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From L-mode to the L-H transition, experiments on ASDEX Upgrade, gyrokinetic simulations and full-radius transport modeling with ASTRA-TGLF-sat2

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ASDEX Upgrade

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*** See the author list of B. Labit et al 2019 Nucl. Fusion 59 086020*

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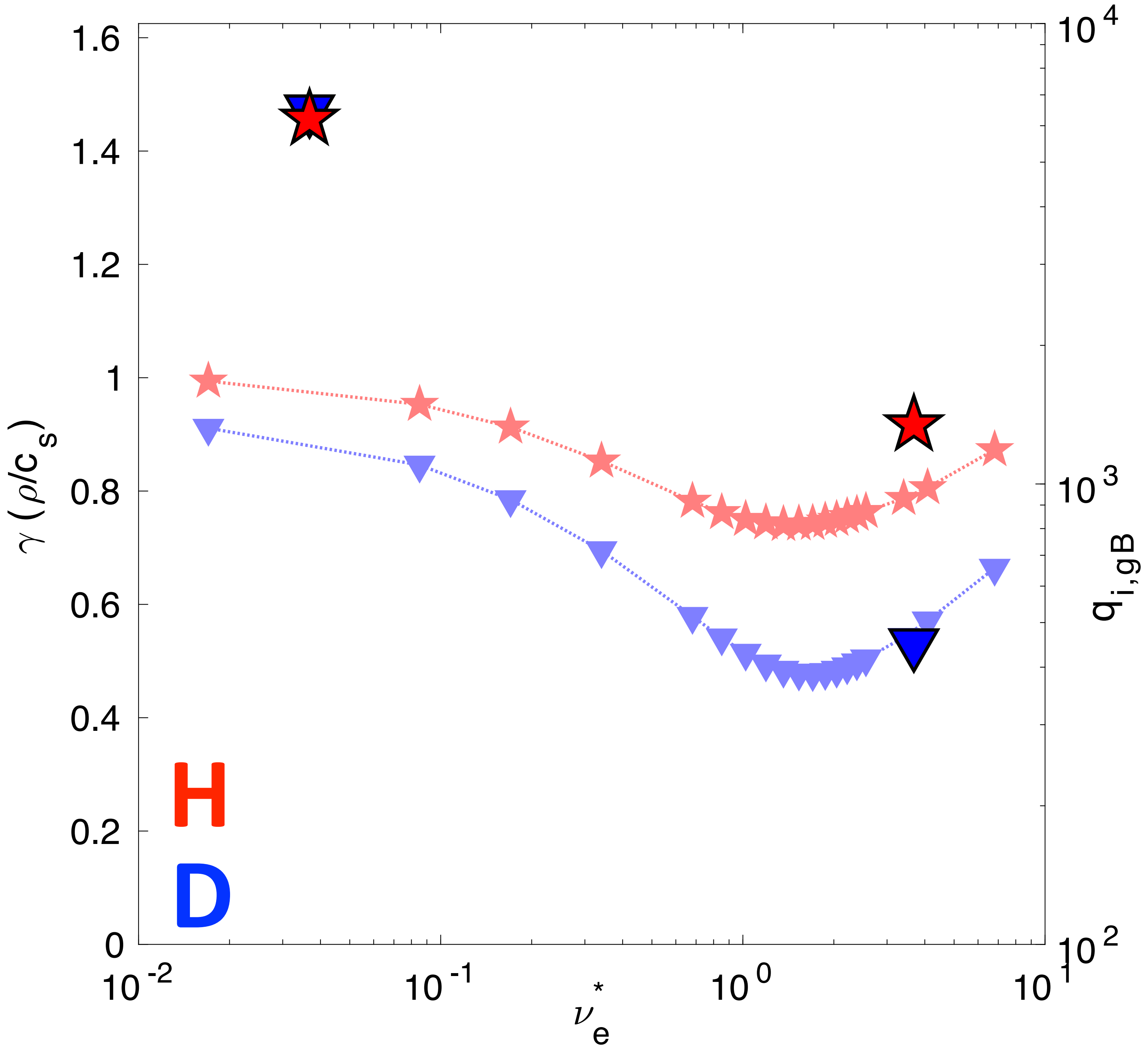
Motivations

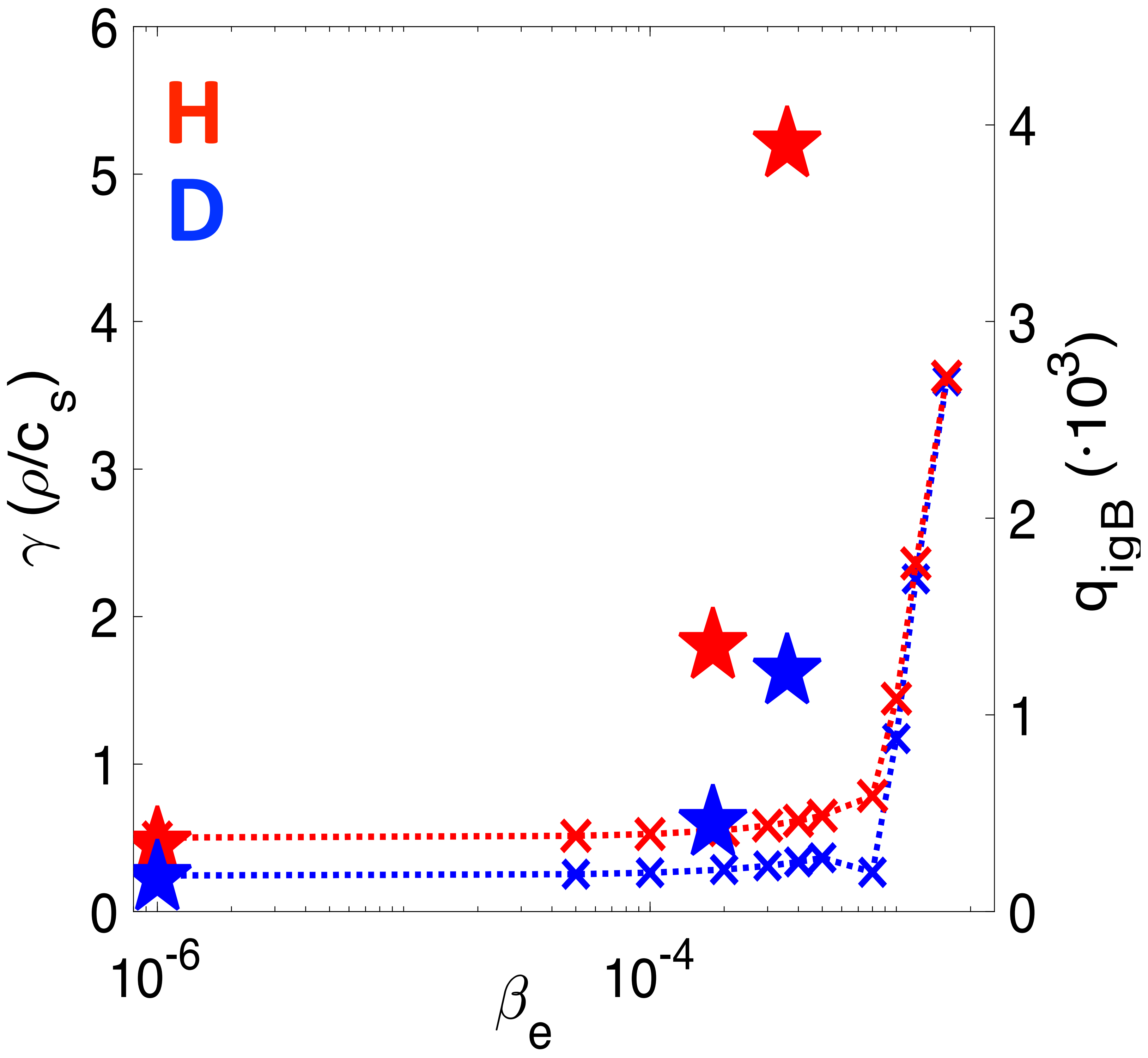
- Turbulence dominates the transport in the L-mode edge $(0.9 < \rho_{tor} < 1.0)$
- Edge turbulent transport and its suppression play a dominant role in the formation of the edge transport barrier during the L-H transition and in the characterization of the edge properties of some ELM-free high confinement regimes
- Edge plasma region plays a strong role for the effect of the isotope mass observed in many experimental conditions
- Understanding of turbulent transport in the edge region is an essential element to develop reliable scenarios and have reliable predictions for future reactors
- The local gyrokinetic (GK) description, and the derived reduced transport model, have been successfully tested and used for predictions of core turbulent transport: we want to test their reliability in the edge and in conditions towards the L-H transition

L-mode edge turbulence: characterization through local GK simulations

Using ASDEX Upgrade (AUG) L-mode parameters we performed local GK simulations at $\rho_{tor} = 0.95$ with GENE (F. Jenko et al. PoP 2001):

- Electron drift-wave instabilities destabilized by collisionality above a certain value of ν_e^*
- **Effect of the isotope mass at high edge collisionality reverse the expected gyro-Bohm behavior**
- **Non-linear electromagnetic effects strongly enhance the turbulence at low k_y**
- Similar results obtained in past studies (B. D. Scott, Phys. Plasmas 12, 062314 (2005), [2]B. D. Scott, Plasma Phys. Control. Fusion 49, S25 (2007);)





(see N. Bonanomi et al., NF 2019)

