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EUROfusion

Experimental investigation and gyrokinetic simulations of multi-scale electron heat transport in JET, AUG and TCV

A. Mariani, N. Bonanomi, P. Mantica, C. Angioni, F.J. Casson, J. Citrin, T. Goerler, D. Keeling, E. Lerche, O. Sauter, M. Sertoli, G. Staebler, D. Taylor, A. Thorman, Eurofusion JET1 contributors, Eurofusion MST1 contributors, ASDEX Upgrade team, TCV team and ITPA transport & confinement group

EUROfusion
JET
Università degli Studi di Milano Bicocca
ISTP Consiglio Nazionale delle Ricerche
EPFL
Swiss Plasma Center
ASDEX Upgrade
IPP Max-Planck-Institut für Plasmaphysik

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Outline

- Introduction: ETGs impact on electron heat transport;
- Experimental results at JET, AUG and TCV;
- Nonlinear ion-scale gyrokinetic simulations (GENE);
- Nonlinear multi-scale gyrokinetic simulations;
- Conclusions.

ETG modes could be detrimental to fusion performances in electron heated tokamaks

New devices like ITER → dominant electron-heating → T_i cannot exceed T_e

Fusion power $\propto T_i^2$ → T_e limited: degradation of fusion performances.

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Main **limit** to **T_e peaking**: **turbulent heat transport** driven by **drift waves:**

- Ion scales: Trapped Electron Modes (TEM): driven by $\nabla \ln(T_e)$, $\nabla \ln(n_e)$
- Electron scales: Electron Temperature Gradient (ETG) modes: driven by $\nabla \ln(T_e)$

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Linear ETG threshold:
[F. Jenko et al. PoP 2001]

$$\left[\frac{R}{L_{Te}}\right]_{crit.} \propto \left(1 + Z_{\text{eff}}\frac{T_e}{T_i}\right)$$

$$R/L_{Te} = -R\nabla T_e \cdot \hat{r}/T_e$$

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From **nonlinear** physics:

ETG destabilised when Ion-scale modes ~ stable (reduced nonlinear ZF damping of ETGs)

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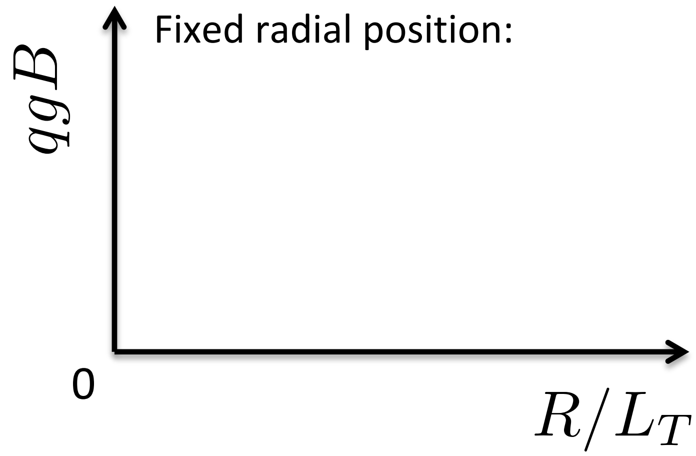
More likely to **observe ETGs** when:

proper **balance** of:

- **electron heating** (increasing R/L_{Te});
- **ion heating** (increasing T_i/T_e and sometimes stabilising ion scales by FI and ExB shearing ← ICH and NBI);

ETG induce electron temperature stiffness

Heat transport:



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Heat flux in gyro-Bohm units:

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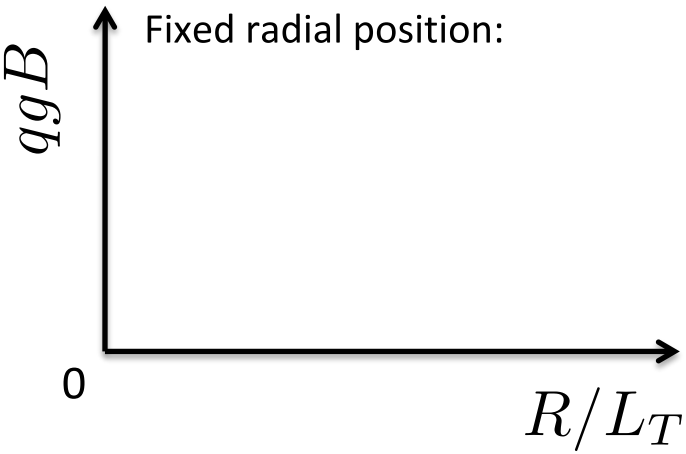

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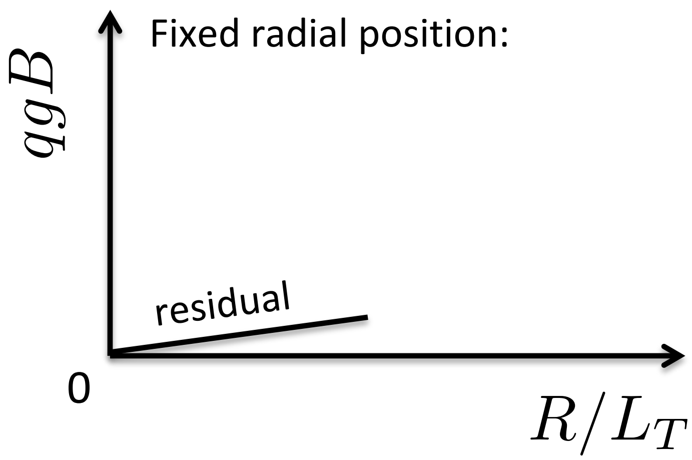

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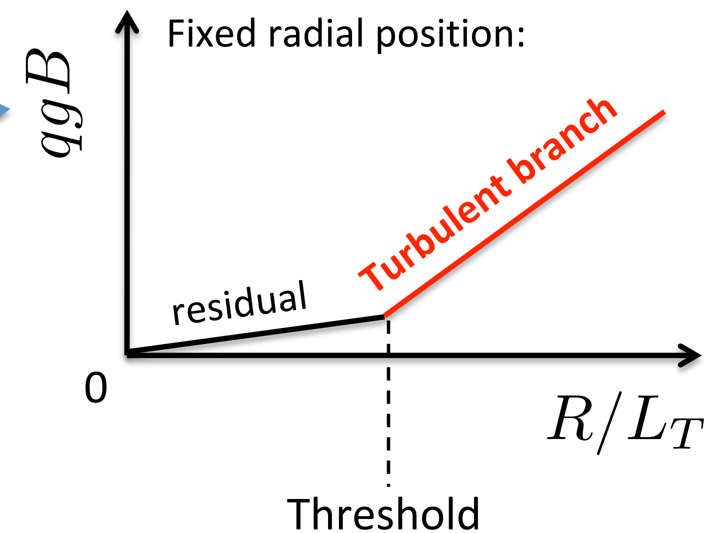

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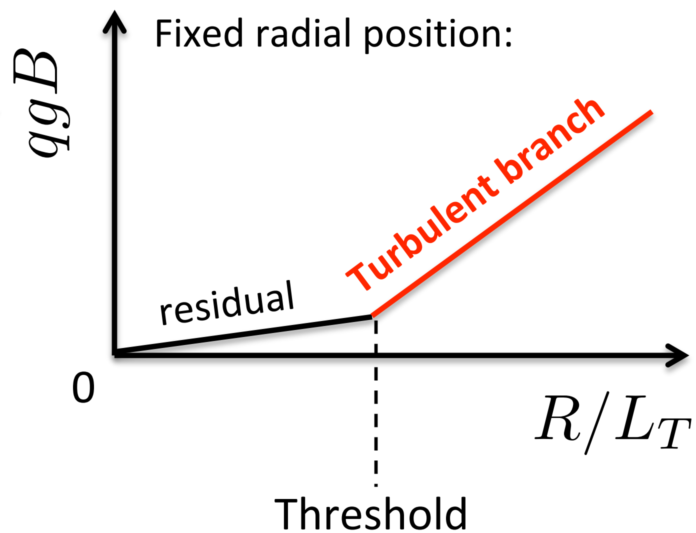

Temperature profile stiffness:

slope of the turbulent branch

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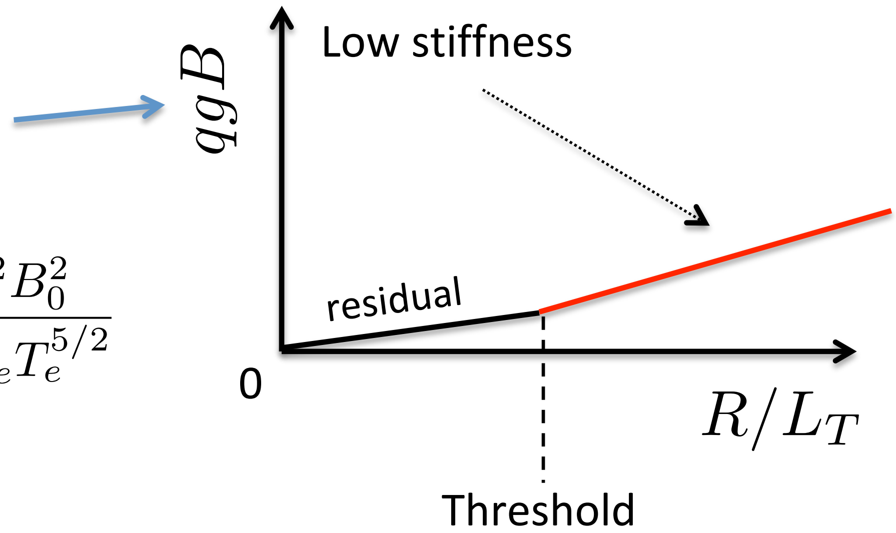

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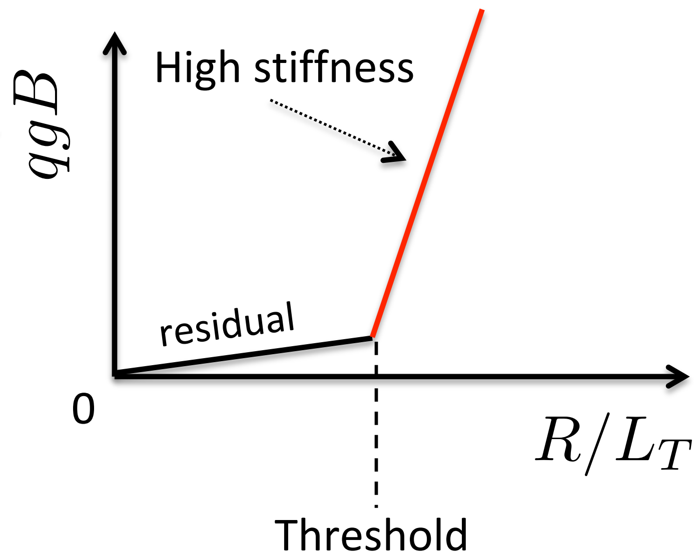

