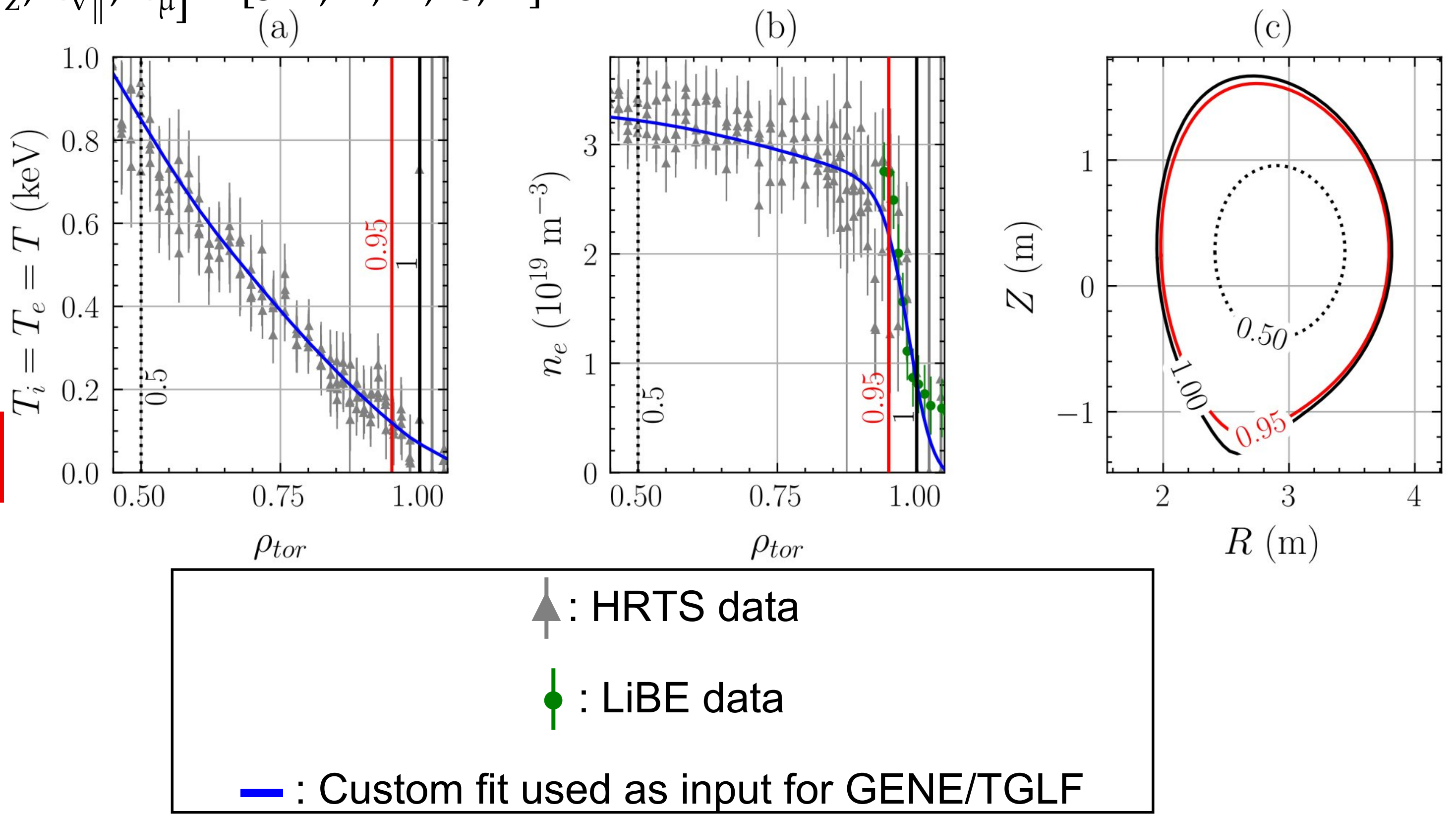
? $Q^{H}_{turb} > Q^{H+T}_{turb} > Q^{D}_{turb} > Q^{D+T}_{turb} > Q^{T}_{turb}$?

SIMULATIONS SETUP

- **GENE flux-tube** used at $\rho_{tor} = 0.95$
- Field-aligned coordinates $[x, y, z, v_{\parallel}, \mu]$ with **Sugama collision operator w/ FLR effects**
- All simulations ran with the same reference values (see below) with $\mathbf{m_{ref}} = \mathbf{m_D} = \mathbf{2}$
- Non-linear simulation resolution set as $[N_x, N_y, N_z, N_{v_\parallel}, N_\mu] = [512,72,72,48,12]$
- $[L_x, L_y] = [248,314]\ \rho_{c,D}$

(c) Flux surfaces taken from EQDSK file – equilibrium reconstruction

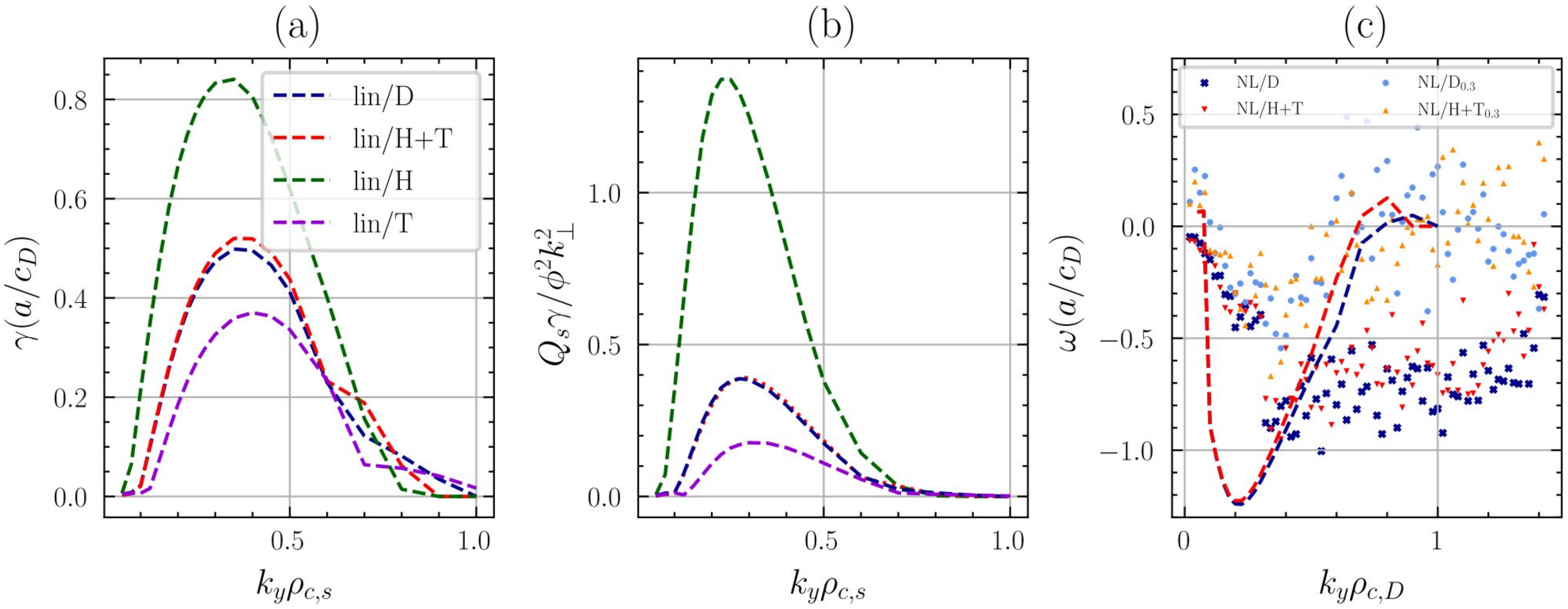
$\nu_e^\star$	6.12	R/L_n	36.29
$\hat{\nu}_{ei}$	12.89	R/L_T	40.6
β_e	3.29×10^{-4}	n_e	$2.07 \times 10^{19}\ m^3$
$s/\hat{q}$	3.63/3.65	$\mathbf{T_i \equiv T_e = T}$	**0.119 keV**
T_i/T_e	1	B_{tor}^{axis}	1.91 T
$\rho_{c,D}$	0.827 mm	$\rho^\star \equiv \rho_{c,D}/L_T$	$\sim 1/87$