L-mode edge turbulence: isotope effect understood

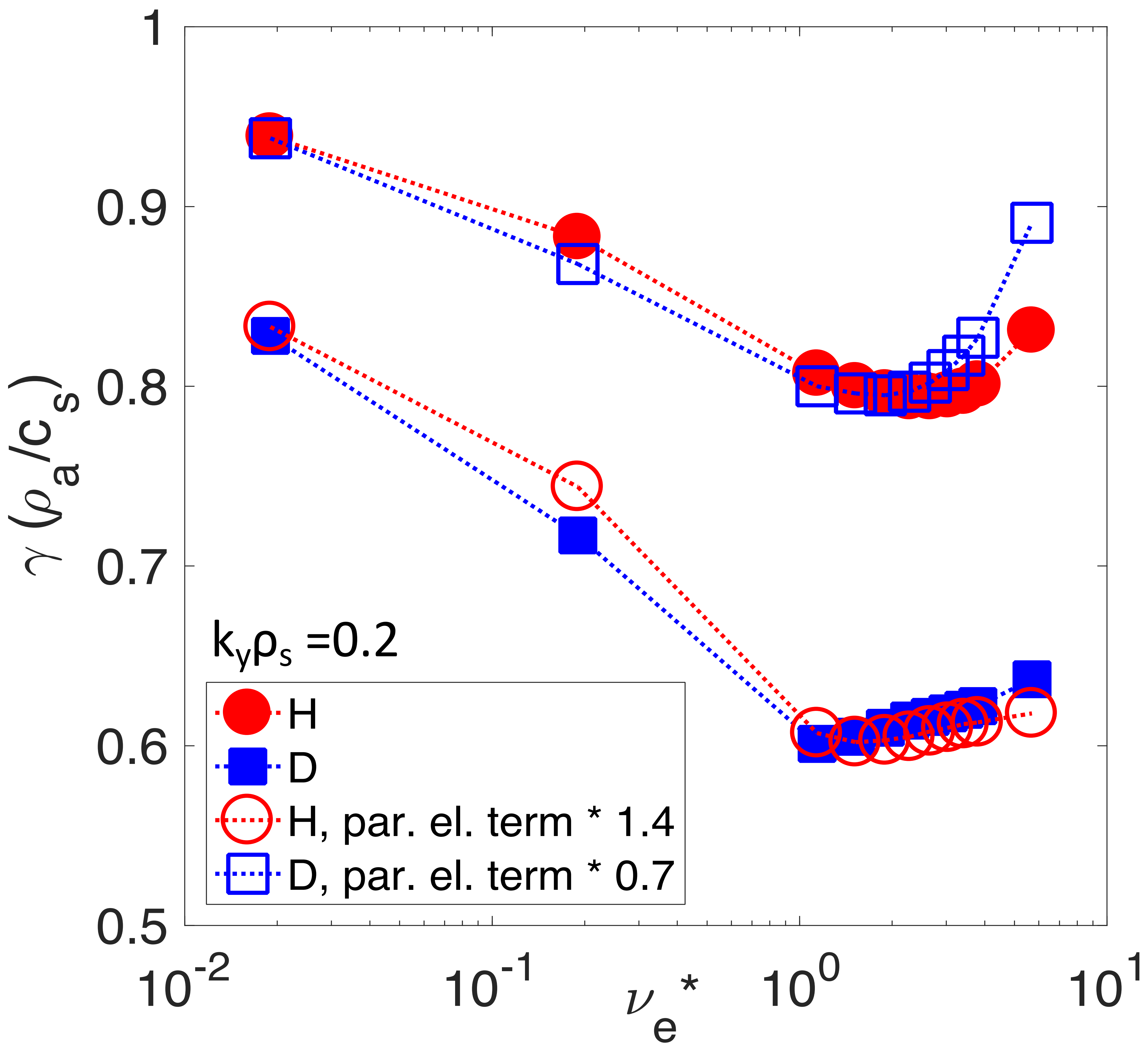
Strong edge collisionality enhance the role of the parallel electron dynamics (N. Bonanomi et al. PoP 2021, E.Belli et al. PRL 2020)

<ins>Linear parallel term in the gyrokinetic equations (in GENE units):</ins>

$$-\boxed{v_{th,s}}\frac{C}{JB_0}\left[v_{//}\left(\partial_z f_{1s}+\frac{q_s}{T_{0s}}F_{0s}\partial_z\phi_1\right)-\mu\partial_z B_0\partial_{v_{//}}f_{1s}\right]$$

--->different passing electrons response depends on m_e/m_i

- Modifying the term of electron parallel dynamic in the linear GK simulations results in the loss of the isotope mass dependence

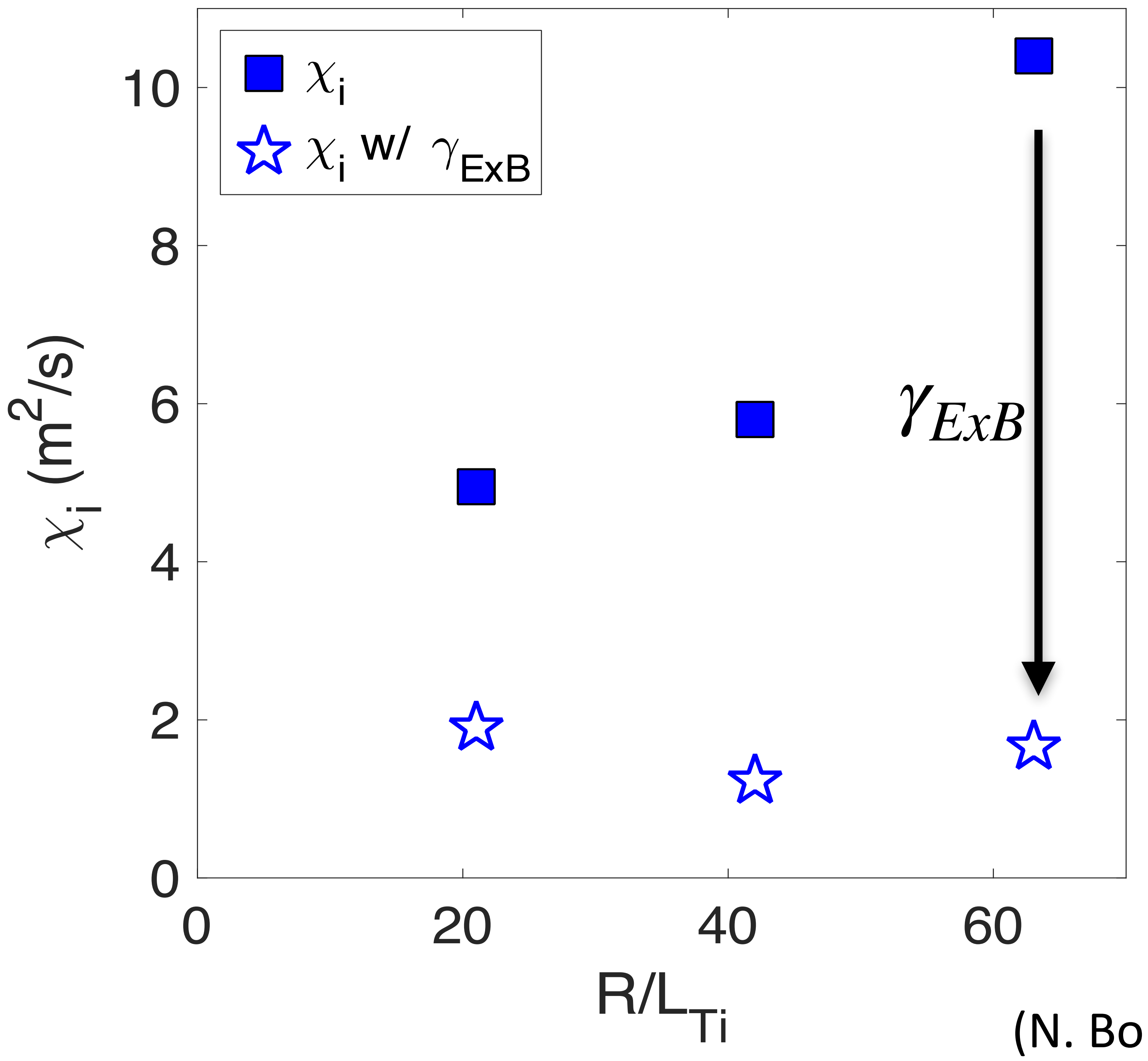


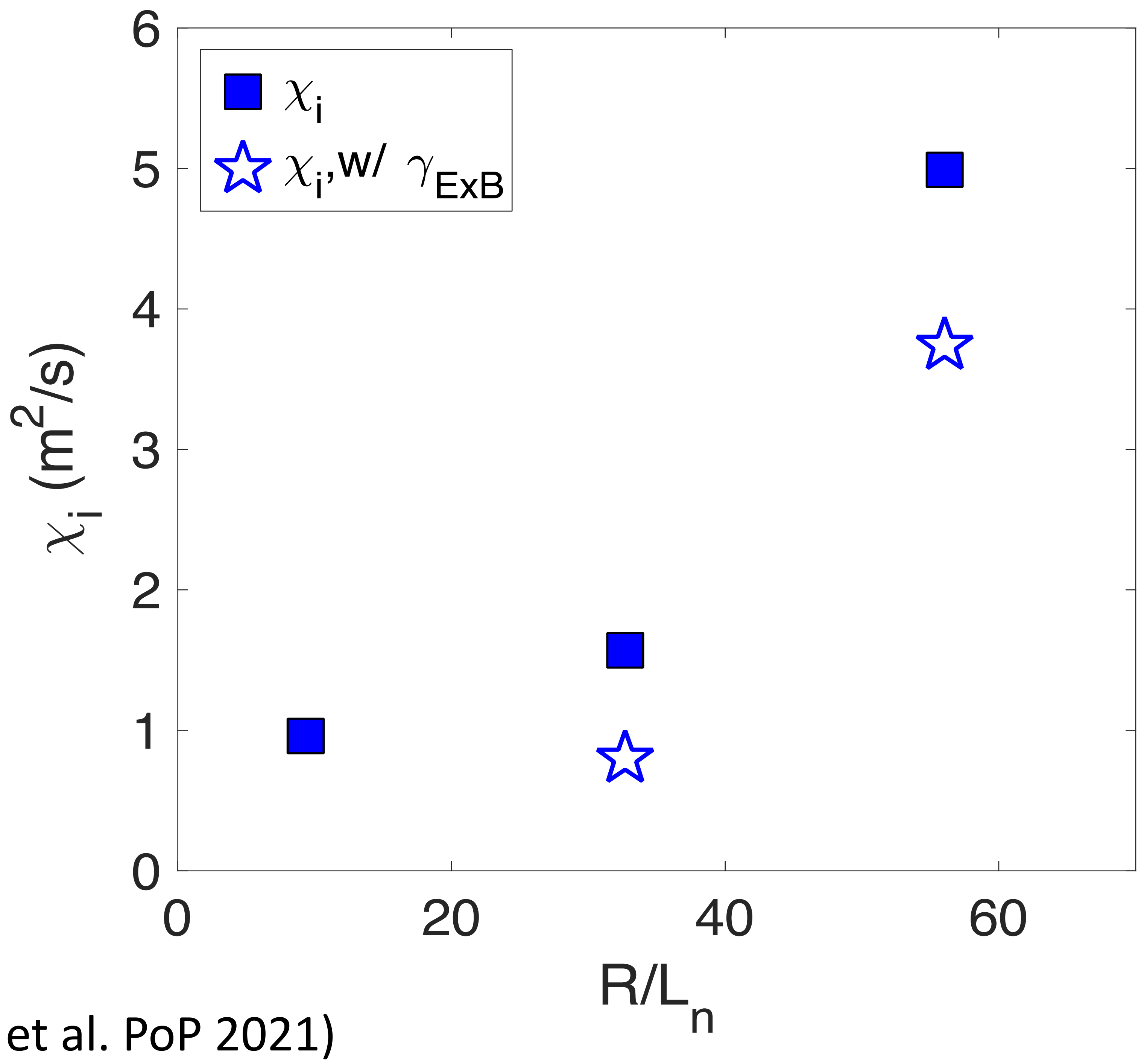
L-mode edge turbulence: different role of the edge normalized gradients and of γ_{ExB}