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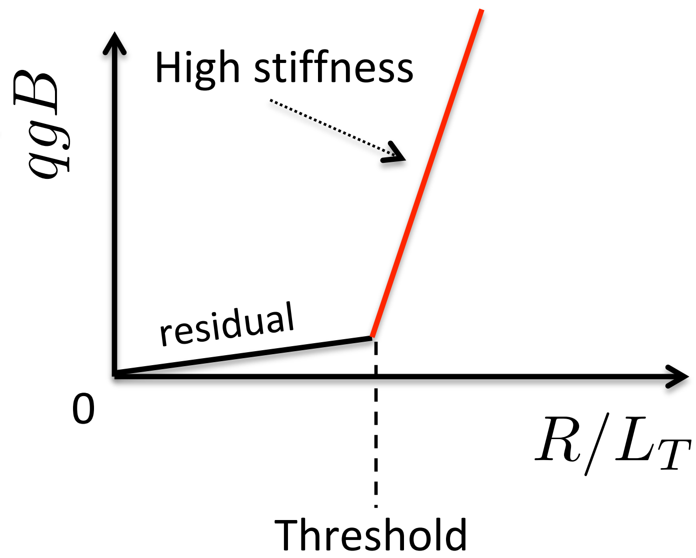

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ETGs ⟶ stiff T_e profile ⟶ T_e peaking has an upper limit due to ETGs

JET

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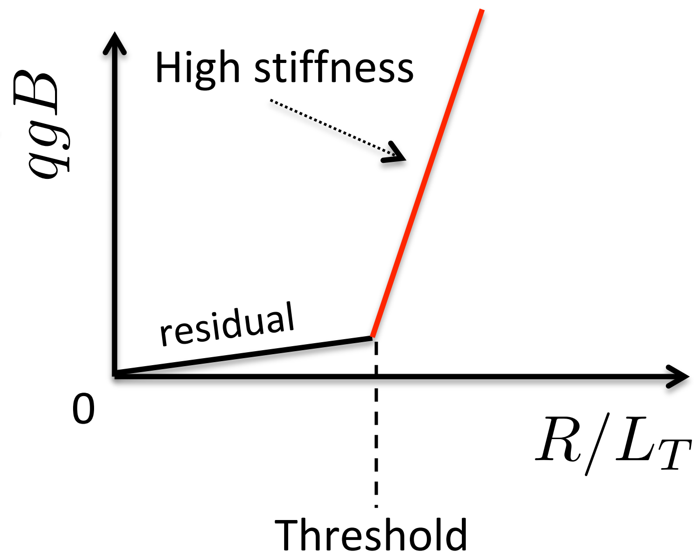


Temperature profile stiffness:

slope of the turbulent branch

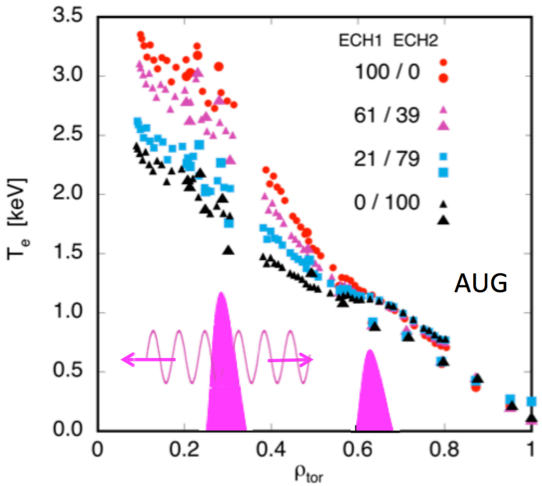
ETGs → stiff T_e profile → T_e peaking has an upper limit due to ETGs

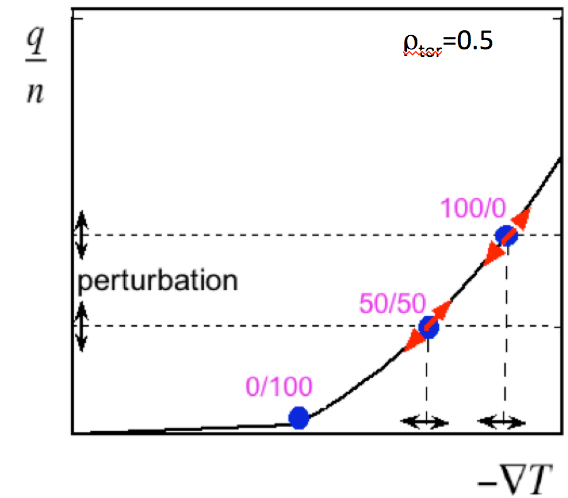
→ **very important: study ETG physics** → **suppress** them in **tokamaks** with **dominant electron heating**

ETGs: experiments and numerical simulations

Experiments:

Two independent methods
→ reconstruct $q_{e,gB}$ vs R/L_{Te} :
evaluate: slope (detect ETGs)





- **Heat flux scan:** change proportion of heating power (two radii)**:** two $q_{e,gB}$ vs R/L_{Te} points;
- **Perturbative analysis**: modulate heating power at one radius → heat wave: local stiffness;

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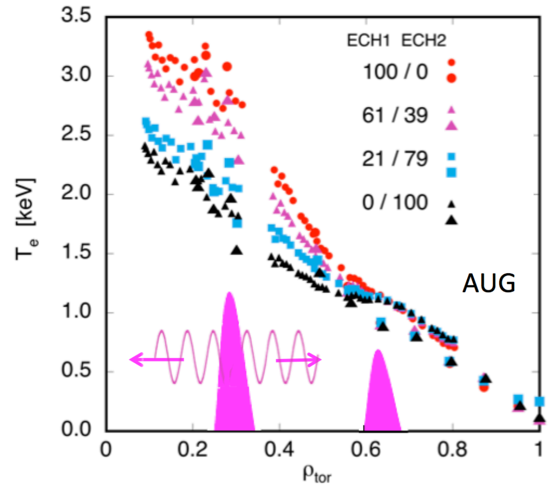

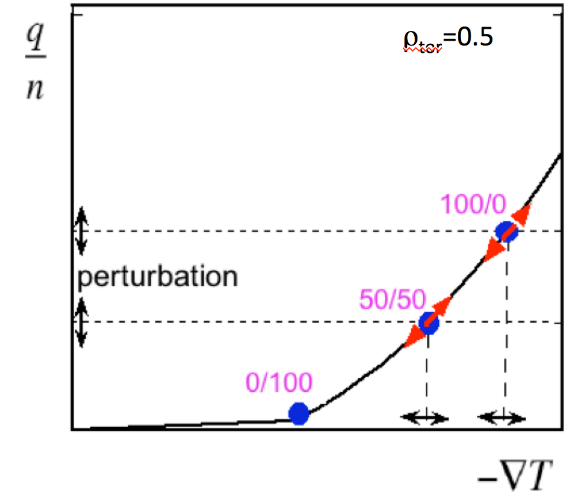

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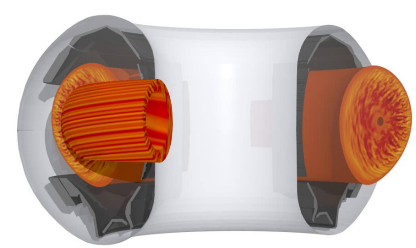
Simulations:

- **Girokinetic simulations** (micro-turbulence, scales: ~ion-electron Larmor radius)

Heavy, based on gyrokinetic (GK) eqs. In 5-dim. phase space

GENE
[Jenko F. *et al.* PoP 2000]



(from http://genecode.org)

Multi-machine investigation of ETGs

EUROfusion and **ITPA** Transport & Confinement group:

Extensive effort: analyse **data** produced by **different tokamaks** investigating **ETG** contribution to **the heat transport**:

comparing: **experiments** ⟷ **numerical simulations**

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Here: comparison of dedicated pulses from the following tokamaks:

- **TCV**: Swiss Plasma Center (SPC)-EPFL, Lausanne, Switzerland
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Analysis: same radial position: ρ_{tor}=0.5:

Experiments at TCV, AUG and JET

TCV

[Mariani A. et al., NF (2019)]

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TCV

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- L-modes, B_0 = 1.41 T , I_p = 170 kA;
- Heat flux scan: vary ECH power (~0.4 – 0.7 MW) deposition on- vs off-axis;
- Perturbative analysis: ECH steady and modulated;
- Each pulse: different phases with different proportion of NBI(~1 MW) /ECH power to vary T_e/T_i.

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AUG

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- H-modes, $B_0 = 2.6\ T$, $I_p = 0.8$ MA;
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- NBI(~5 MW) to have T_e~T_i.

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Very recent experiments (2020)

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Very recent experiments (2020)

JET

[Mantica P. et al., To be submitted]

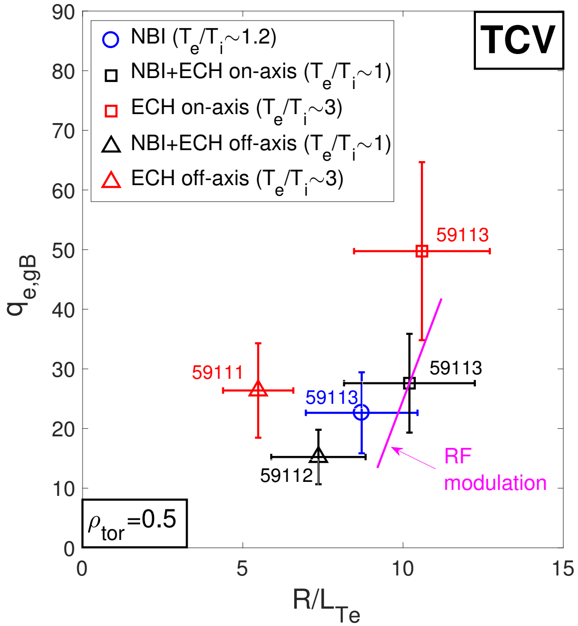
- L-modes and H-modes, B_0 = 3.3 T , I_p = 2 MA;
- Heat flux scan: vary ICH power (<6 MW, H minority to mainly heat electrons) deposition;
- ICH only steady (no perturbative analysis);
- NBI(<20 MW) to have a T_e/T_i range.