TURBULENCE NATURE – LINEAR SCANS

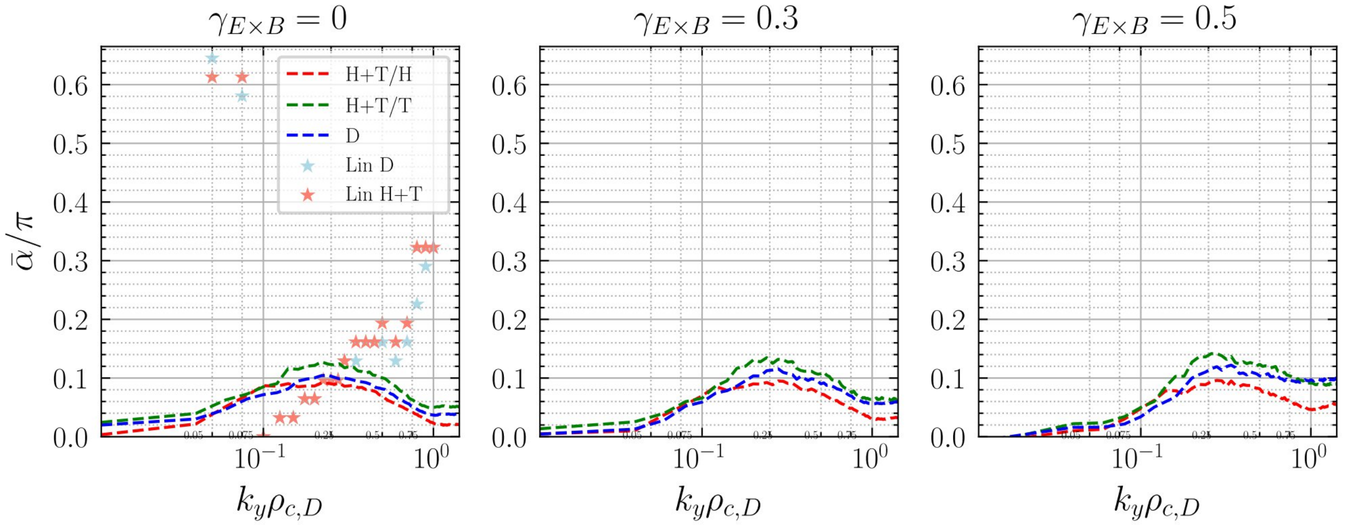
- Anti-gyroBohm scaling of γ and QL heat fluxes
- Negative frequencies, similar between linear and NL simulations

No differences between H+T and pure deuterium !!



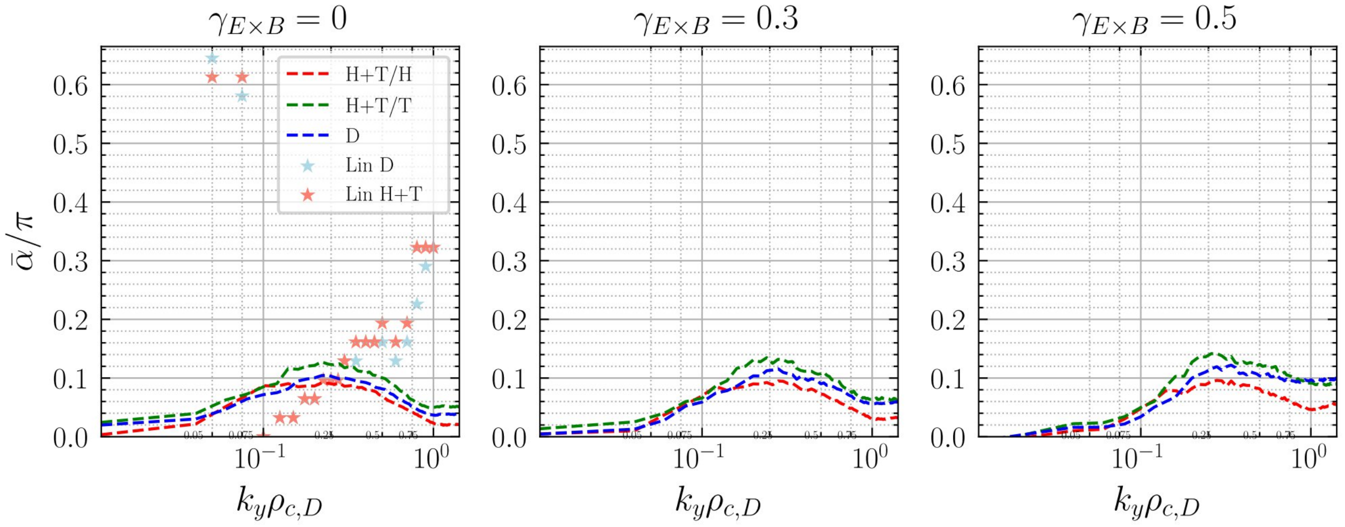
TURBULENCE NATURE – CROSS-PHASES

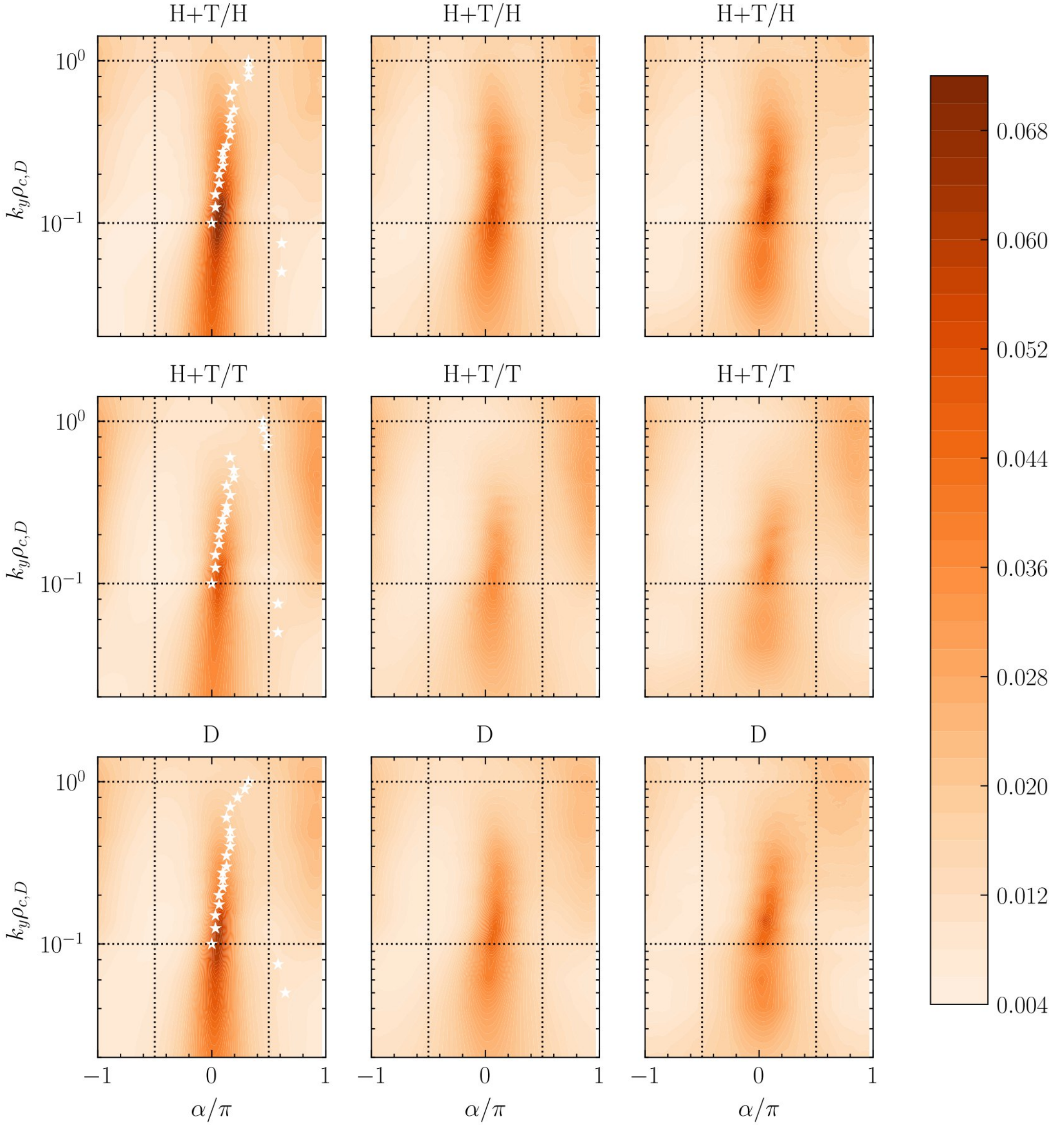
- Linear and non-linear simulations cross-phases : $\alpha(\phi \times T_\perp) \rightarrow 0$