Starting from the AUG experimental values, local gyrokinetic simulations are performed at $\rho_{tor} = 0.95$:

- **R/L$_{Ti}$ destabilizes the low k_y turbulence** related to the nonlinear electromagnetic effects
- **R/L$_n$ destabilizes intermediate k_y turbulence**
- **The external flow shear (γ_{ExB}) strongly stabilize the low k_y turbulence** but mildly affects the intermediate k_y turbulence:

  increase or T$_i$R/L$_{Ti}$ combined with consistent increase of E$_r$ and of γ_{ExB} does not increase the heat conductivity





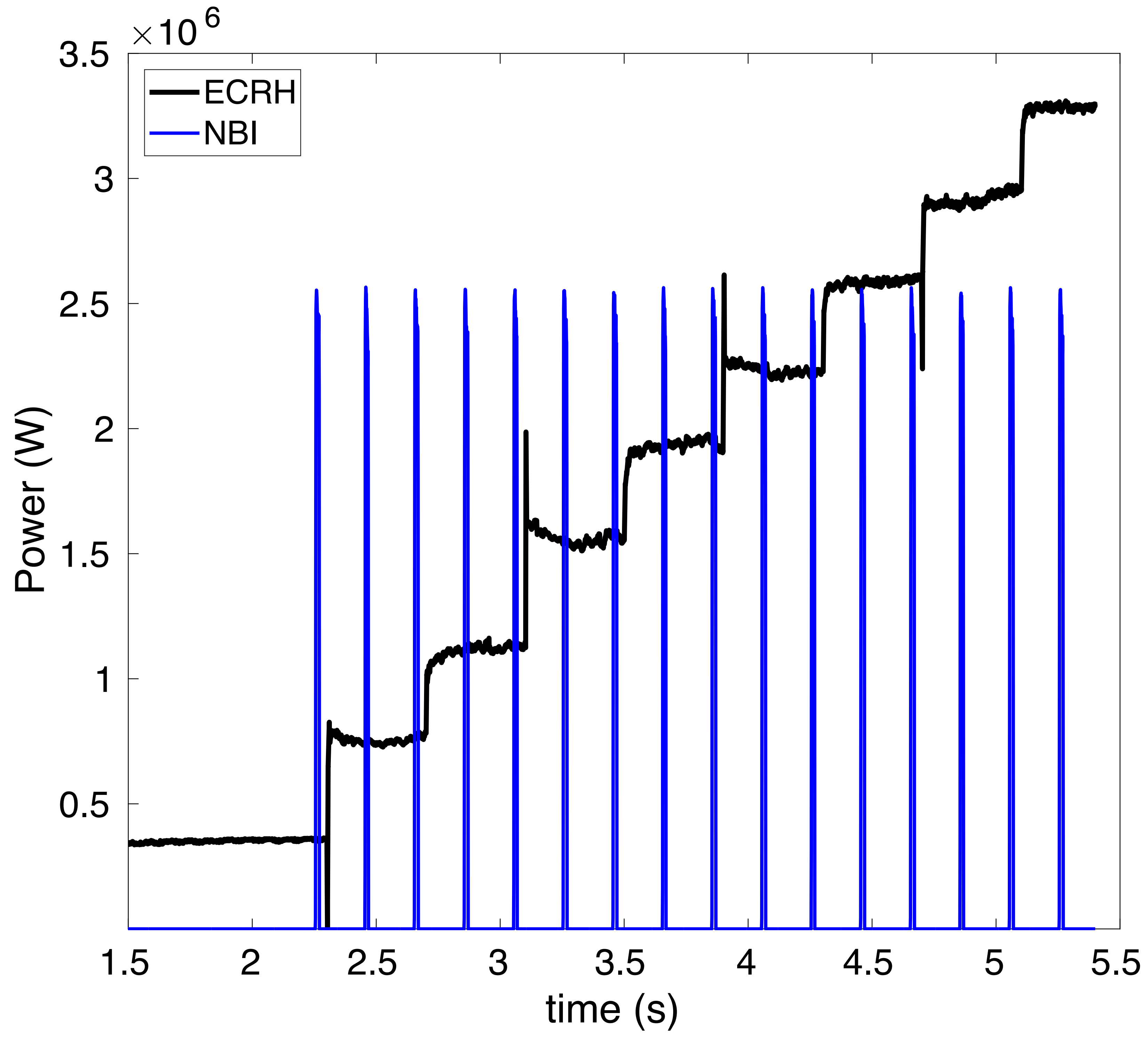
(N. Bonanomi et al. PoP 2021)

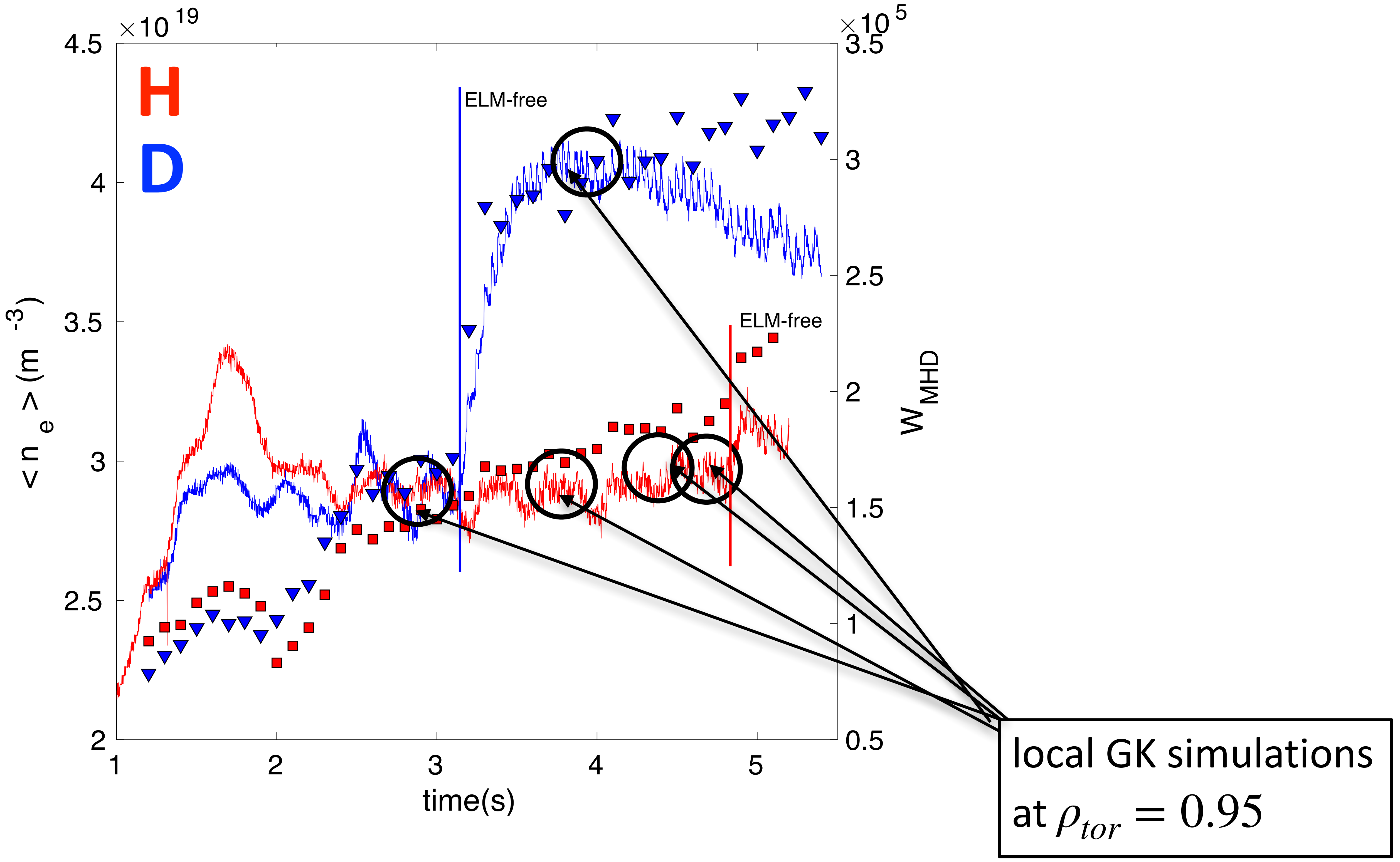
Dedicated experiments at ASDEX Upgrade

AUG #37909 in deuterium and #38176 in hydrogen at I_p= 1.2 MA, B_T= -2.5 T, $\langle n_e \rangle \sim 3 \cdot 10^{19}$ m^{-3}. ECRH scan with NBI blips.

Both discharges show a stationary ELM-free H-mode phase: $P_{LH} \approx 1.7$ MW in deuterium and $P_{LH} \approx 3$MW in hydrogen.

E_r measured in hydrogen with Doppler reflectometers to calculate the γ_{ExB}

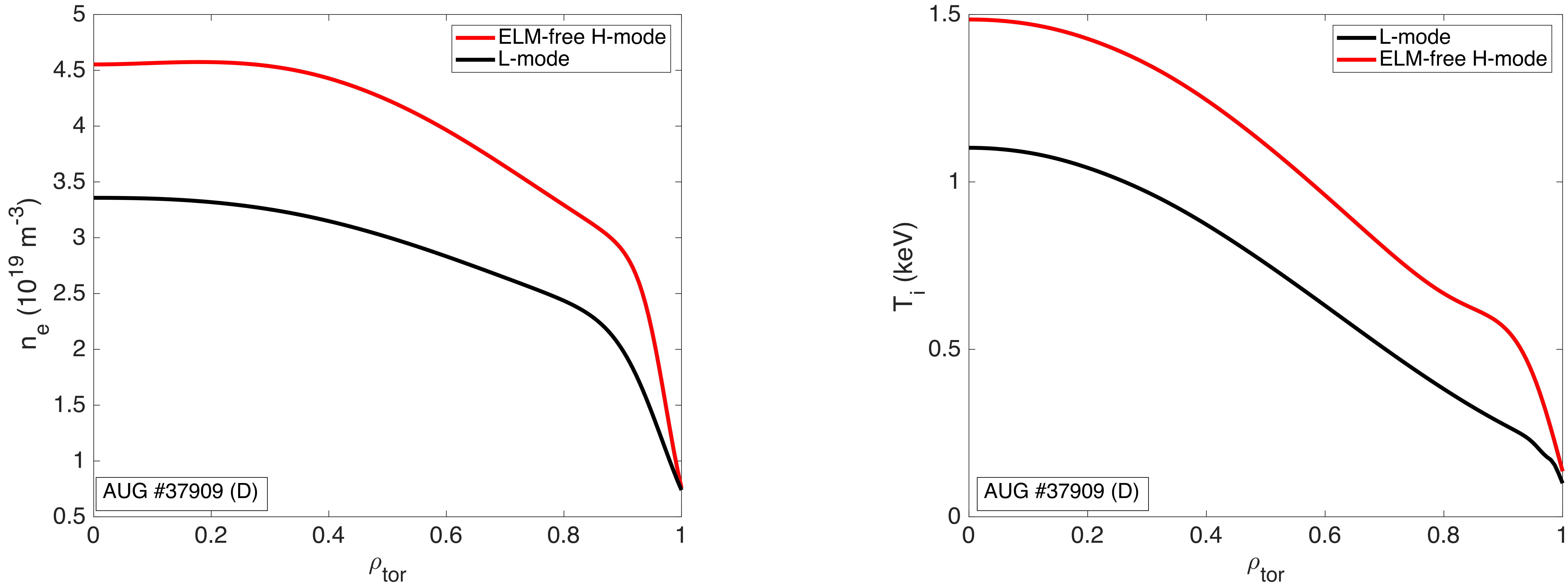




local GK simulations at $\rho_{tor} = 0.95$

- 4 time-steps (black circles in the plot) chosen in hydrogen at different power level: P_{ECRH}/P_{LH} = 0.5,0.8,0.95,0.99
- 1 time-step chosen in deuterium in the stationary ELM-free H-mode phase