Experimental results: electron heat flux scans

TCV

- **ECH only**, **mixed NBI-ECH** ($T_e \sim T_i$), and **NBI only** cases:

- ECH modulation: **mixed NBI-ECH** with **ECH on-axis**



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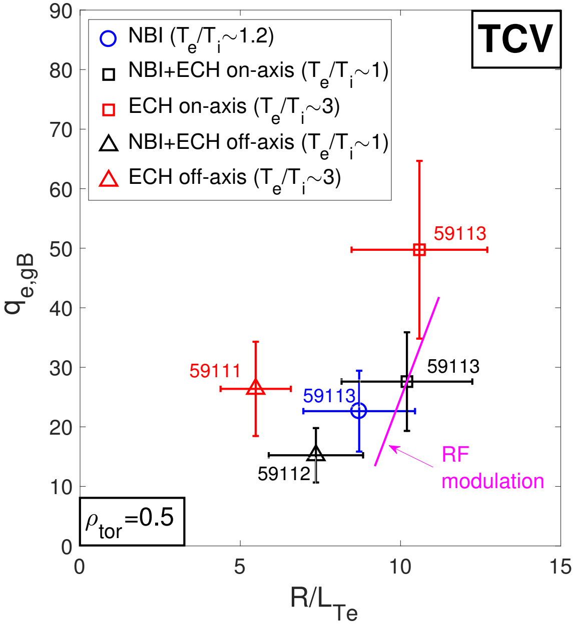

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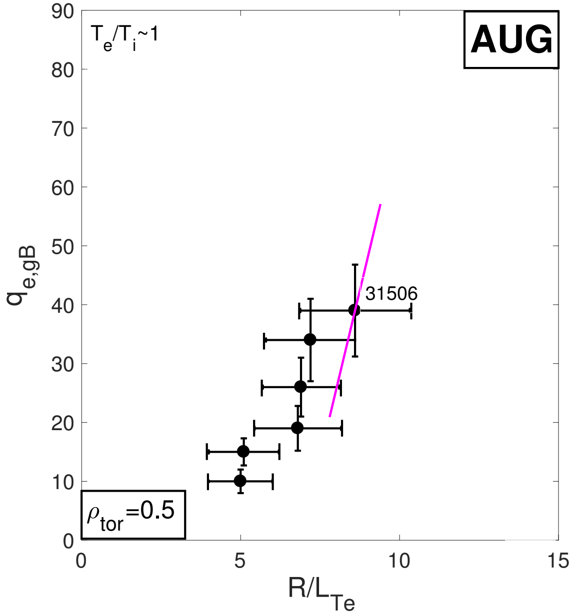
AUG

- All experimental cases (T_e~T_i);
- ECH modulation: highest $q_{e,gB}$ point



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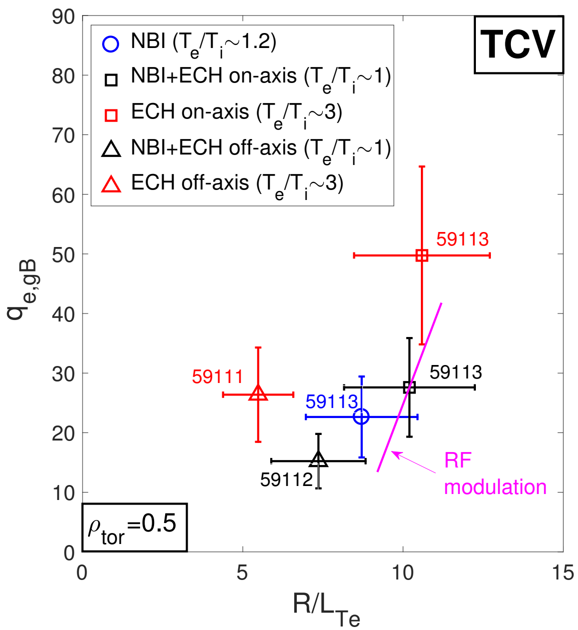

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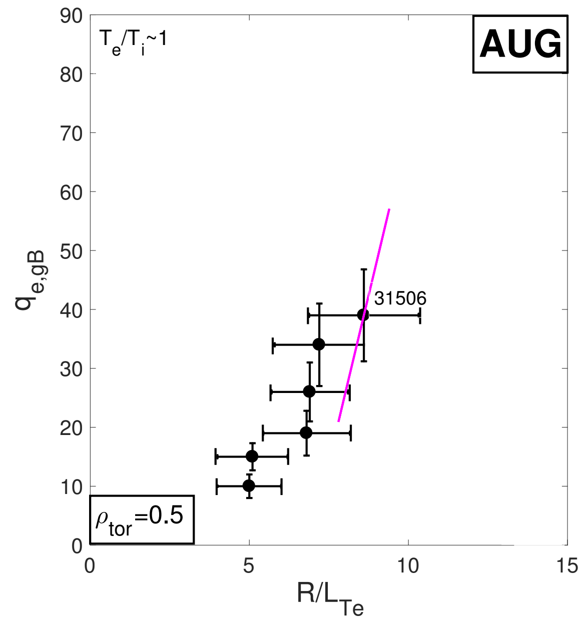
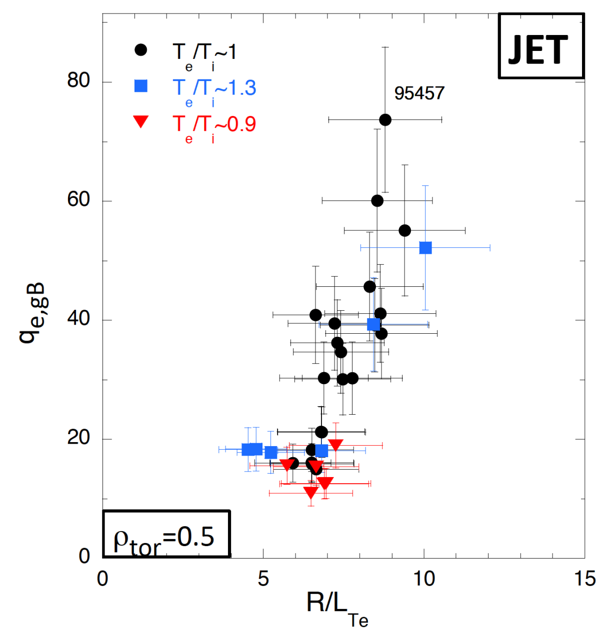


[Bonanomi N. et al., to be submitted]

JET

- All experimental cases (T_e/T_i range);
- No RF modulation;



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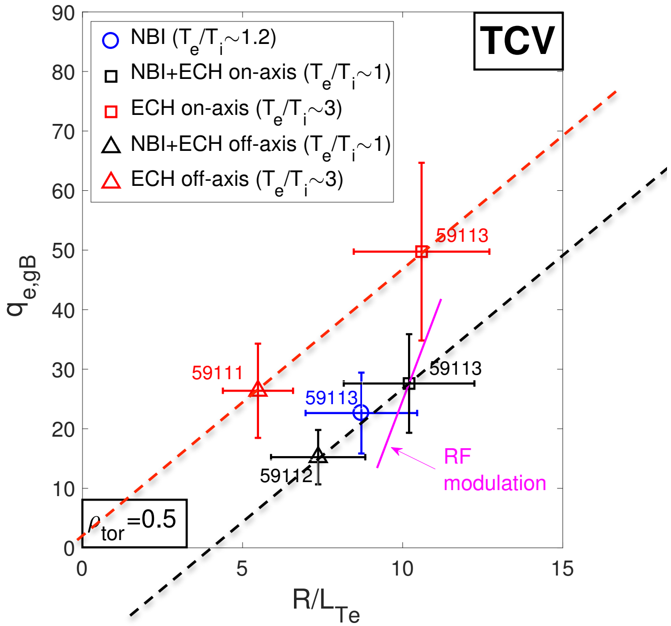

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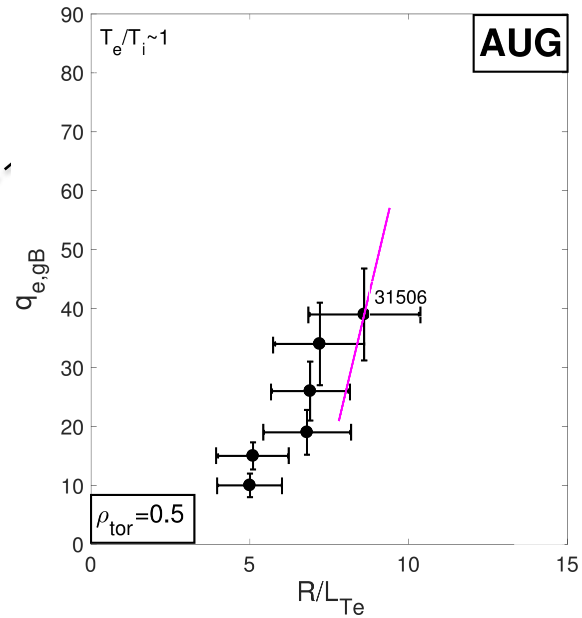

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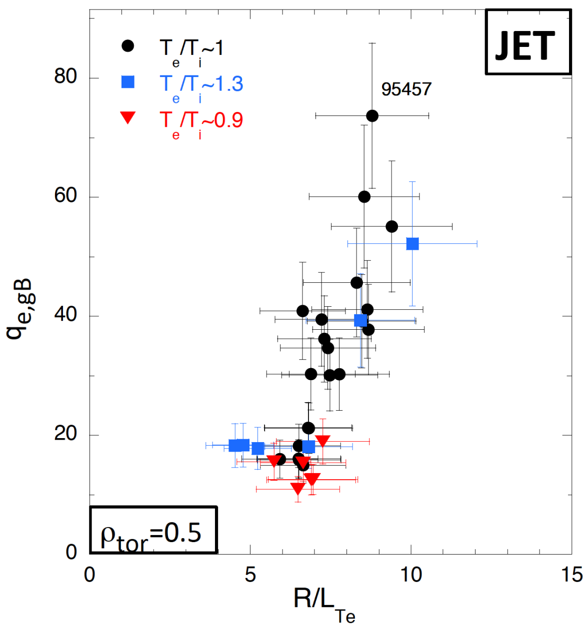

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- Steady state: TEM-compatible moderate stiffness;