TURBULENCE NATURE – CROSS-PHASES

- Linear and non-linear simulations cross-phases : $\alpha(\phi \times T_\perp) \rightarrow 0$
- $\alpha(\phi \times T_\perp) \rightarrow 0$ on all $k_y \rho_{c,D}$ range, broadening with $\gamma_{E\times B}$



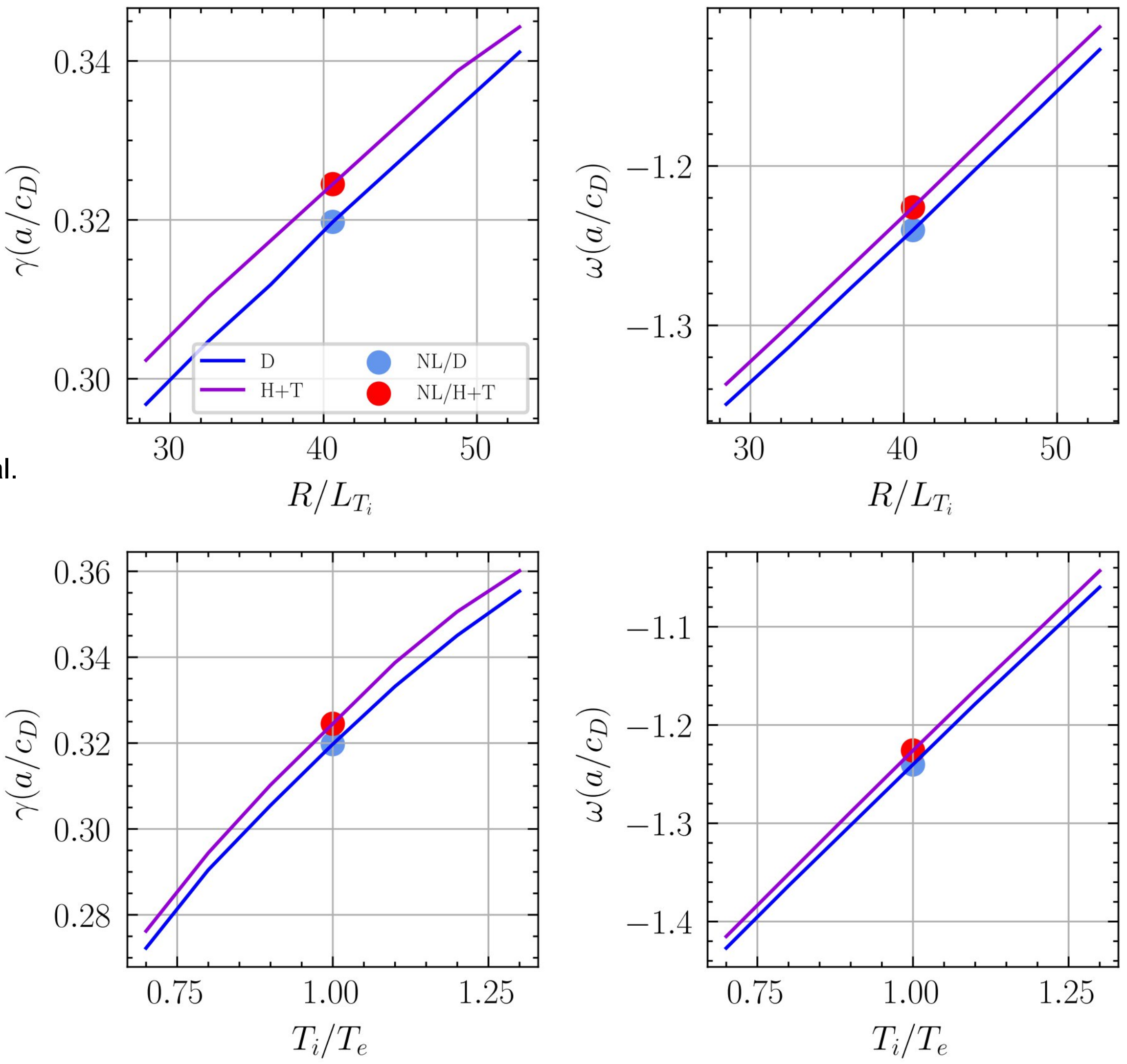


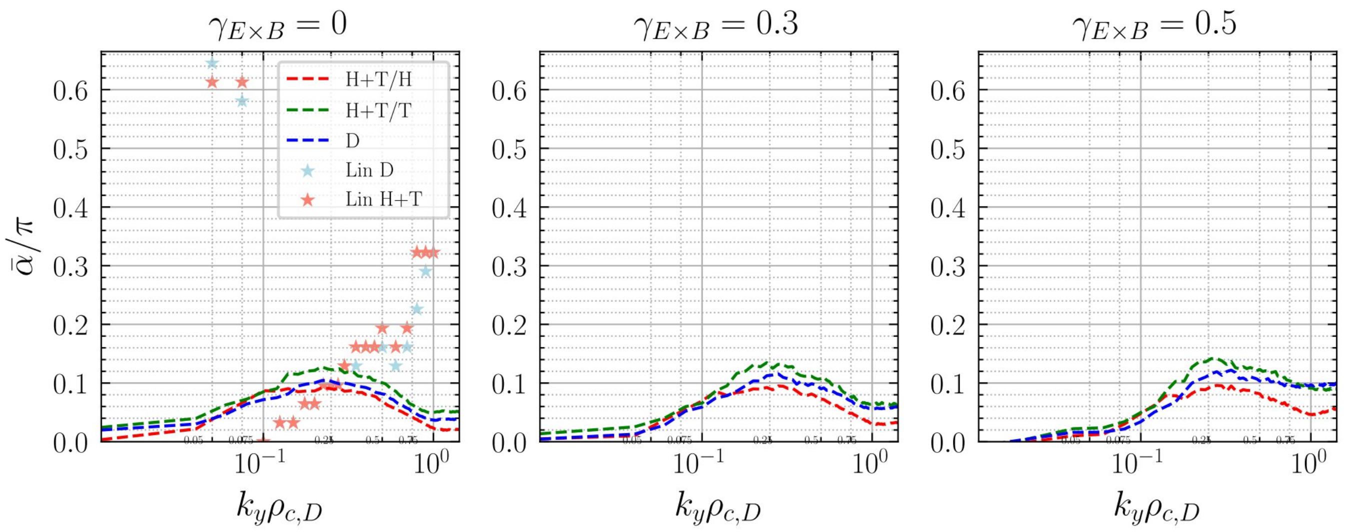
TURBULENCE NATURE – T_I SENSITIVITY

- Linear and non-linear simulations cross-phases : $\alpha(\phi \times T_\perp) \rightarrow 0$
- $\alpha(\phi \times T_\perp) \rightarrow 0$ on all $k_y \rho_{c,D}$ range, broadening with $\gamma_{E\times B}$
- No major scaling with T_i profile