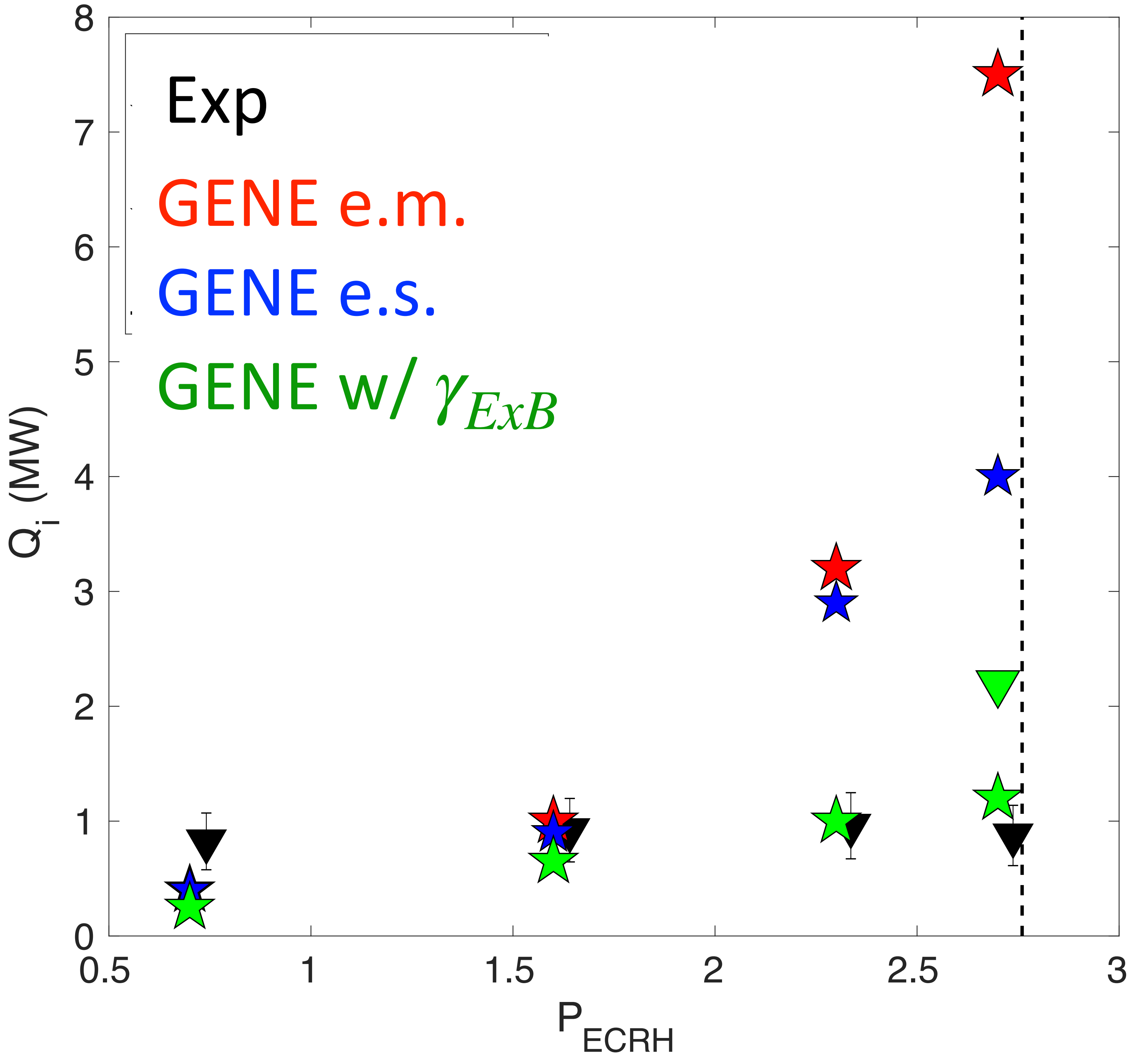
AUG #37909: experimental profiles in L- and stationary ELM-free H-mode