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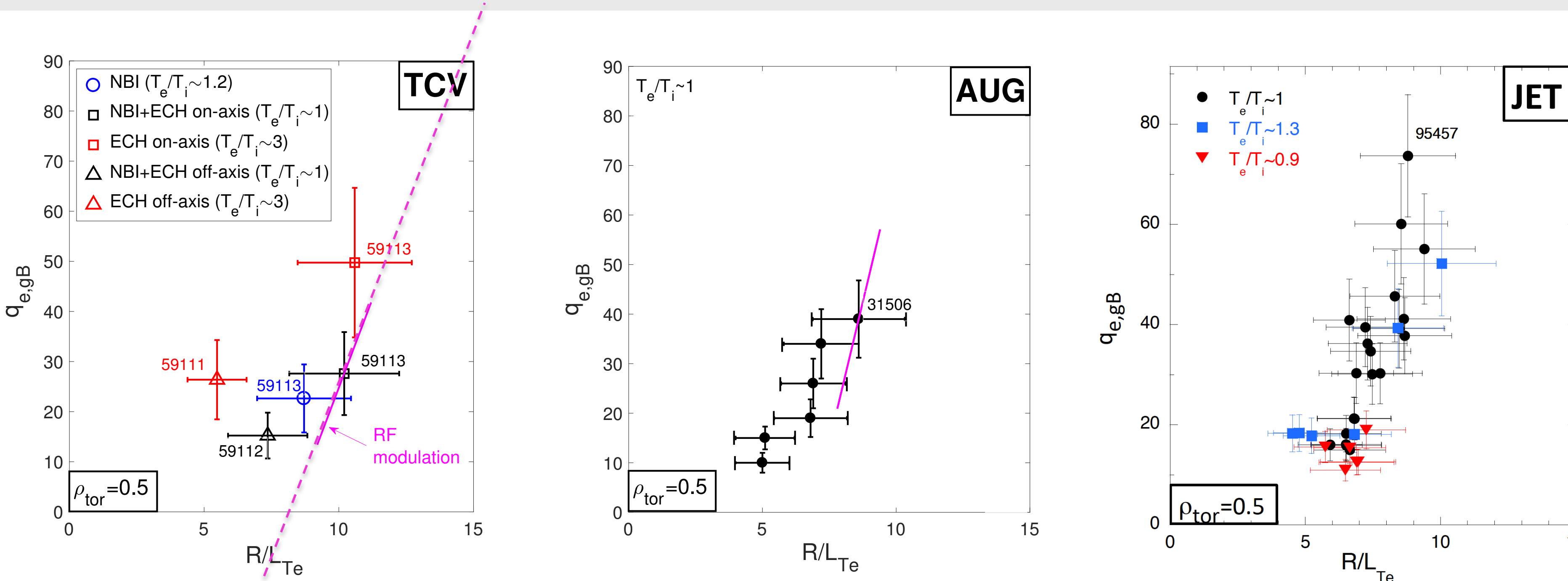

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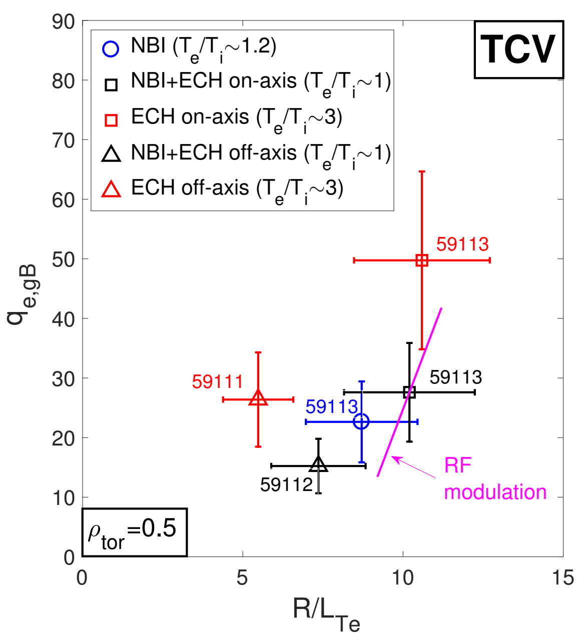

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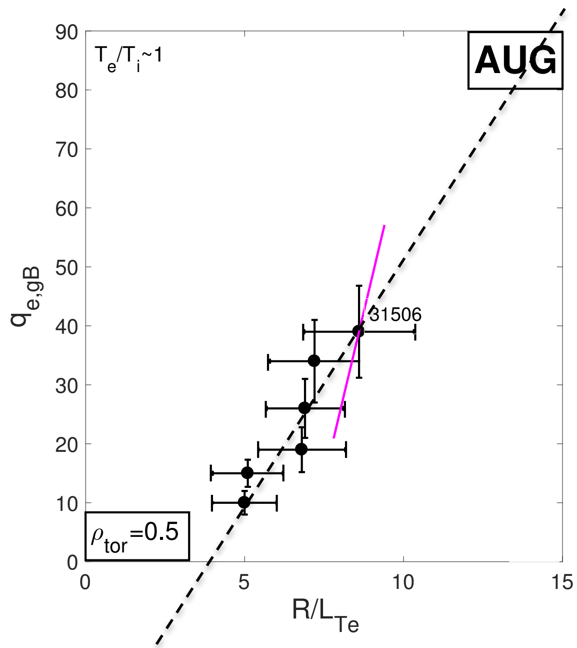

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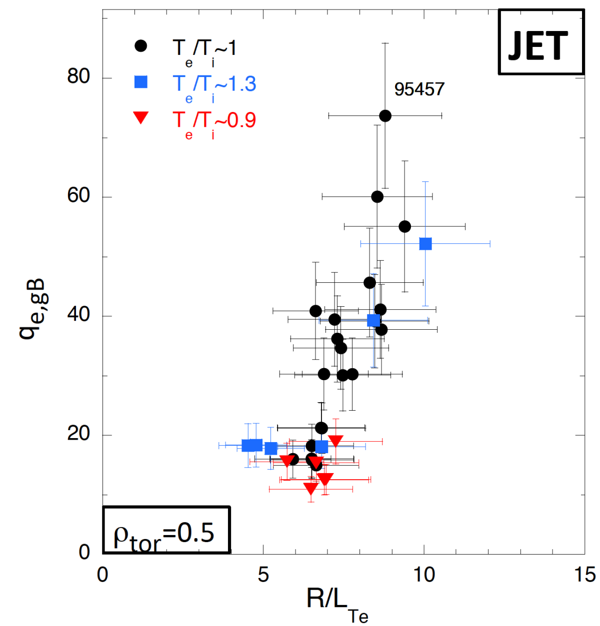

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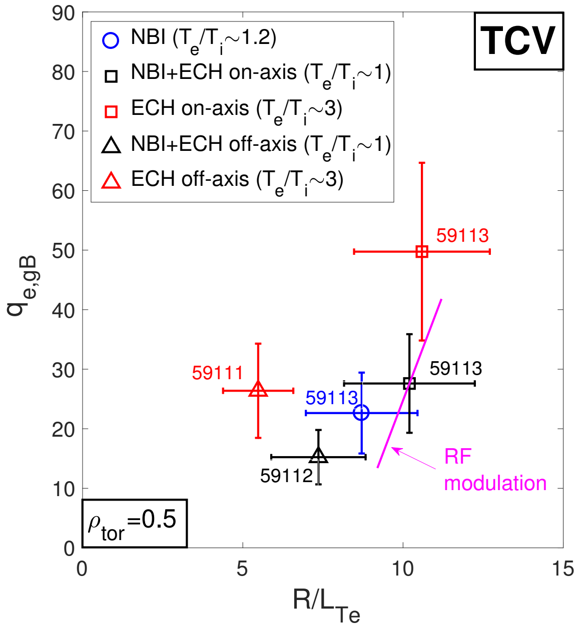

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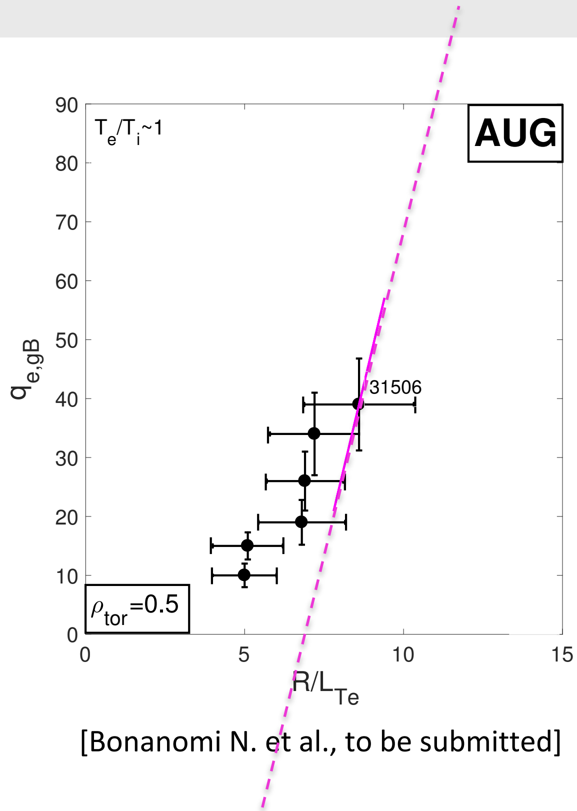

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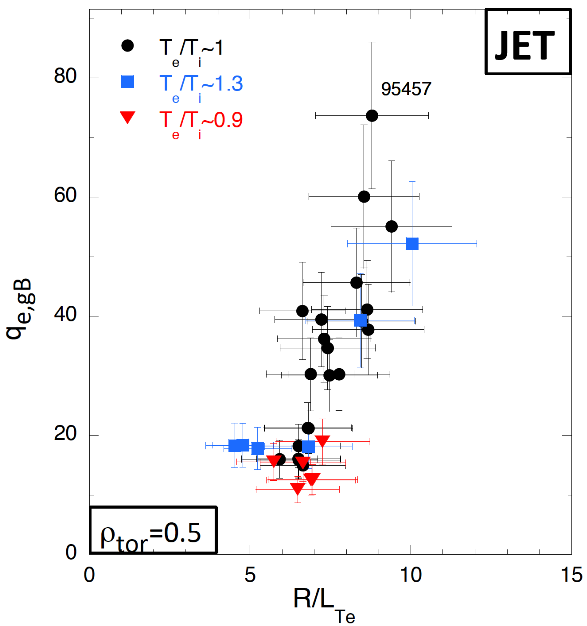

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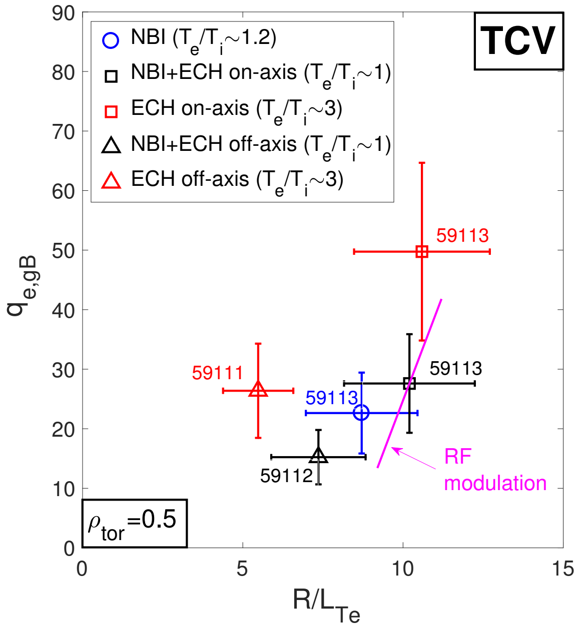
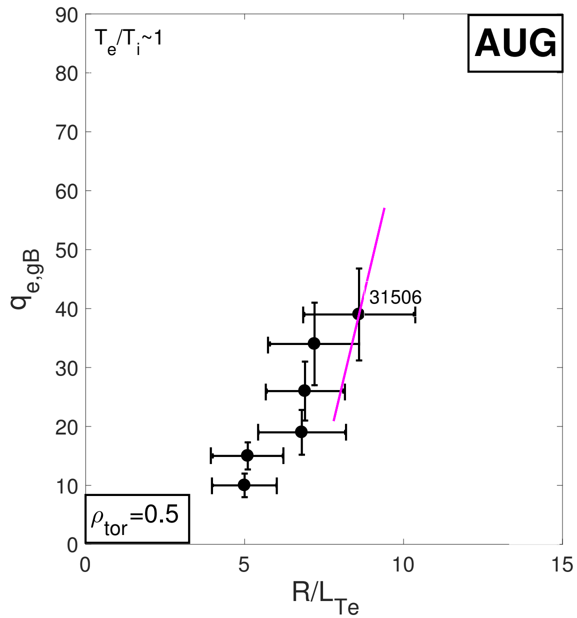
Experimental results: electron heat flux scans