Resistive electron drift-wave modes

[Bonanomi et al. NF, 2019], [Bonanomi et al. PoP, 2021], [Bonanomi et al. PoP, 2024], [Bonanomi et al. PPCF, 2025]



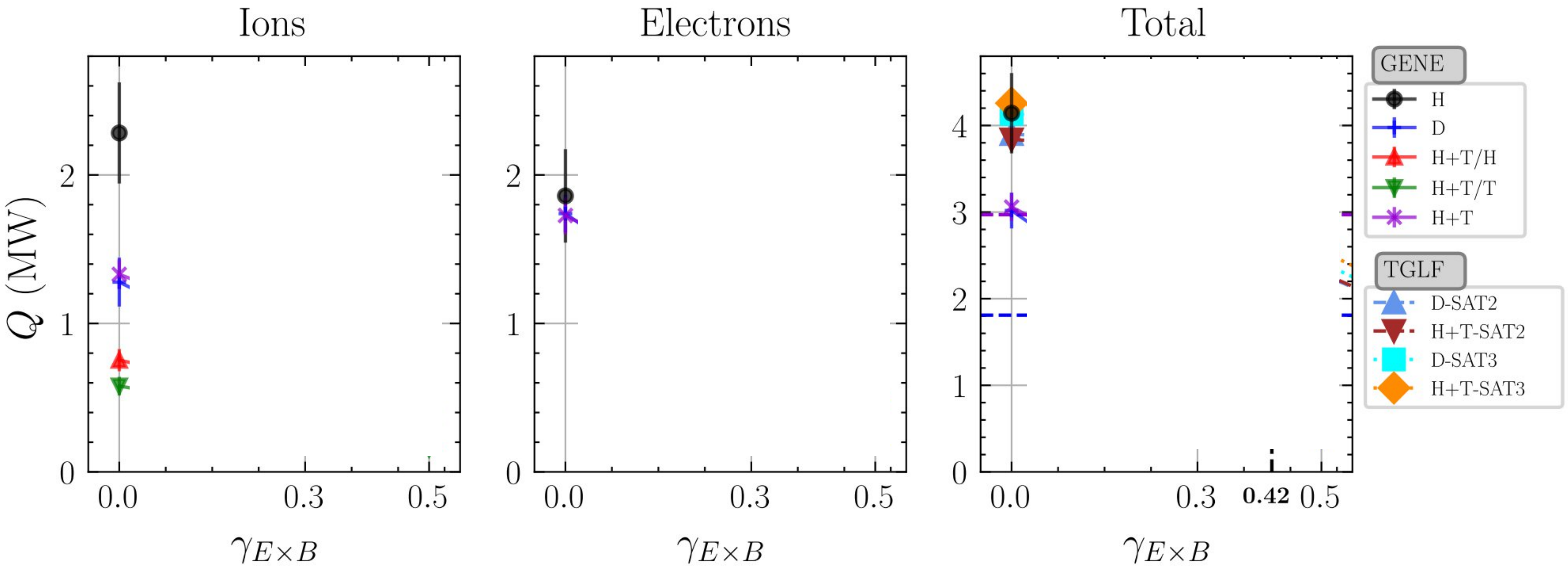


NON-LINEAR RESULTS – HEAT FLUXES – PART 1

- Anti-gyroBohm scaling retrieved for non-linear heat fluxes

$$Q_{H}^{\gamma_{E\times B}=0} > Q_{D}^{\gamma_{E\times B}=0} = Q_{H+T}^{\gamma_{E\times B}=0}$$

Good agreement with experimental flux levels BUT no differences at same effective mass between H+T and pure D…



NON-LINEAR RESULTS – $E \times B$ SHEAR

- Anti-gyroBohm scaling retrieved for non-linear heat fluxes

$$Q_{H}^{\gamma_{E\times B}=0} > \boxed{Q_{D}^{\gamma_{E\times B}=0} = Q_{H+T}^{\gamma_{E\times B}=0}}$$

Good agreement with experimental flux levels BUT no differences at same effective mass between H+T and pure D…

What about $\gamma_{E\times B}$ effect ? -> not measured, but **expected to be non-zero !**

$$\gamma_{E\times B} = \frac{\rho_{tor}}{q} \frac{\partial}{\partial \rho_{tor}} \left(\frac{E_r}{B_p R} \right) \frac{\rho_a}{c_D}$$

- **Estimated** using $\mathbf{T_i} = \mathbf{T_e}$ and the **diamagnetic component only**

$$\gamma_{E\times B}^{est} \approx 0.42$$

- Fork the simulations by adding $\gamma_{E\times B}$ after saturation is reached

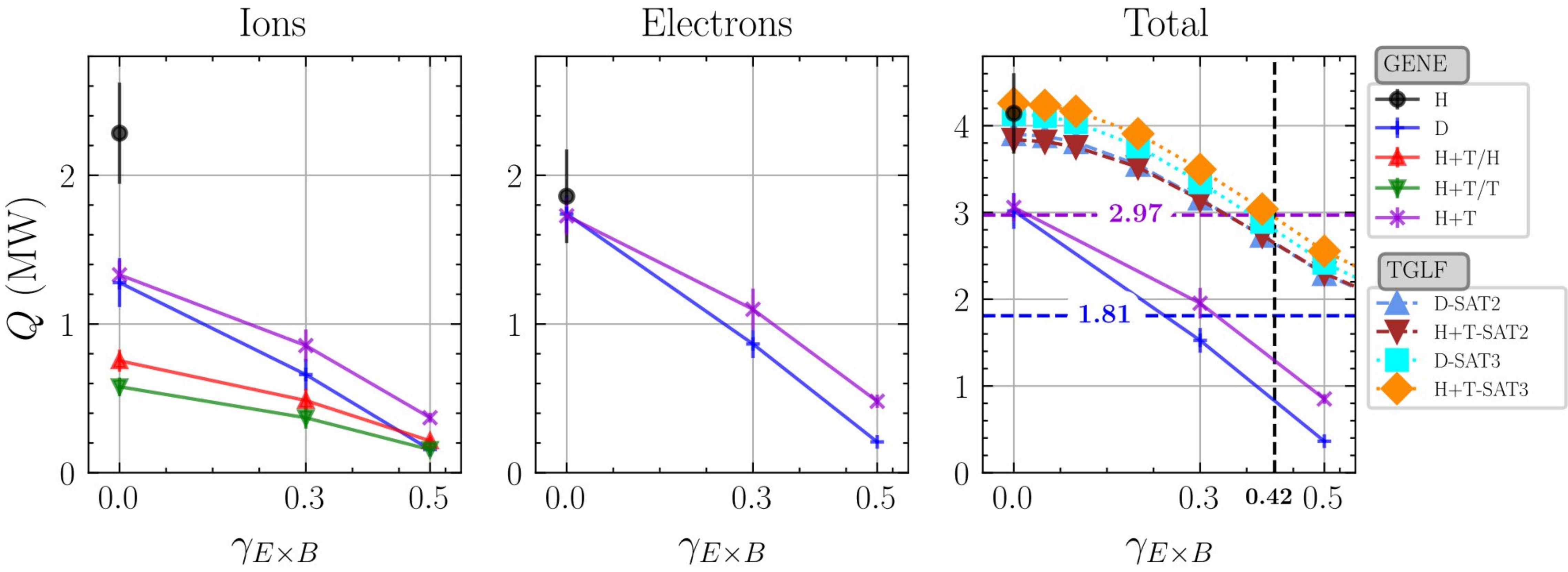
- Pure deuterium $\gamma_{E\times B} = 0$
  - $\gamma_{E\times B} = 0.3$
  - $\gamma_{E\times B} = 0.5$
- 50% H + 50% T $\gamma_{E\times B} = 0$
  - $\gamma_{E\times B} = 0.3$
  - $\gamma_{E\times B} = 0.5$