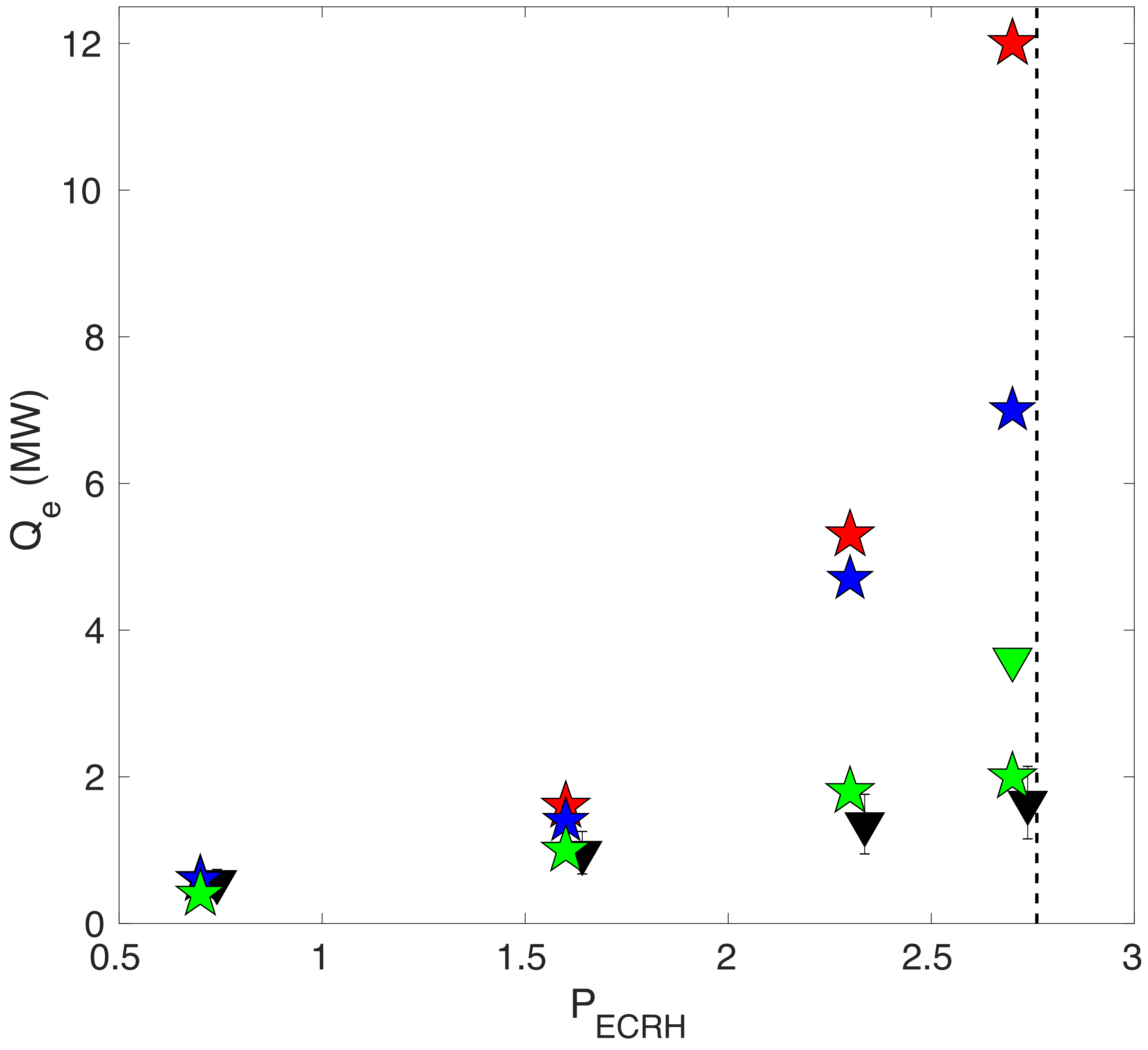


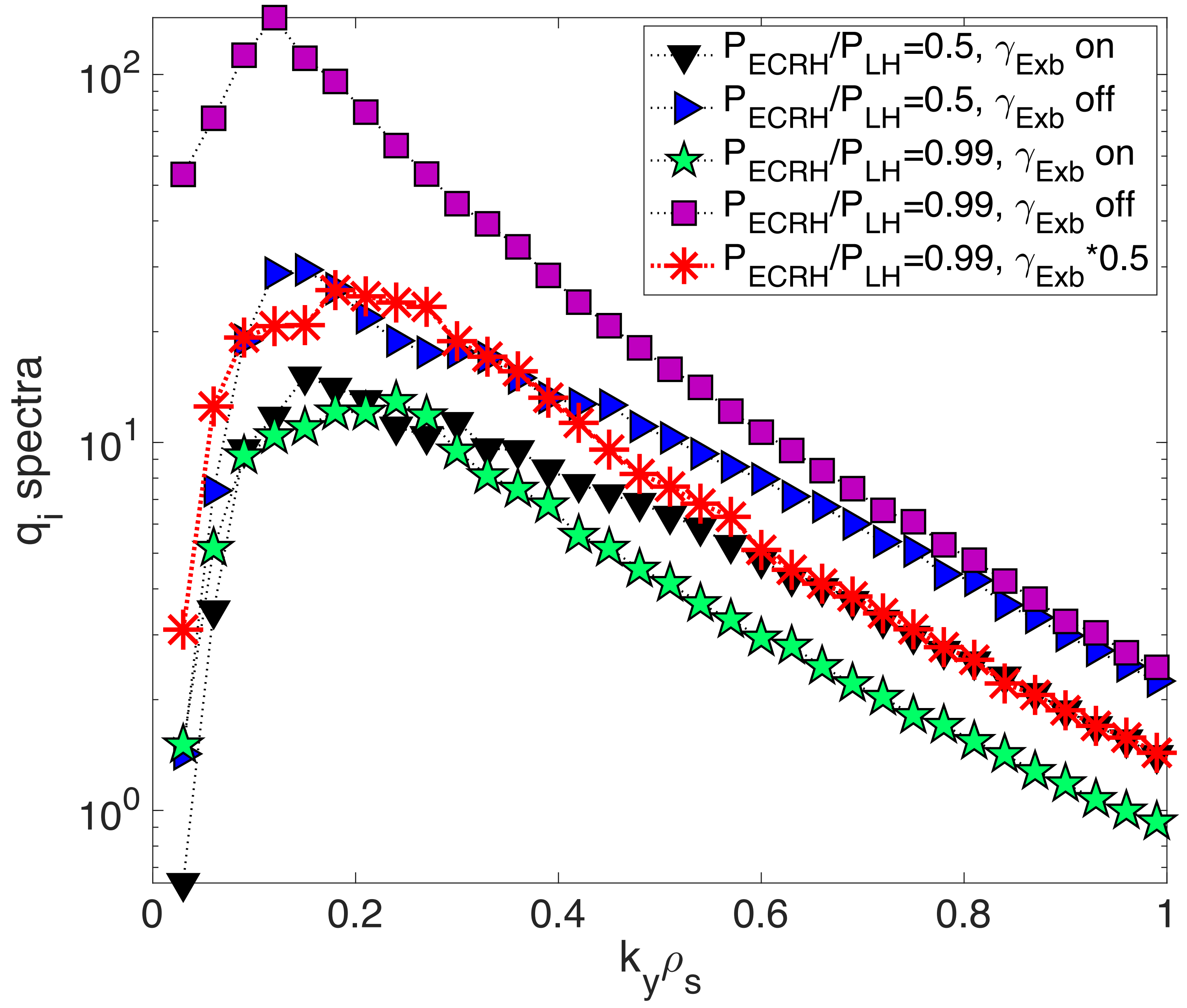
L-mode edge turbulence: local GK simulations towards the L-H transition

Simulations of AUG #38176 (hydrogen): we follow the evolution of the plasma parameters up to just before the L-H transition

- **The GK simulations are able to reproduce the heat fluxes of both ions and electrons along the whole heat power scan**
- Fundamental role of γ_{ExB} and β_e, especially when approaching the L-H transition: **increasing β_e destabilizes low k_y turbulence that is strongly suppressed by γ_{ExB}**



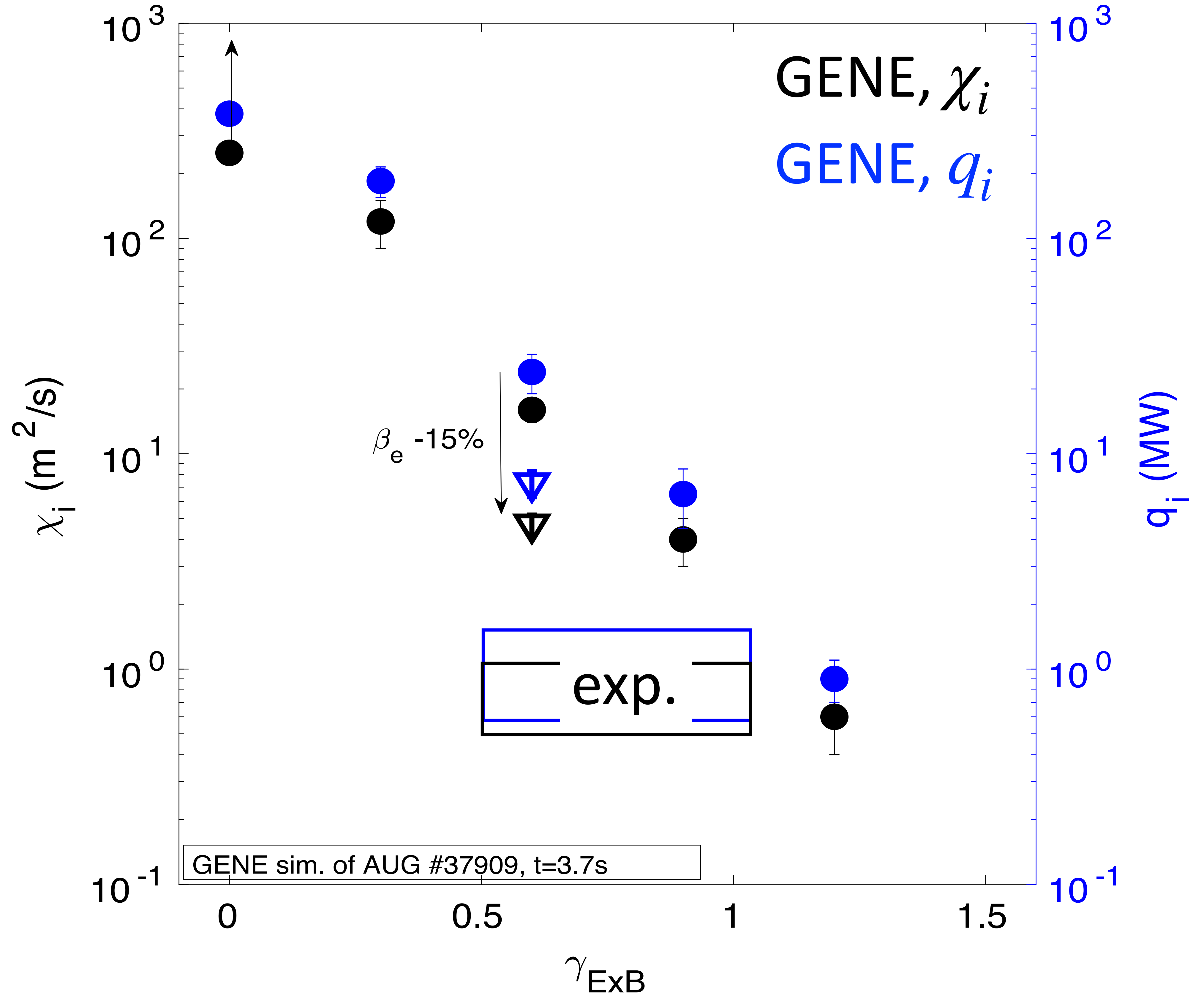


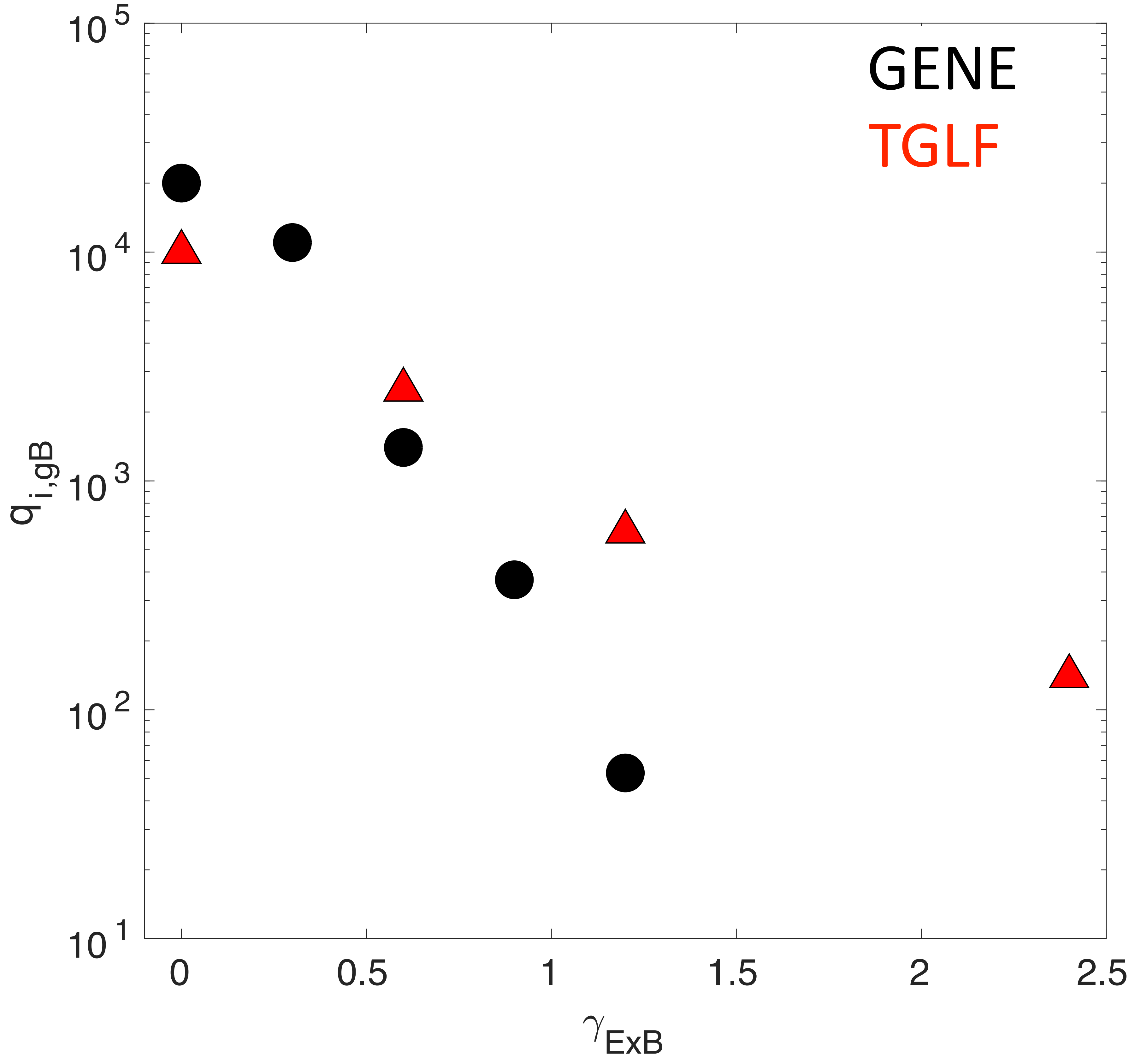


Local GK simulations in the ELM-free H-mode phase

Simulations of AUG #37909 (deuterium): we use the parameters in the ELM-free stationary H-mode phase and scan in γ_{ExB}