Adapted from [Mariani A. et al., NF (2019)]



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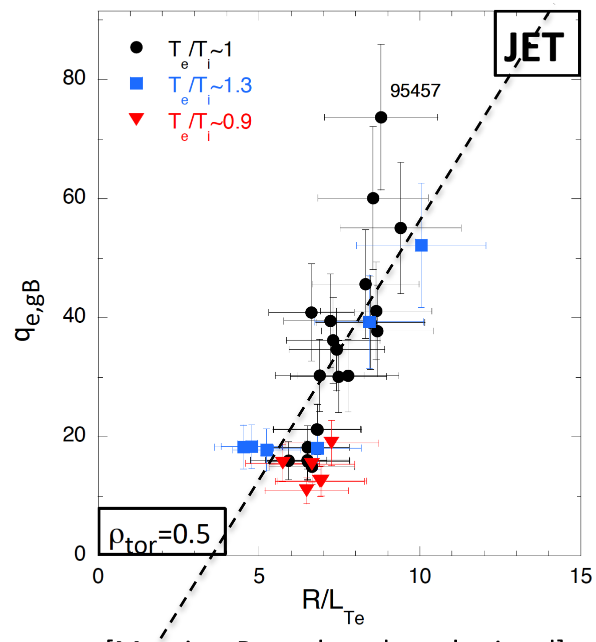

[Mantica. P. et al., to be submitted]

- Steady state: TEM-compatible moderate stiffness;
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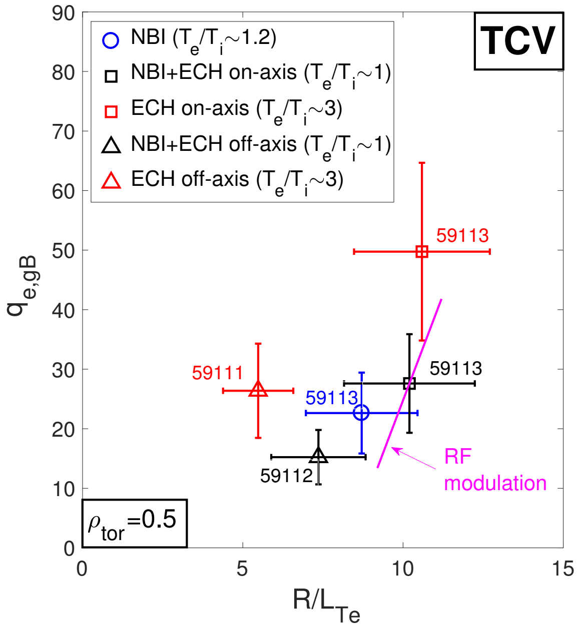

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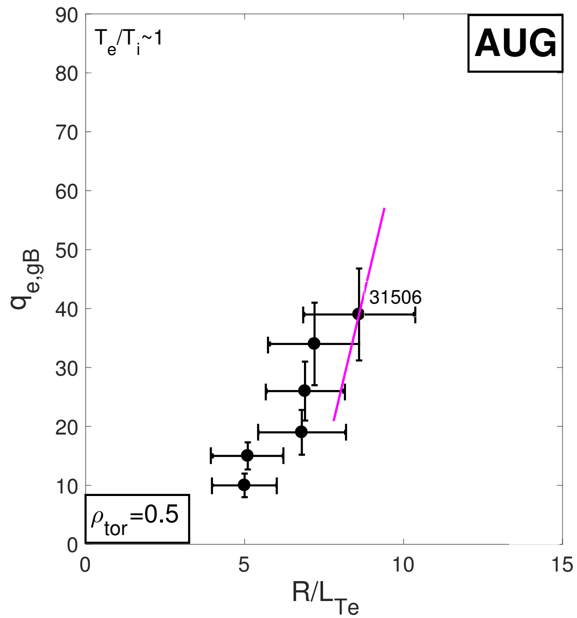

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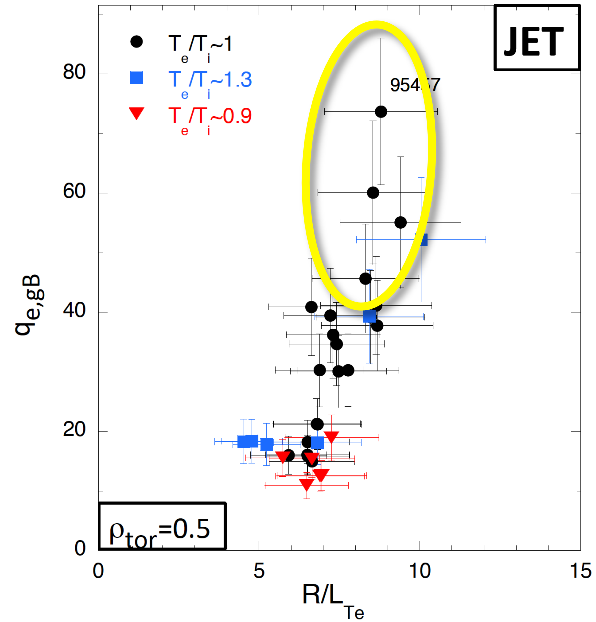

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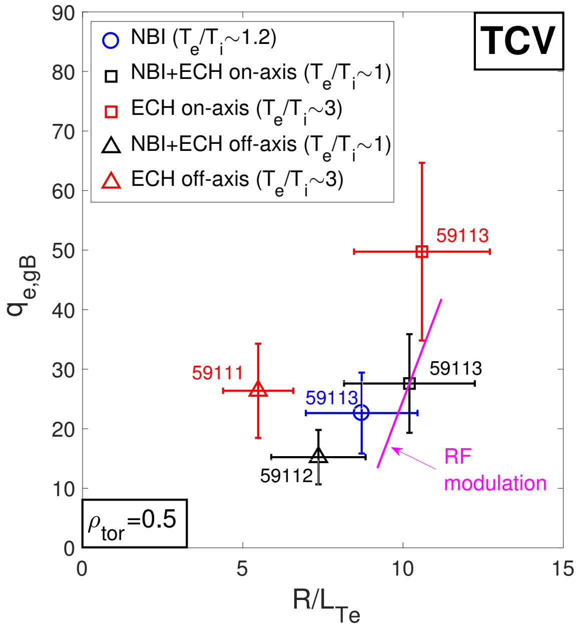

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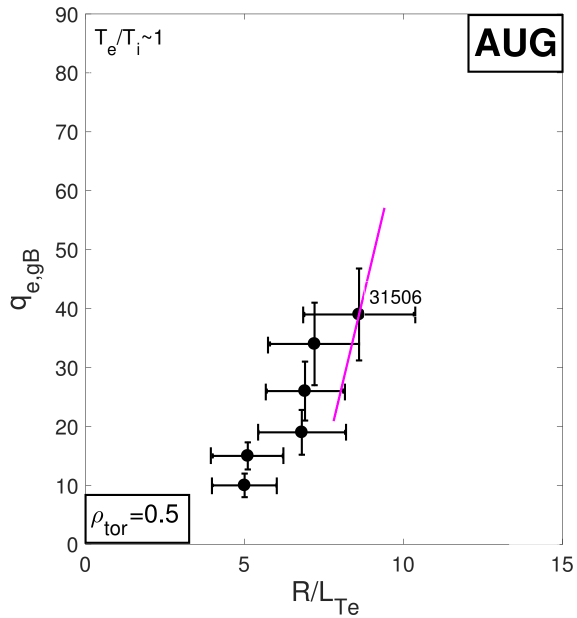

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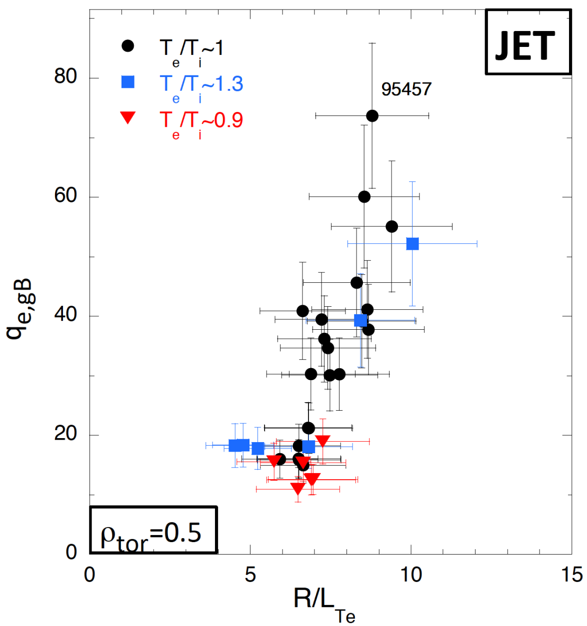

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Comparison: **possible ETGs role**: cases with **balanced electron/ion-heating: T_e~T_i** and **large R/L_{Te}** .

Gyrokinetic simulations (GENE)

- Flux-tube (radially local) version of GENE;

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JET

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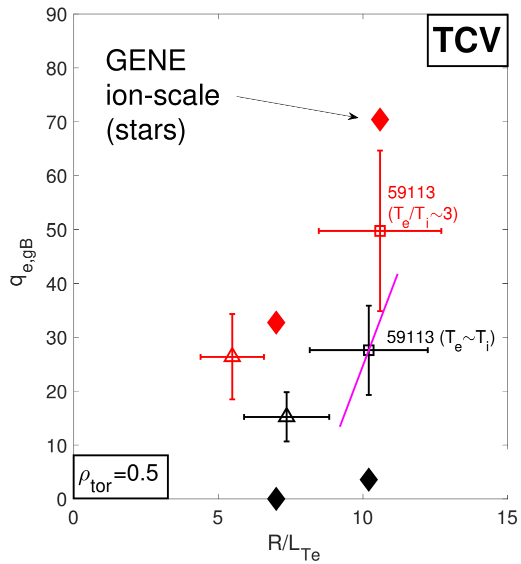
- ExB shearing: considered for TCV; neglected for AUG and JET (much smaller values).