NON-LINEAR RESULTS – HEAT FLUXES – PART 2

- Non-zero $\gamma_{E\times B}$ allows to retrieve a behaviour similar to experiments

$$Q_D^{\gamma_{E\times B}\neq 0} < Q_{H+T}^{\gamma_{E\times B}\neq 0}$$

- This behaviour **is not** retrieved with TGLF SAT2 and 3



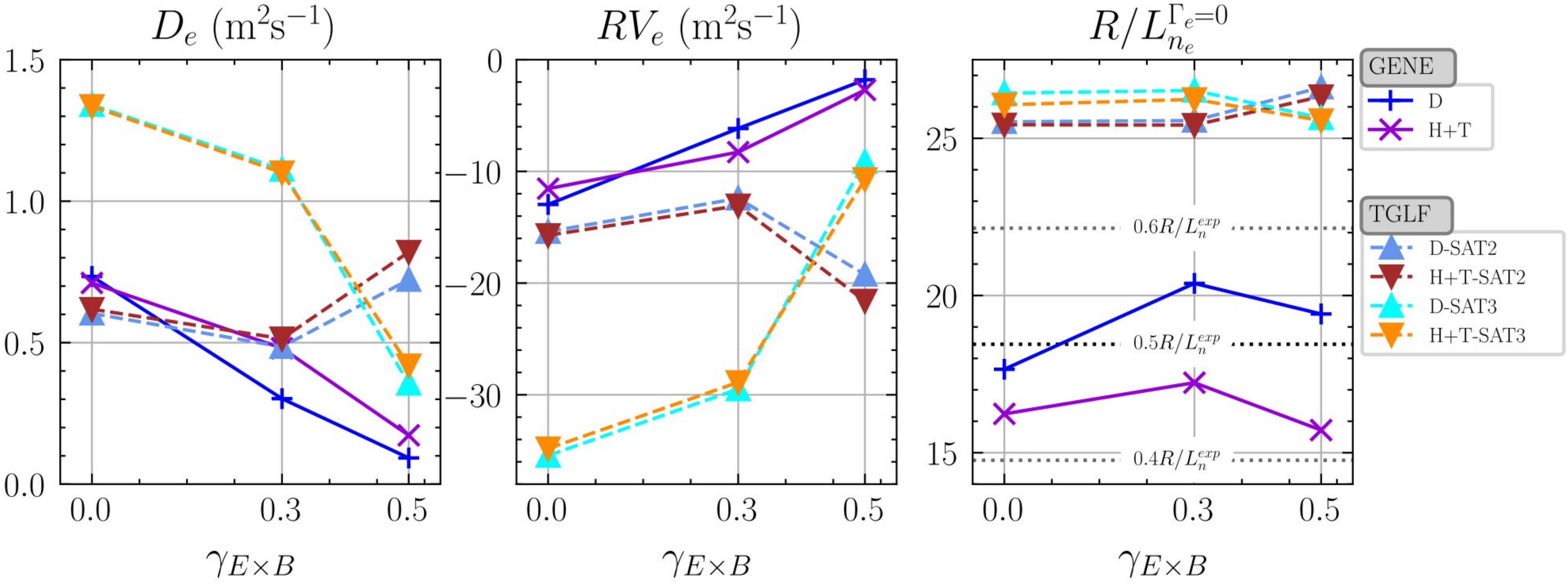
NON-LINEAR RESULTS – PARTICLE TRANSPORT

- Two electron population; one with $R/L_n = 0$, one with $R/L_n = 2 \times R/L_{ni}$
- Allows to extract diffusion and convection, as well as zero flux gradients

$$\Gamma_e = -\mathbf{D_e} \nabla n_e + n_e \mathbf{V_e}$$

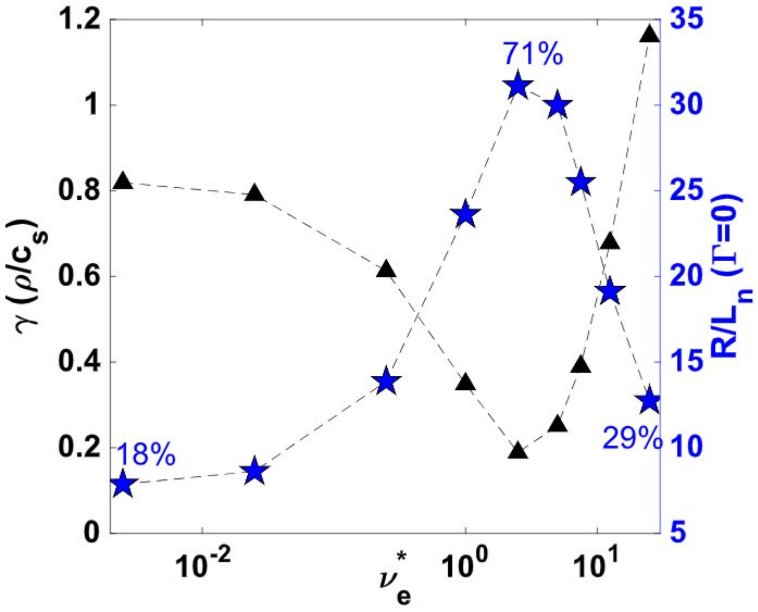
Overestimated convection for TGLF SAT2/3 compared to GENE

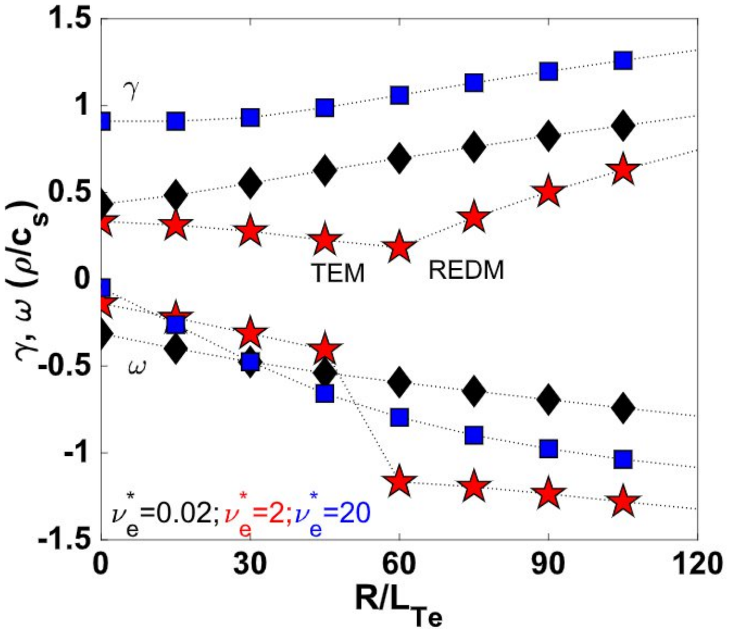
Turbulence represents here ~ half the density peaking ! (rest are sources)