- **Strong effect of γ_{ExB}, non-linear behavior**
- In H-mode condition global effects might start to play a role but the predicted fluxes are not too far from the experiment
- **TGLF-sat2 follows the trend found with local GK** but needs an higher γ_{ExB} to predict the experimental fluxes
- *Neoclassical transport calculated with NCLASS accounts for 10-20 % of the ion heat flux

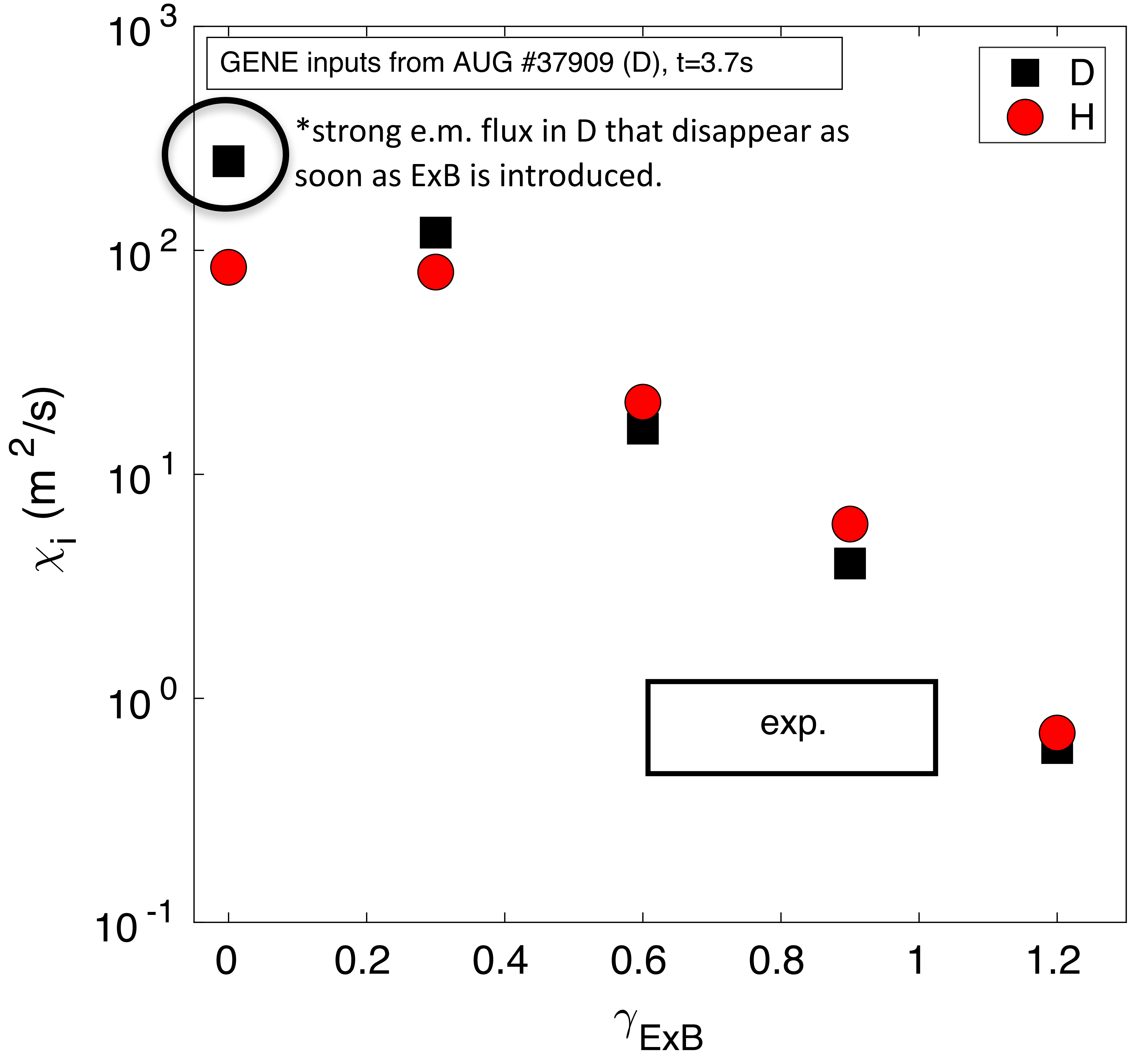




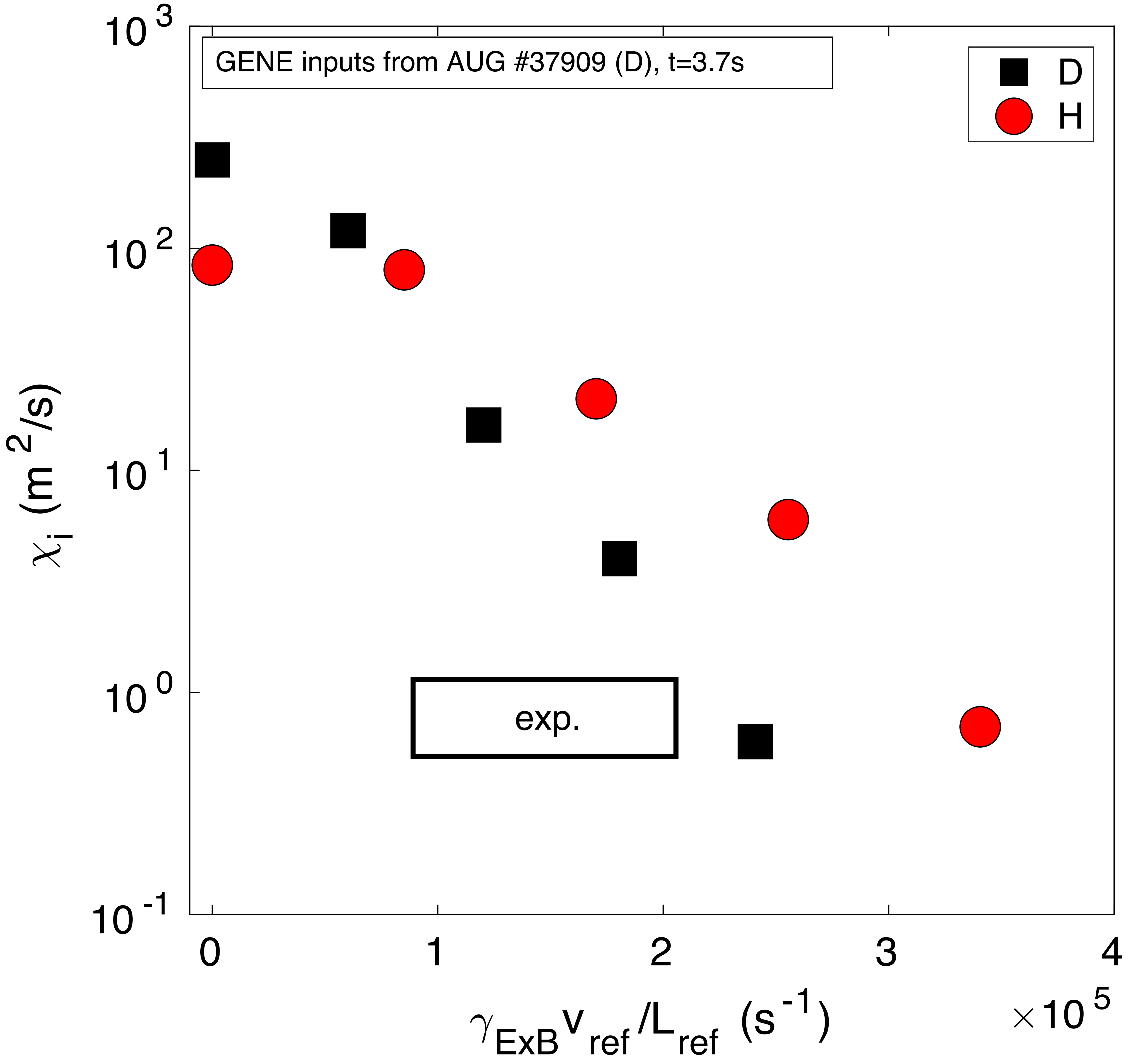
Local GK simulations in the ELM-free H-mode phase: Deuterium v/s Hydrogen

- Same normalized ExB shear is needed in H to obtain the same fluxes as in D with the same input parameters.
- ExB normalization depends on the ion mass in GENE -> **higher values of ExB shear in rad/s are needed in H to obtain the same flux reduction as in D with the same plasma parameters**

ExB shear normalized (GENE units ~ v_i/a):



ExB shear in rad/s:



Test of reduced models: ASTRA-TGLF-sat2* full radius simulations

*(G.M.Staebler et al. Nucl. Fusion 61 2021)

Results shown so far and previous studies using full-radius simulations on L-mode plasmas confinement properties with reduced models (C. Angioni et al., 2022 Nucl. Fusion 62 066015) motivates ASTRA-TGLF-sat2 full-radius simulations of AUG shot #37909 including γ_{ExB} effects:

- Only engineering parameters as inputs (B_T, I_p, heating, $\langle n_e \rangle$). Plasma heating from TORBEAM, RABBIT and artificial Gaussian heating profiles on electrons and ions used for heating scans.
- Plasma boundary prescribed
- Boundary condition at $\rho = 1$ with 2-point mode, $T_i = 1.3T_e$, $n_{e,sep}=0.3\langle ne \rangle_{Vol}$
- Experimental electron density imposed using feed-back control of the neutral source at the separatrix (as in C. Angioni NF 2022)
- E_r from main ion radial force balance with self-consistent pressure term and neoclassical rotations. We impose $E_r=0$ at the separatrix. (A 2-D momentum transport system is required to capture the way the plasma poloidal velocity departs from neoclassical as the separatrix is approached (viscous shear layer) [Staebler NF 2015]. This is left for future work.)