Nonlinear ion-scale gyrokinetic simulations

TCV

- GENE (diamonds) compared with exp. points and ECH modulation



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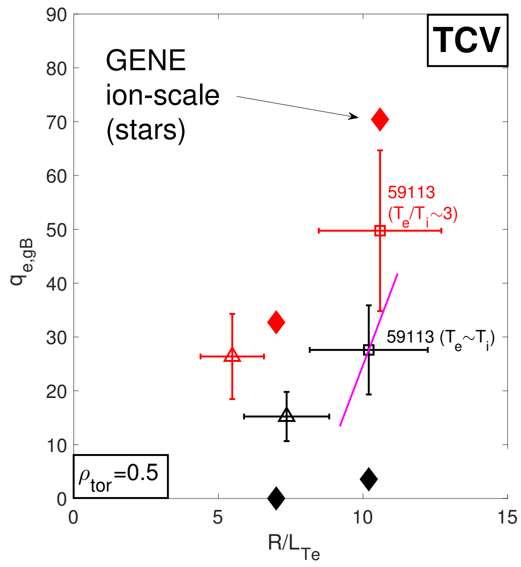

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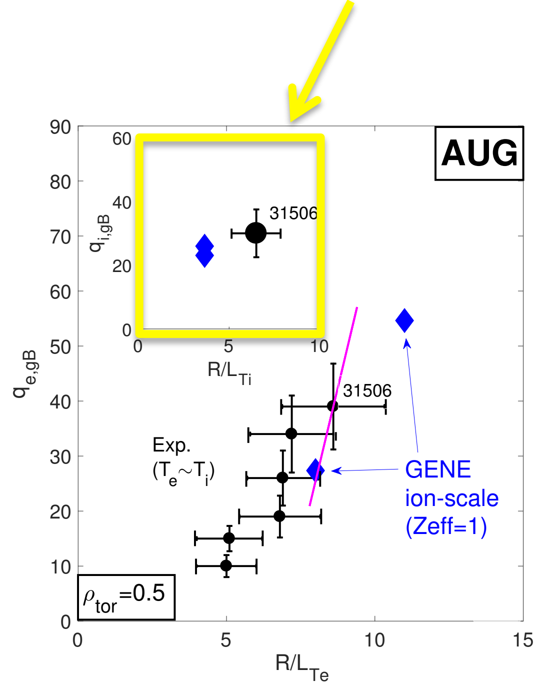
AUG

- Same as TCV, but also looking at the ion channel;



[Bonanomi N. et al., to be submitted]

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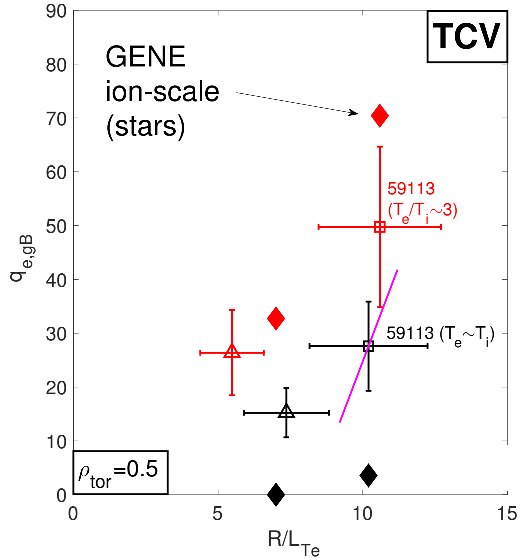

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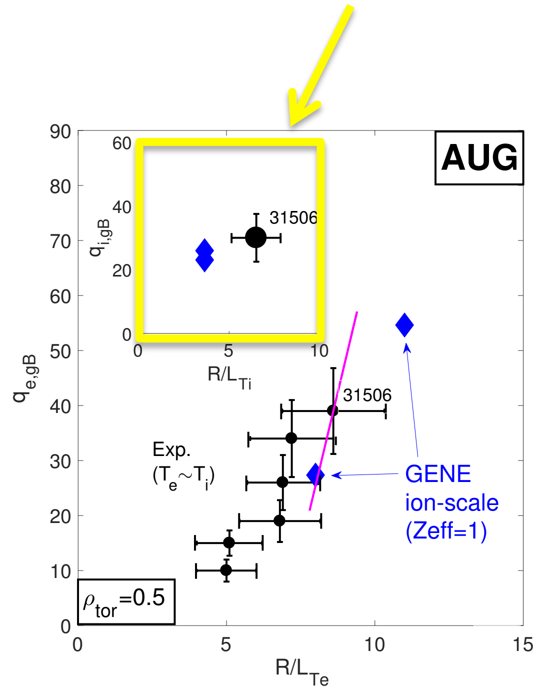

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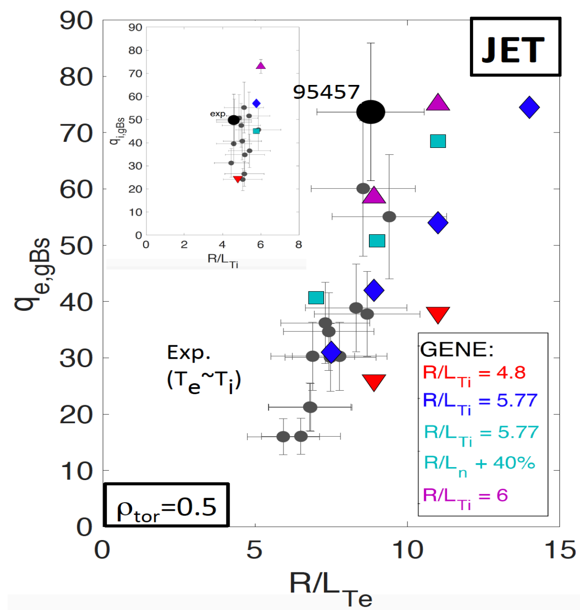
JET

- Similar, but the sensitivity to R/L_{Ti} and R/L_{ne} is tested (colored markers);



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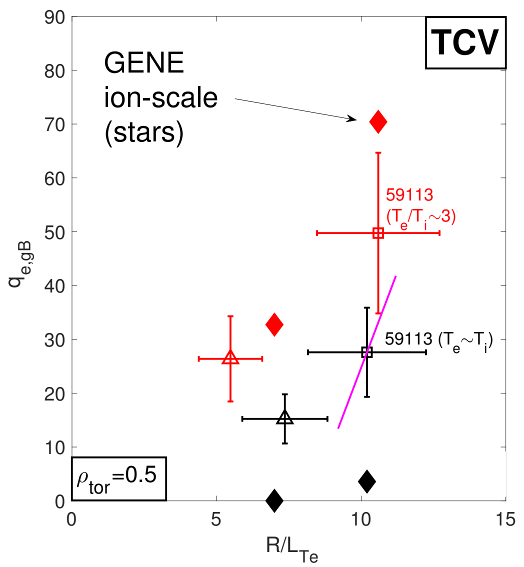
Nonlinear ion-scale gyrokinetic simulations



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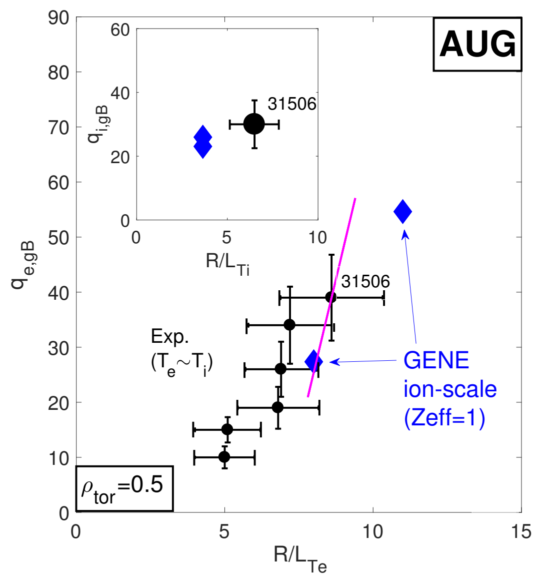

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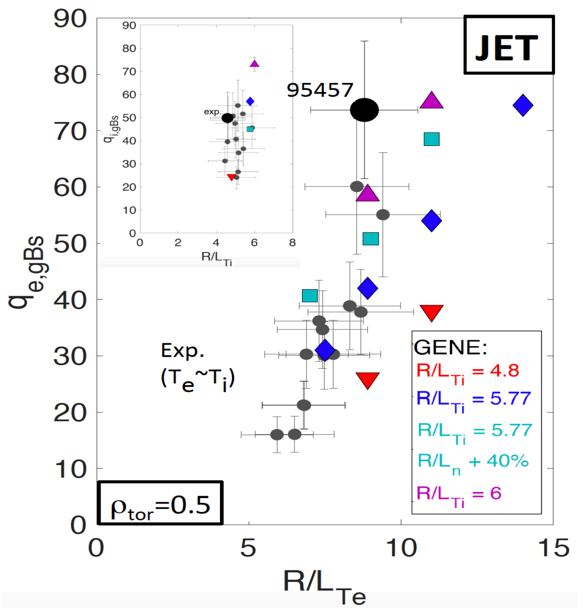

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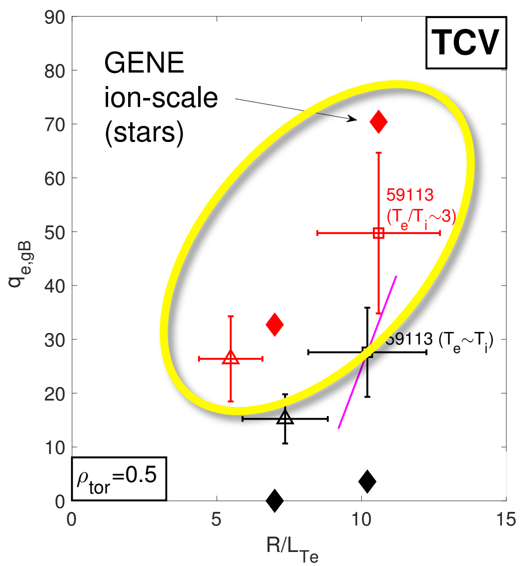

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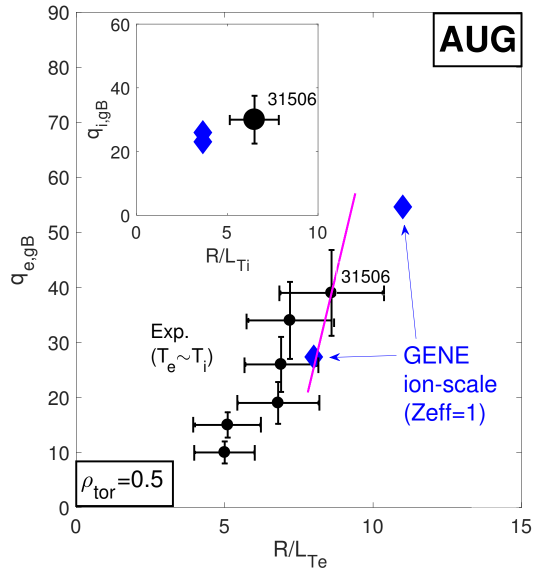