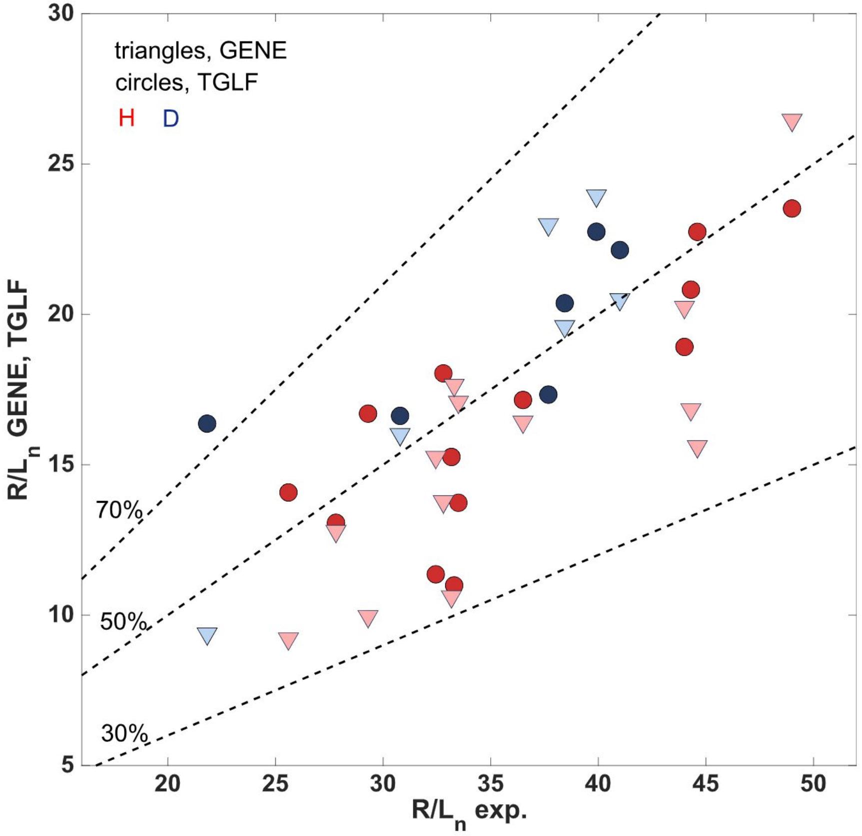


NON-LINEAR RESULTS – PARTICLE TRANSPORT

- GENE and TGLF with L-mode ASDEX Upgrade experimental data also show **half the density peaking is coming from turbulence**
- $R/L_{ni} = 36.29$ in our case, similar conditions as previous study from Nicola Bonanomi
- Comparable turbulent modes, scales with R/L_{Te}







[Bonanomi et al. *PPCF*, 2025]

CONCLUSION AND FUTURE WORK

- Linear simulations: **electron drift wave modes** with decreasing γ for increasing A_{eff}, consistently with P_{LH}

$\gamma_{E\times B} = 0$: linear, non-linear GENE and TGLF simulations yield no differences at $A_{eff} = 2$

$\gamma_{E\times B} > 0$: only non-linear GENE simulations provide $Q_D < Q_{H+T}$, similarly to P_{LH} experimental scaling ($P_{LH}^{D} < P_{LH}^{H+T}$)

- Separation of both cases due **to asymmetrical response of turbulence levels**, stronger for D than H+T
- **Differential effect on fluxes** (heat & particle) increases with $\gamma_{E\times B}$ magnitude
- Heat fluxes are in the experimental range (of P_{LH}) at ~ 3MW
- **No such effect is observed in TGLF** SAT2 and SAT3

Next steps:

- Explore similar simulations at $A_{eff} = 2.5$ for H(25%)+T(75%), D(50%)+T(50%) and « fake » 2.5 pure isotope
- Explore more in depth turbulence nature (look at ZF for instance)
- Check the latest version of TGLF and try integrated modelling of these pulses

ISOTOPE EFFECT – PARALLEL ELECTRON DYNAMICS

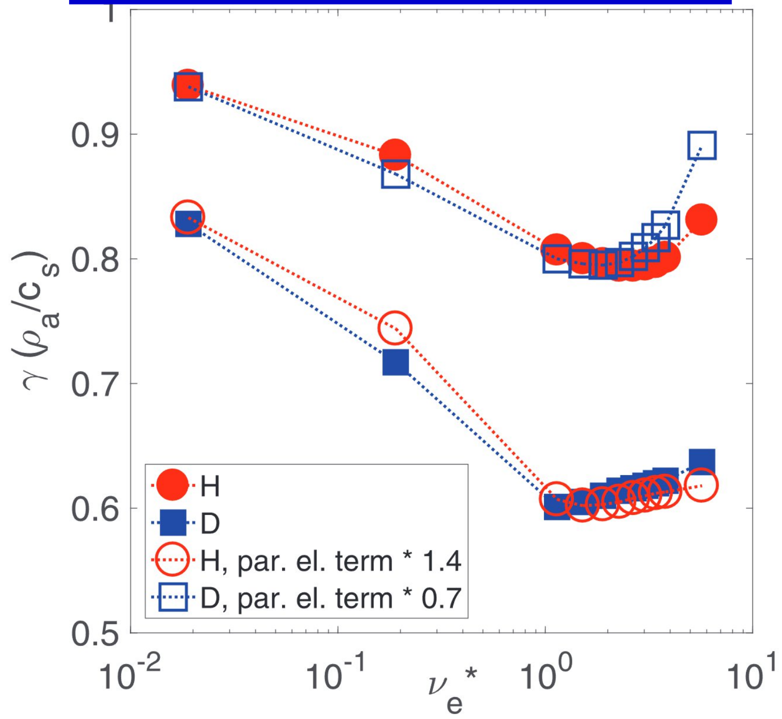
What is driving this isotope effect ?

$$C_m\left\{-\hat{v}_{e,th}\frac{\hat{C}}{JB_0}\left[v_\parallel\left(\frac{\partial f_{e,1}}{\partial z}-\frac{e}{T_e}F_{e,0}\frac{\partial\phi}{\partial z}+F_{e,0}\mu\frac{\partial B_{1,\parallel}}{\partial z}\right)-\mu\frac{\partial}{\partial z}\left(B_0\frac{\partial f_{e,1}}{\partial v_\parallel}\right)\right]\right\}$$

$$C=\left(0{,}51\nu_{ei}\frac{L_\perp}{c_s}\frac{m_e}{m_i}\left(\frac{qR}{L_\perp}\right)^2\right)$$

- Parallel electron dynamics term $\propto 1/m_i$ (i.e. can be recast as $\propto 1/A_{eff}$)
- Increased coupling between electrons and ions for lower ion masses
- Artificially changing C_m allowed match turbulent states between H and D

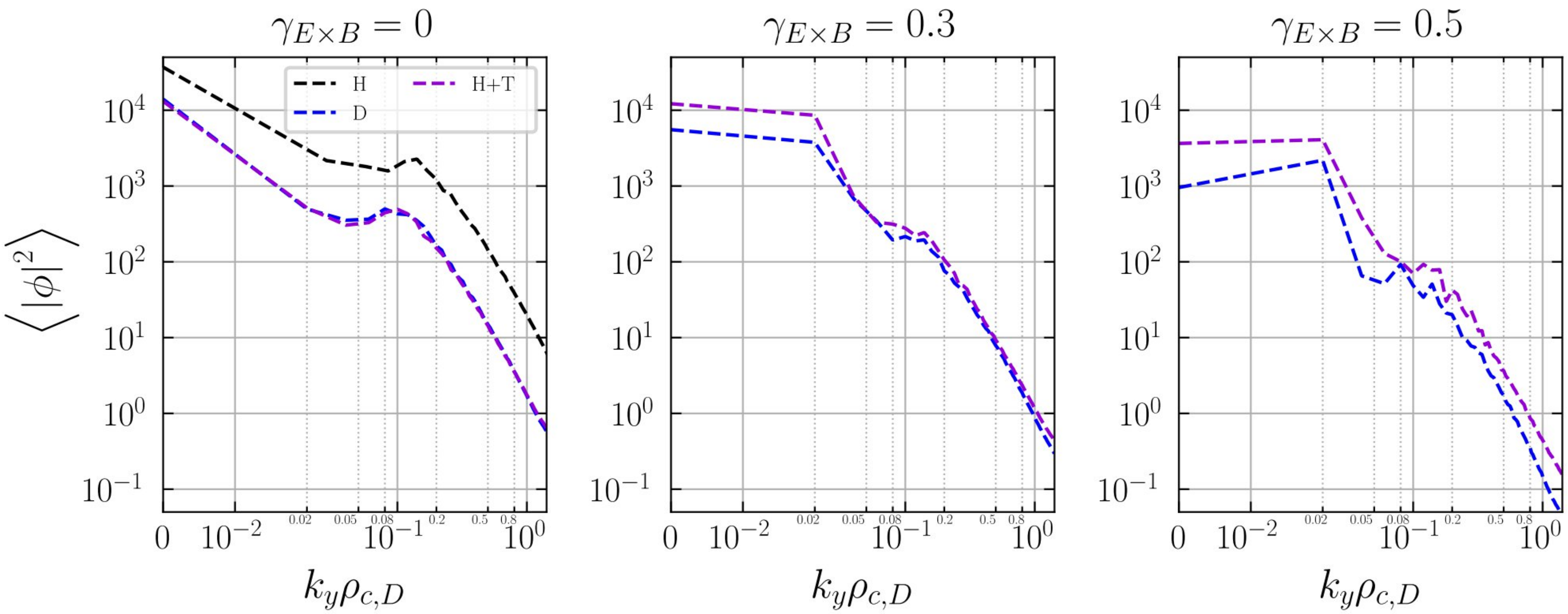
<u>**What about this term when we have two species ?**</u>