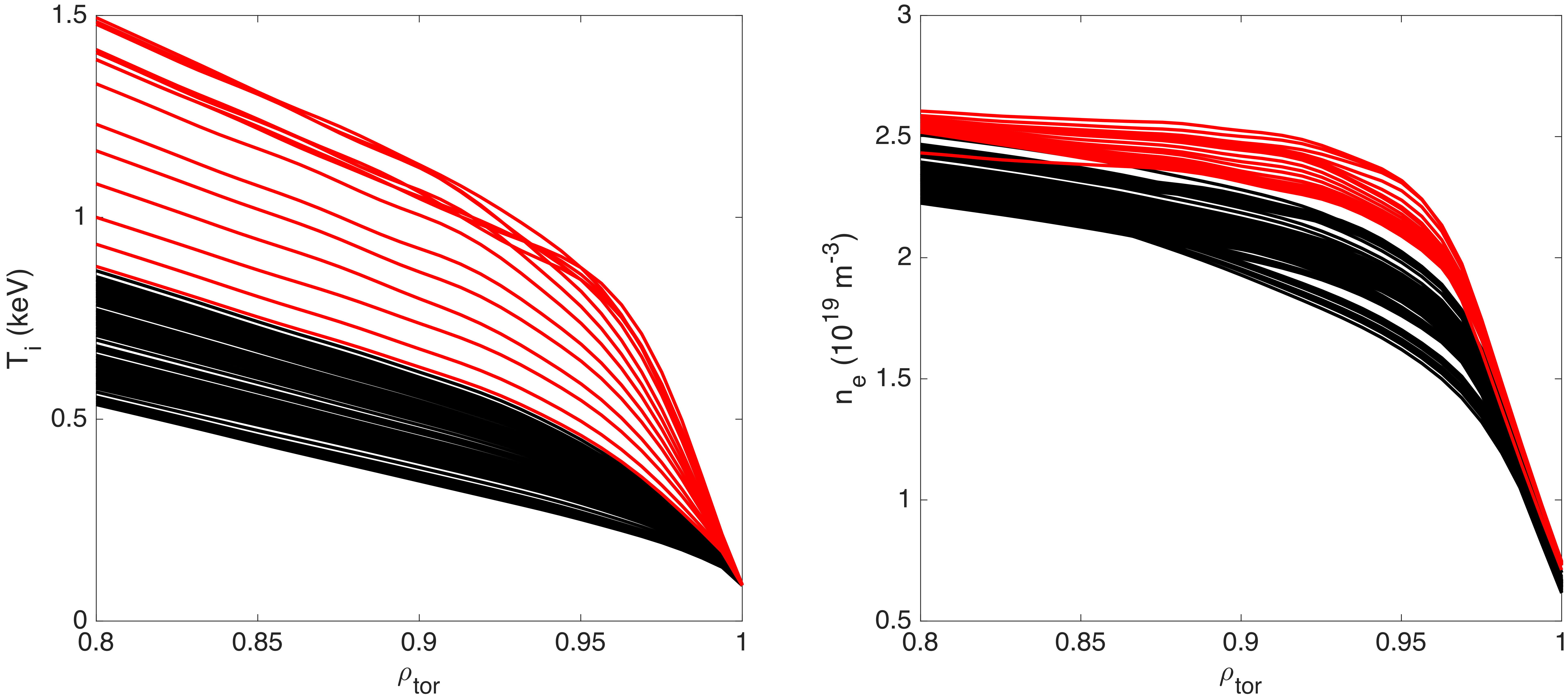
$$E_r = \begin{cases} \dfrac{\nabla p_i}{Z_i e\, n_i} - \mathrm{v}_{i\theta} B_\varphi + \mathrm{v}_{i\varphi} B_\theta, & \rho_{\mathrm{pol}} \le \rho_{\mathrm{min}} \\ \left(\dfrac{1-\rho_{\mathrm{pol}}}{1-\rho_{\mathrm{min}}}\right)^{\alpha} E_r(\rho_{\mathrm{min}}), & \rho_{\mathrm{min}} < \rho_{\mathrm{pol}} \le 1 \end{cases}$$

- TGLF-sat2 for turbulent transport
- NCLASS for neoclassical transport

ASTRA-TGLF-sat2 full radius simulations

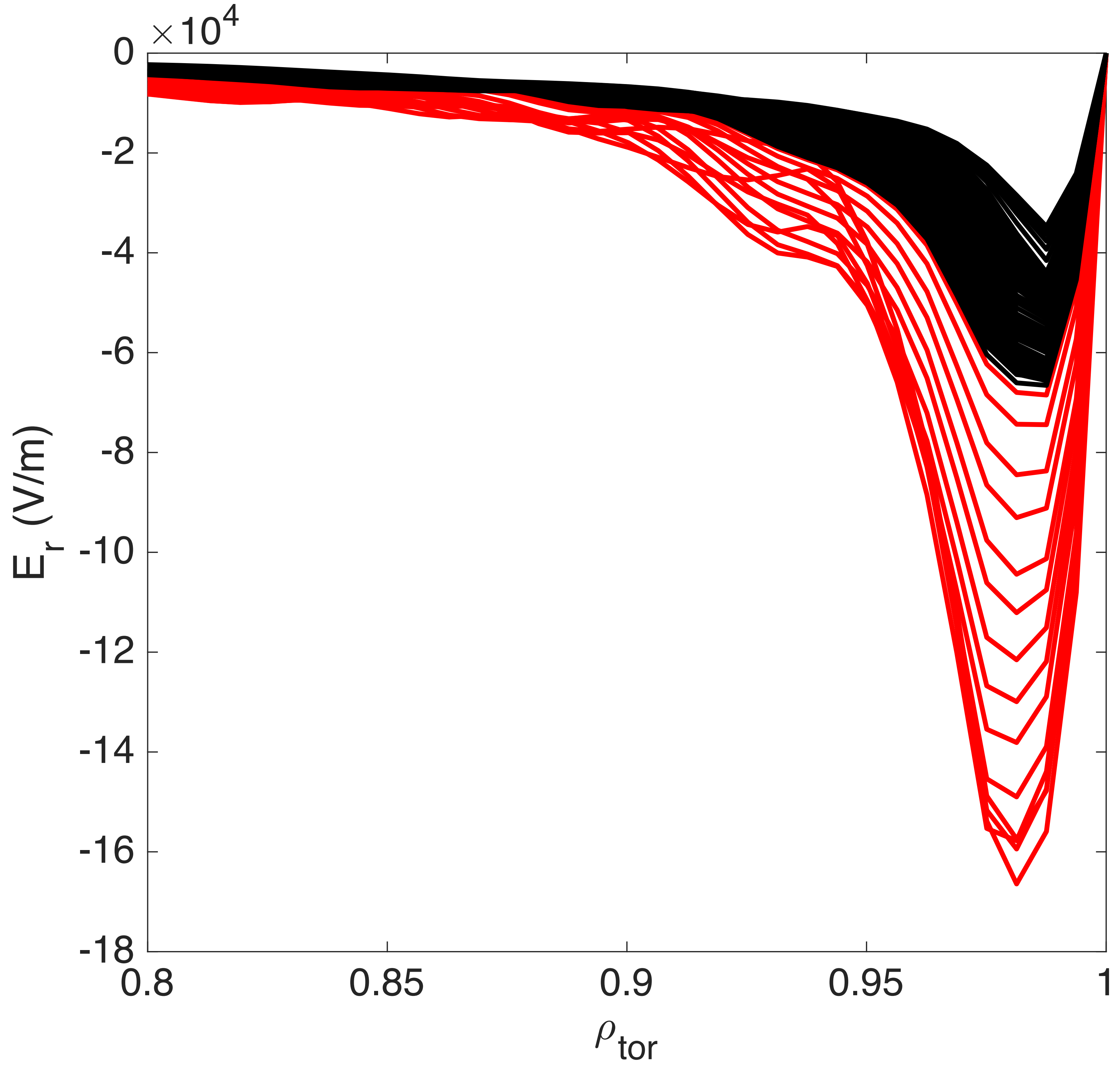
Additional heating was necessary in these cases to obtain a strong pedestal formation in the ASTRA-TGLF simulations

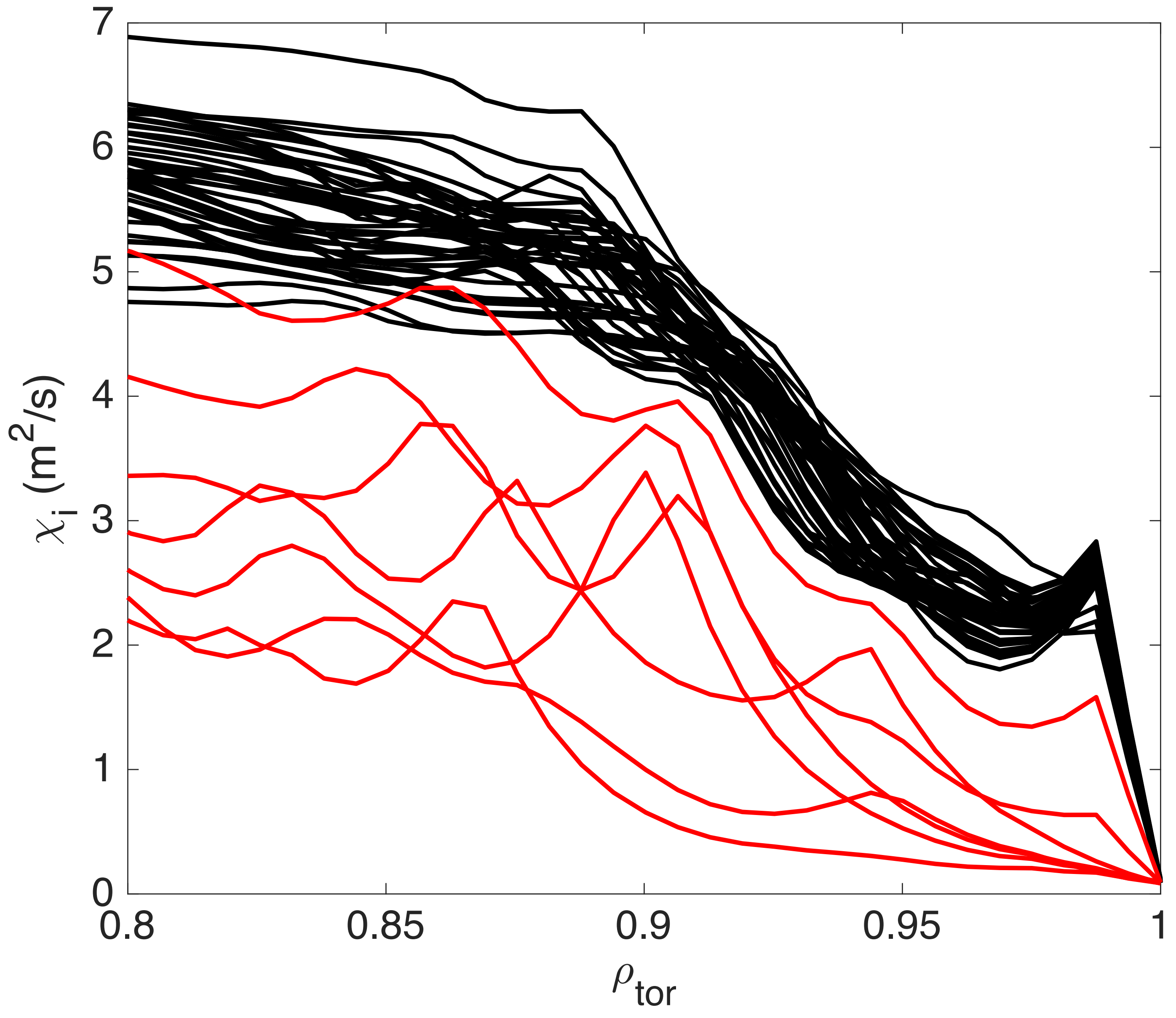
- $Q_{i,exp}$ ~ 0.75 MW v/s $Q_{i,sim}$ ~ 2.5 MW to reproduce the experimental profiles of the ELM-free H-mode phase
- $Q_{i,sim}$ ~ 4.0 MW at the strong pedestal formation