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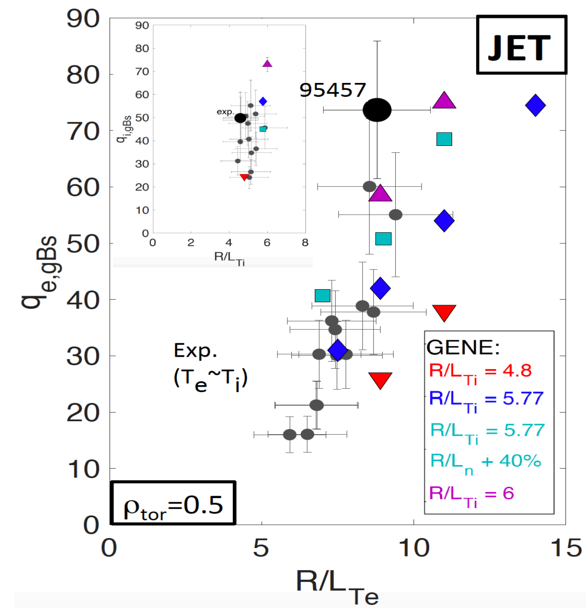

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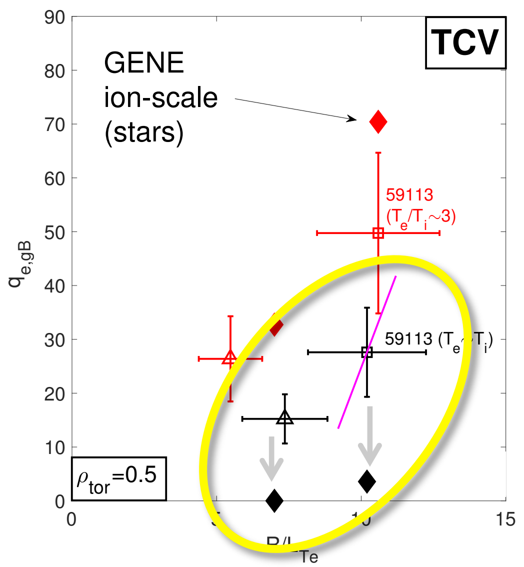
Nonlinear ion-scale gyrokinetic simulations



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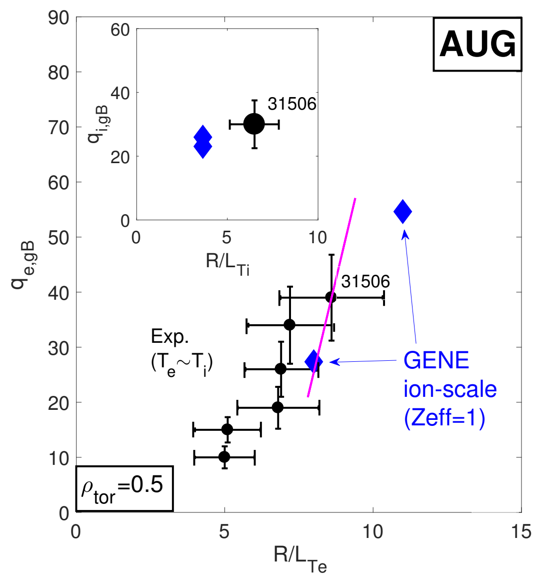

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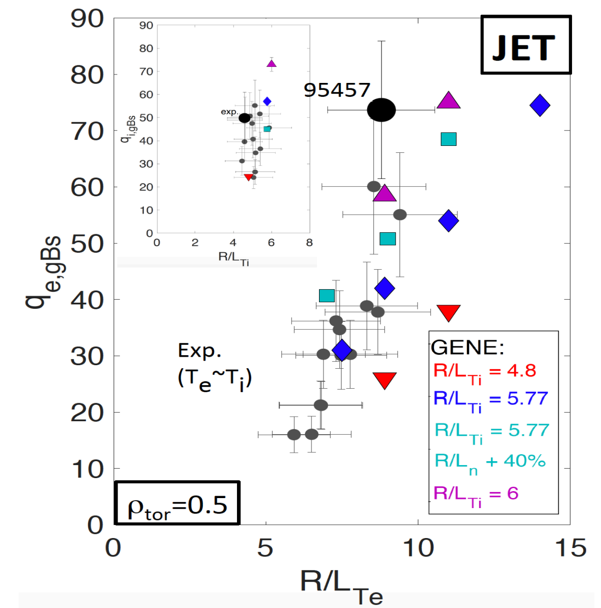

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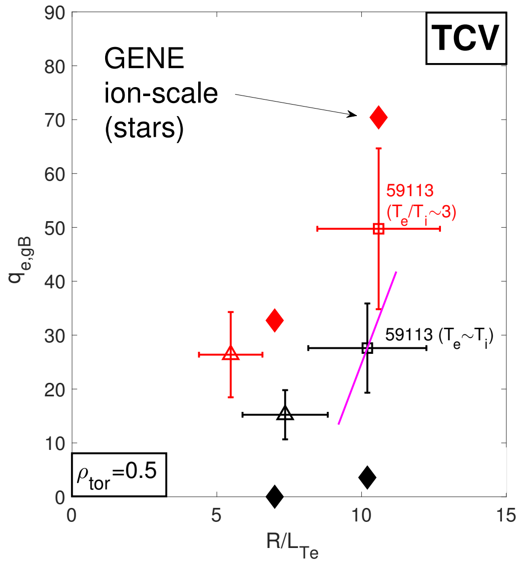

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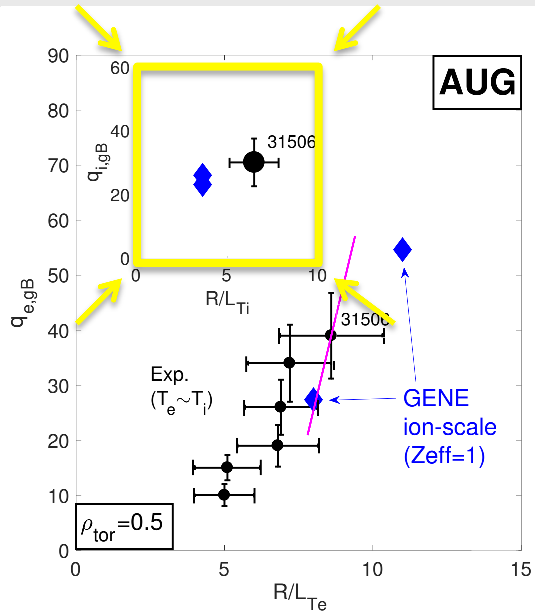

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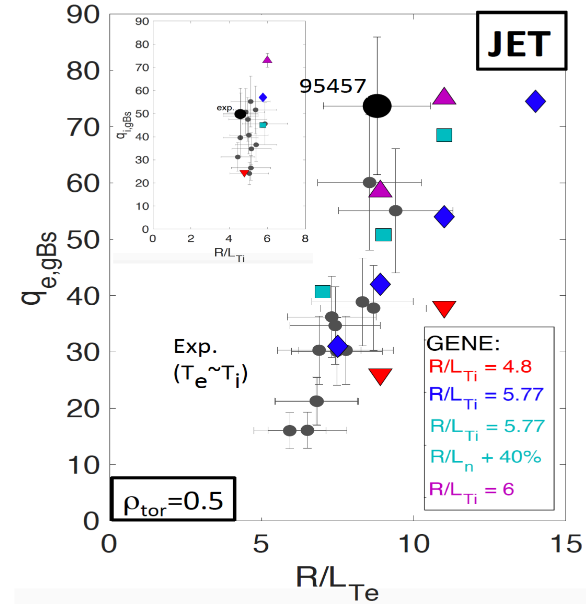

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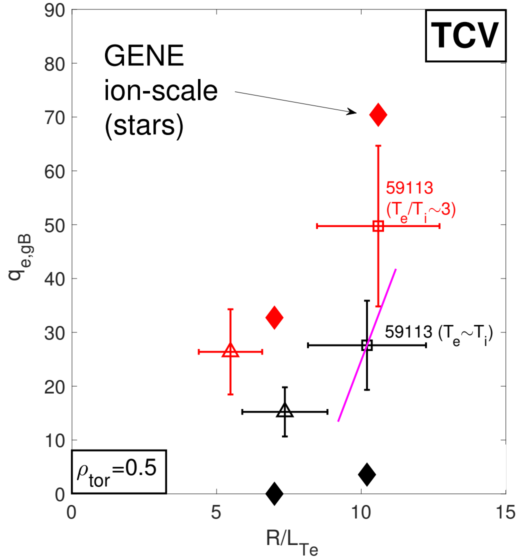
Nonlinear ion-scale gyrokinetic simulations



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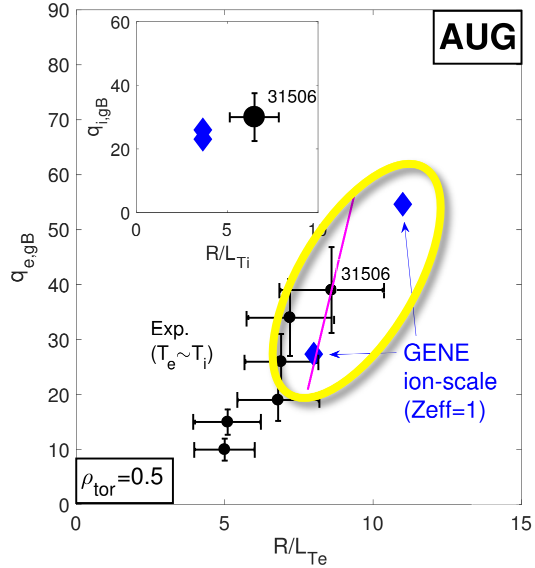

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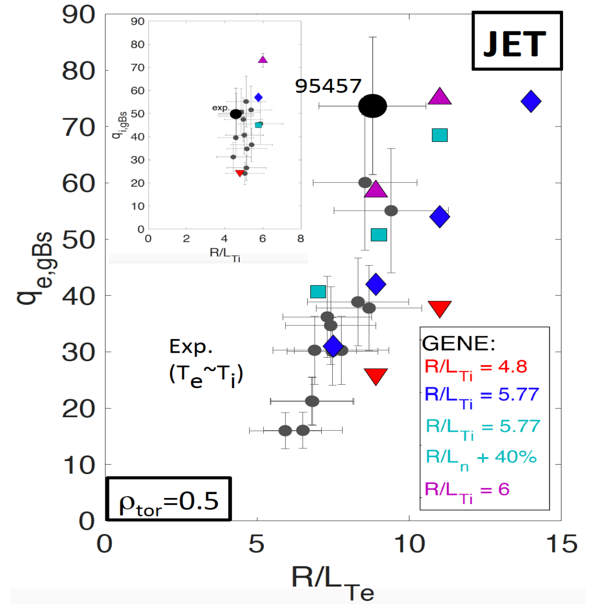