[Bonanomi et al. *PoP*, 2021]

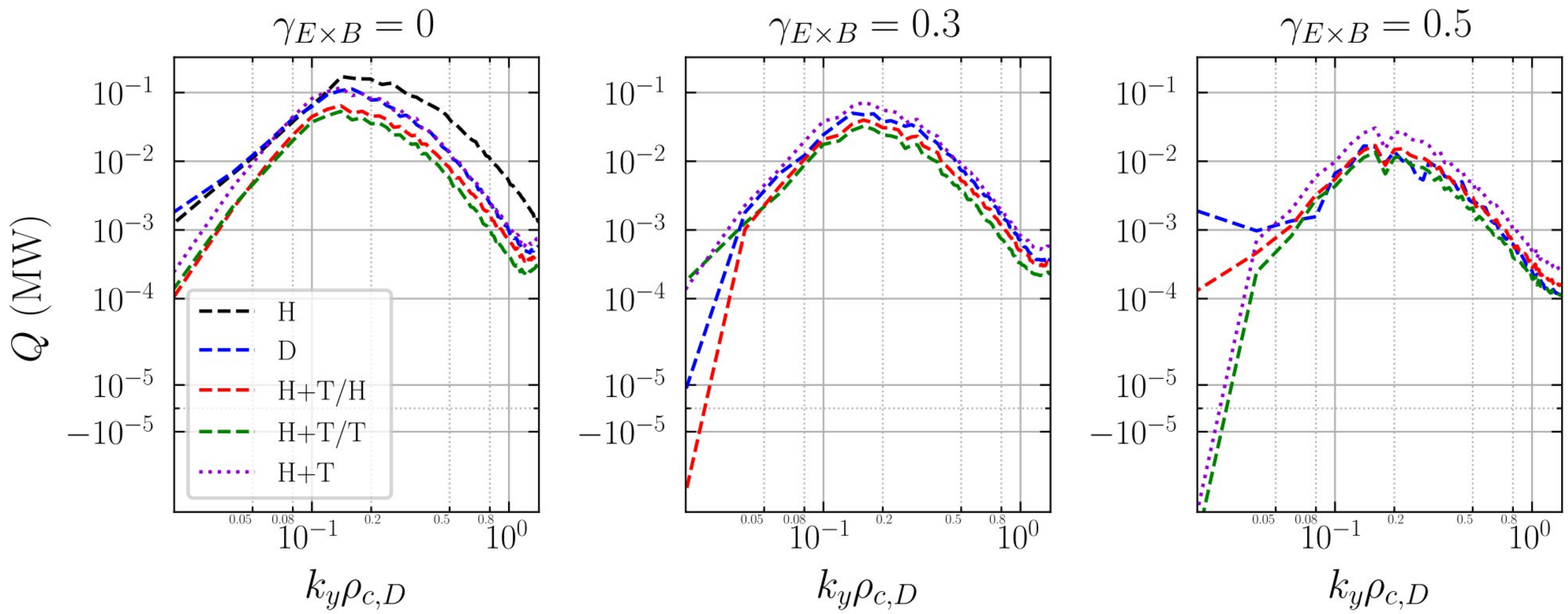
NON-LINEAR RESULTS – POTENTIAL SPECTRA

- Identical spectra / turbulence between cases, H case has stronger modes
- Reduction of amplitude for bigger scales
- Generalized to smaller scales when increasing $\mathrm{E} \times \mathrm{B}$ shear
- Suspicion of **different ZF activities**



NON-LINEAR RESULTS – IONS HEAT FLUX SPECTRA

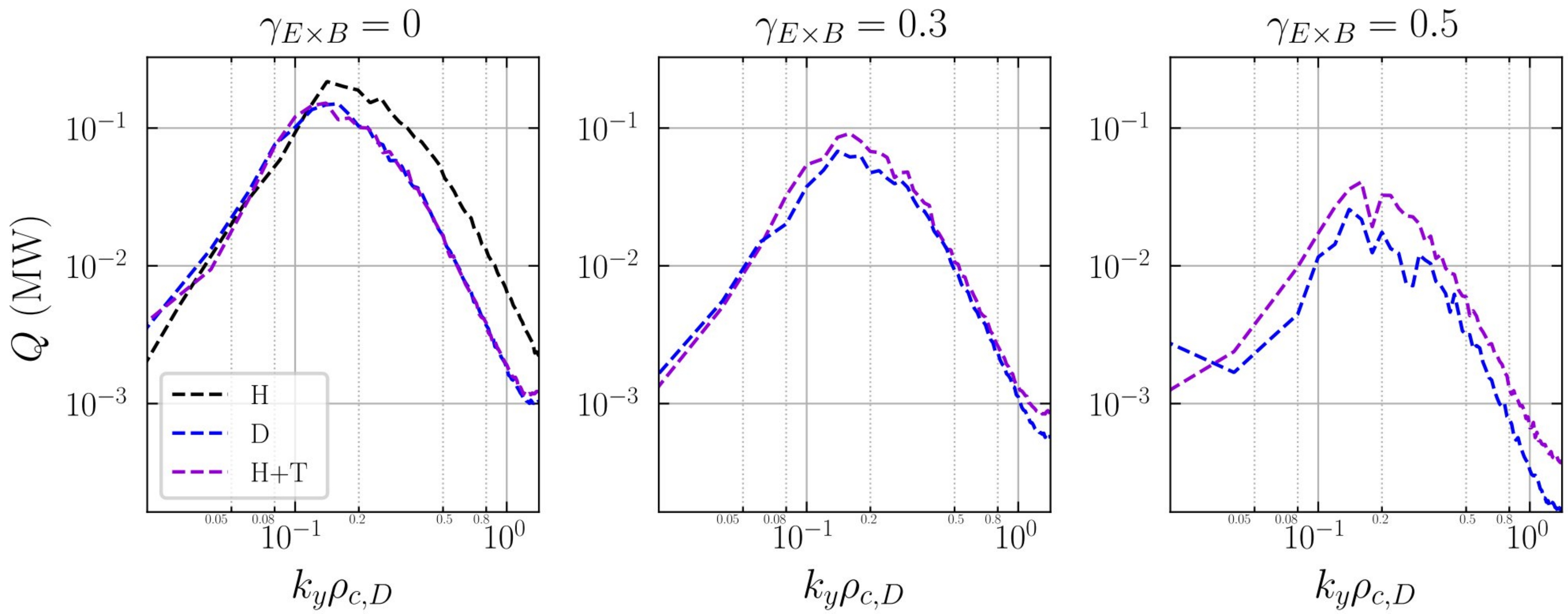
- Between pure H and H+T/D, smaller scales makes the difference for the ion heat flux
- For larger scales, difference is larger for H+T and D, but magnitudes are low
- The main difference is, as expected, in the range $0.07 < \mathrm{k_y}\rho_{c,D} < 0.4$ for $\gamma_{\mathrm{E\times B}} = 0.3$
- This is extended to $0.06 < \mathrm{k_y}\rho_{c,D} < 1.2$ for $\gamma_{\mathrm{E\times B}} = 0.5$