ASTRA-TGLF-sat2 full radius simulations

- Once the pedestal formation starts, a broadening of the edge electric field well is observed with a inner shift of the E_r minimum, as observed experimentally
- Also a strong suppression of the transport coefficient is observed in the edge region



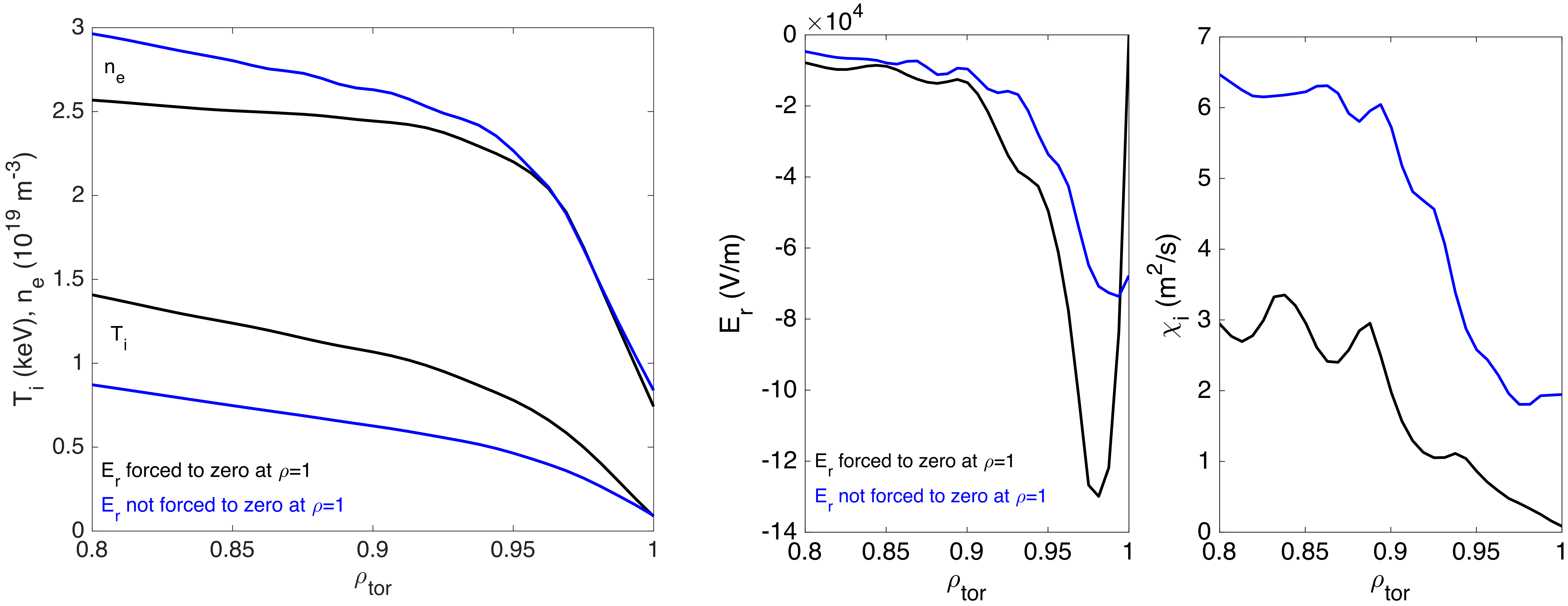


ASTRA-TGLF-sat2 full radius simulations

- A strong sensitivity of the results on all the parameters that can affect the edge radial electric field profile is observed (Z_{eff}, E_r values at the separatrix, boundary conditions etc.)

Here an example of the effect of the E_r condition at the separatrix is shown: BLUE = E_r is forced towards zero outside r_{tor}=0.995; BLACK = E_r follows the plasma profiles with no imposition at the separatrix

- Higher heating powers are needed when E_r is not forced towards zero at the separatrix in order to obtain the strong suppression of the turbulent fluxes

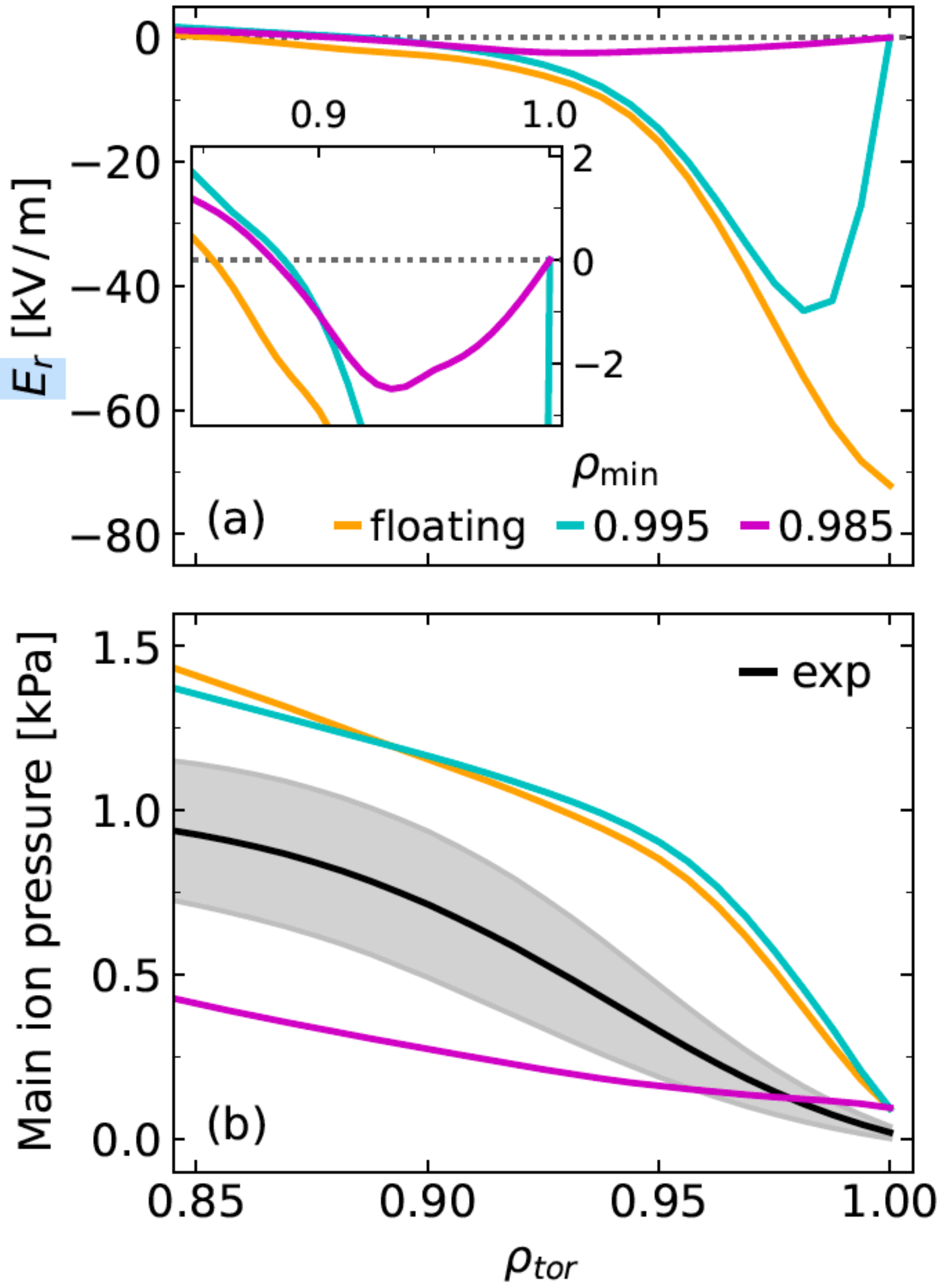


Dependence also on the plasma parameters

D. Fajardo et al., Submitted to Nucl. Fusion 2023

AUG 39323 t=5.0−6.0 s **NBI:1.49 MW** Ip=0.52 MA q95=8.17 --> **ion heated discharged**, power close to the L-H transition

--> similar workflow used for the previous simulations, here also the impurities are evolved with FACIT



Impact of self generated Reynolds stresses on the rotation terms entering in the radial force balance [Staebler G. et al 2015 Nucl. Fusion 55 073008]

Effects due to ion orbit losses [Hongxuan Zhu *et al* 2023 *Nucl. Fusion* **63** 066009]

--> Provide a self-consistent description of the Er well that is better reconciled with the positive SOL Er values set by parallel dynamics on the open field lines and sheath boundary conditions at the target

Next steps for a reduced model for the L-H transition

--> **Adjust the reduced models to GK simulations in the edge region**

Further studies with GK simulation of the edge turbulence just prior/after the L-H transition, possibly using stationary ELM-free cases at low power

Non-linear EM effects?
ExB shear effect?
Saturation rule?
Geometry effects?
Parallel dynamics?

--> **Provide a self-consistent description of the Er well evolution** that is better reconciled with the positive SOL Er values set by parallel dynamics on the open field lines and sheath boundary conditions at the target

Impact of self generated Reynolds stresses on the rotation terms entering in the radial force balance [Staebler G. et al 2015 Nucl. Fusion 55 073008]

Effects due to ion orbit losses [Hongxuan Zhu *et al* 2023 *Nucl. Fusion* **63** 066009]

Conclusions

Local GK theory applied to describe edge turbulence from L-mode to H-mode transition:

- **Explain the experimental observed role of the isotope mass**: strong role of the parallel kinetic electron dynamics
- **Strong role of γ_{ExB} and of β_e are found** --> when all the parameters are taken into account consistently, **the GK simulations reproduce the heat fluxes behavior of dedicated experiments at ASDEX Upgrade up to the L-H transition**

- **TGLF-sat2 is found to follow the general trends of the GK simulations**, but the effect of the ExB shear is found to be weaker than in GENE and it lacks the nonlinear electromagnetic effects for edge parameters and large ExB shear.

- **Full radius simulations with ASTRA-TGLF-sat2 perform quite well and are able to predict pedestal-like structures** in the edge plasma region that resemble the experimental ones

These results pave the way to many future applications, including full radius simulations of the discharge evolution from L- to H-mode, also in combination with IMEP (Luda NF 21) for H-mode phase. An application to DTT power ramp-up is shown in Casiraghi et al EPS 2022.