NON-LINEAR RESULTS – ELECTRONS HEAT FLUX SPECTRA

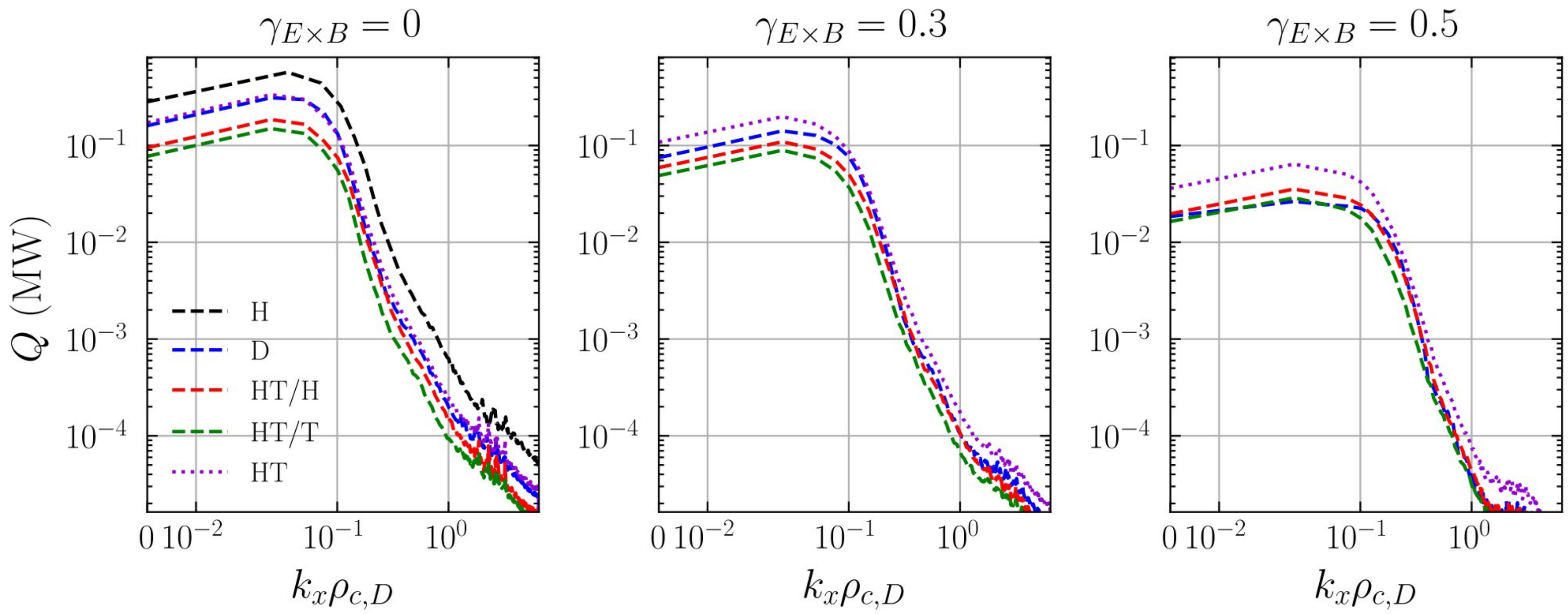
Similarly as before:

- The main difference is, as expected, in the range $0.07 < \mathrm{k_y}\rho_{c,D} < 0.4$ for $\gamma_{\mathrm{E\times B}} = 0.3$
- This is extended to $0.06 < \mathrm{k_y}\rho_{c,D} < 1.2$ for $\gamma_{\mathrm{E\times B}} = 0.5$



NON-LINEAR RESULTS – IONS HEAT FLUX SPECTRA

- Difference between H and H+T/D is present on all scales
- Again, larger scales is where the difference is larger for H+T and D
- The main difference is in the range $0 < \mathrm{k_x} \rho_{c,D} < 0.1$ for $\gamma_{\mathrm{E \times B}} = 0.3$
- This is extended to $0 < \mathrm{k_x} \rho_{c,D} < 0.2$ for $\gamma_{\mathrm{E \times B}} = 0.5$



NON-LINEAR RESULTS – ELECTRONS HEAT FLUX SPECTRA

Similarly as before:

- The main difference is in the range $0 < k_x \rho_{c,D} < 0.1$ for $\gamma_{E\times B} = 0.3$
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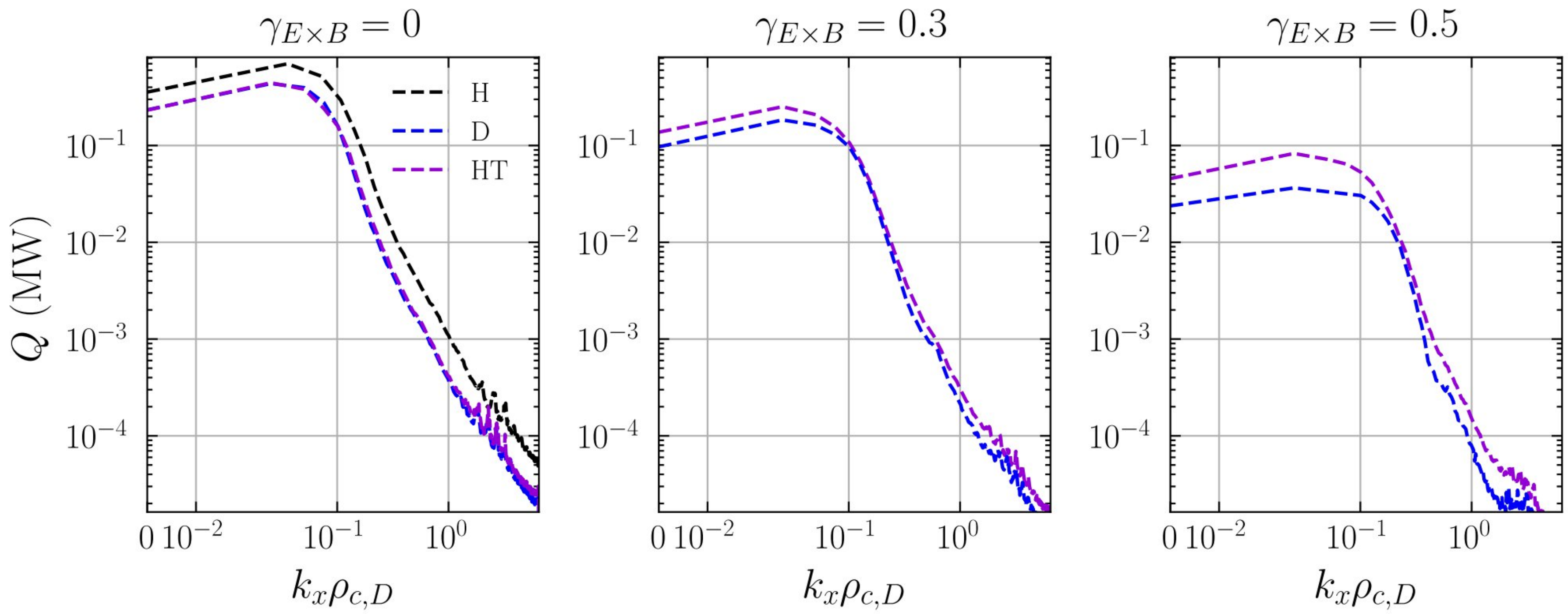

NON-LINEAR RESULTS – PARTICLE FLUX

- Expected fluxes are also in a “reasonable” range
- Also more H flux than T in the H+T mixtures
- Could the additional particle transport lead to higher convective heat flux ? (need to check)
- Similar trend as heat flux though (reason why not shown)
- Again, TGLF is not “that bad”