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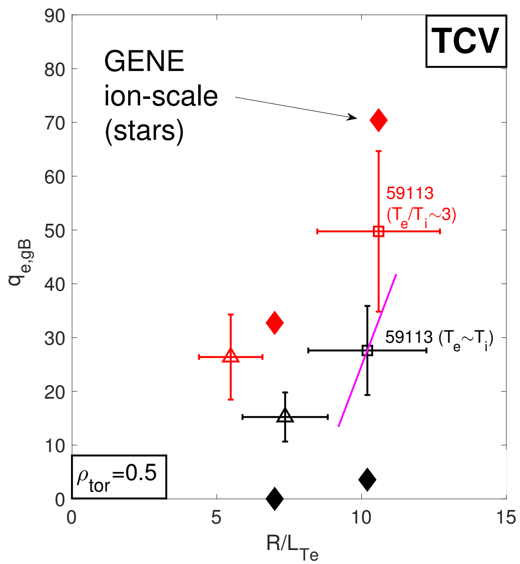
Nonlinear ion-scale gyrokinetic simulations



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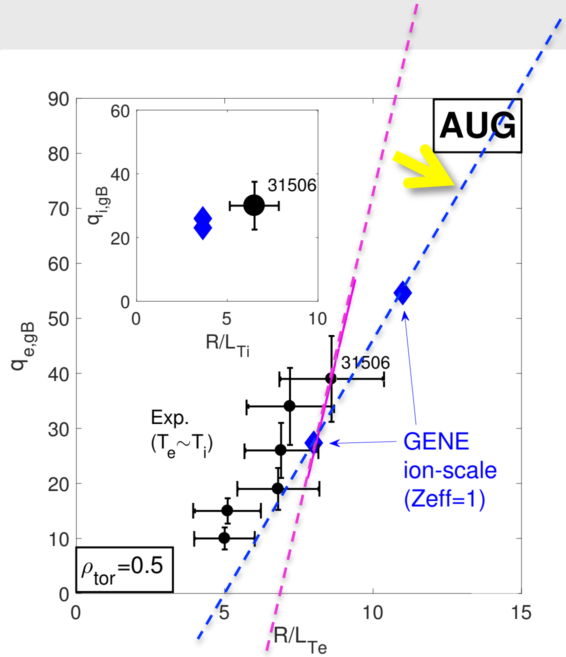

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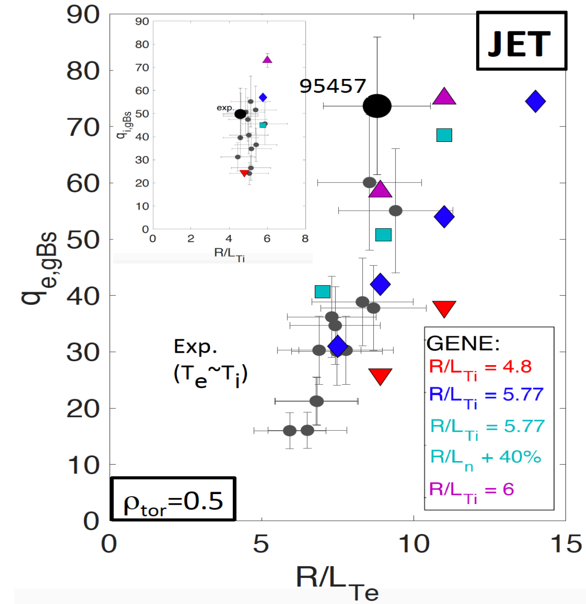

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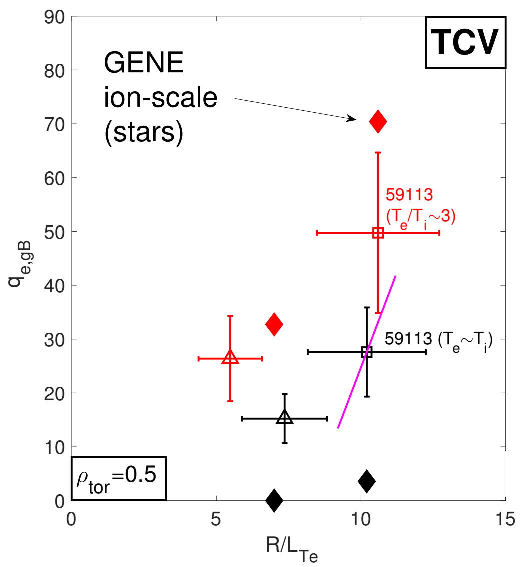

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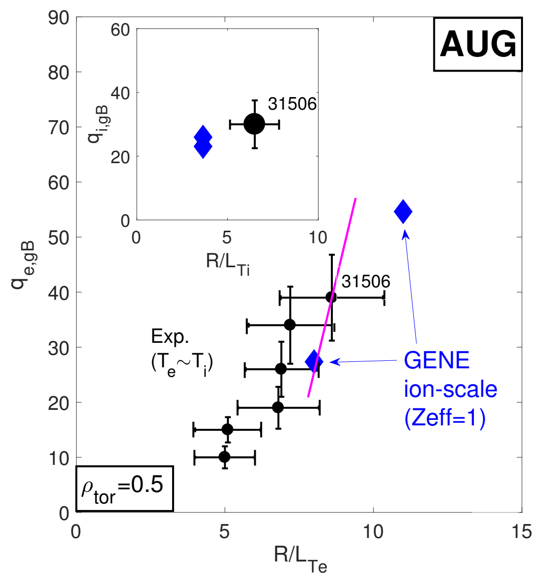

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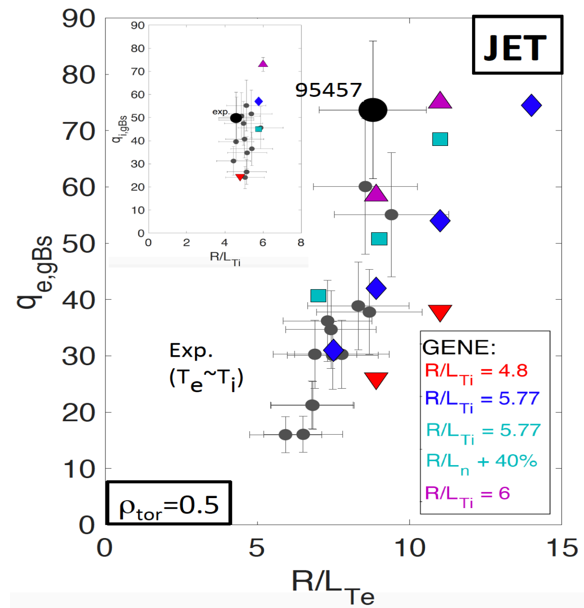

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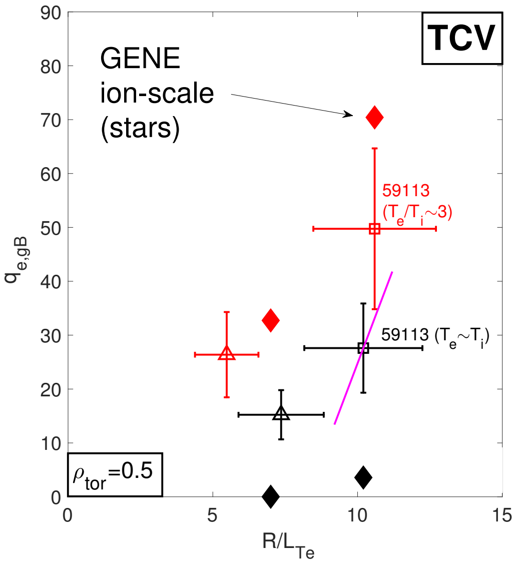

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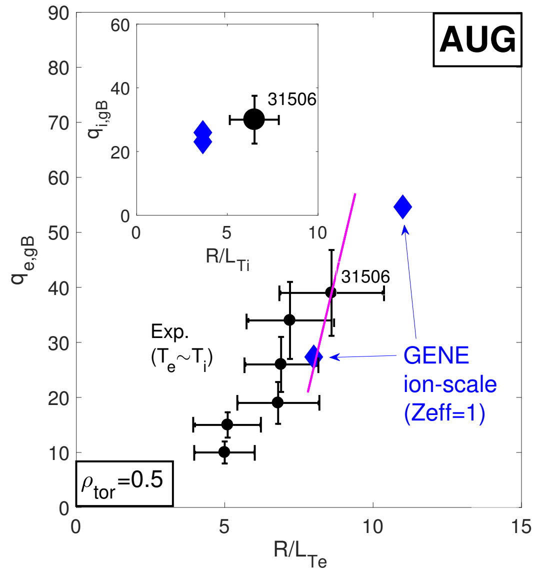

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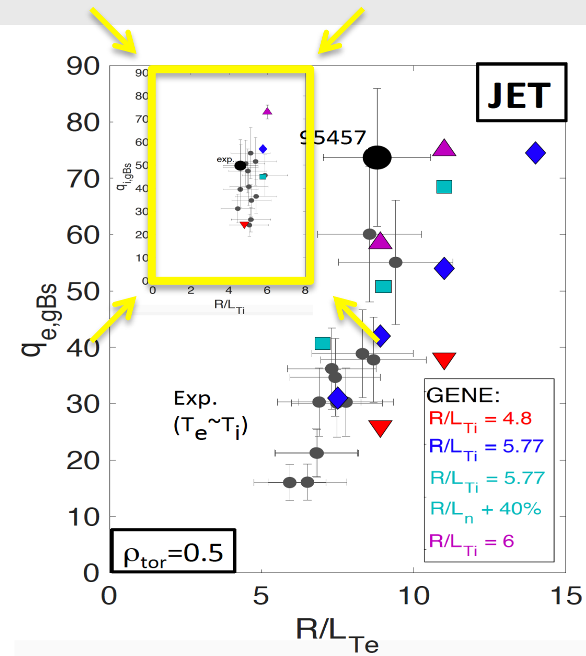

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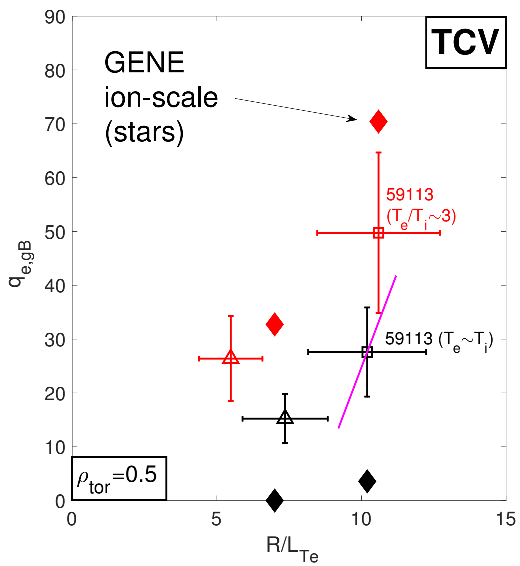
- Ions are very stiff

Nonlinear ion-scale gyrokinetic simulations



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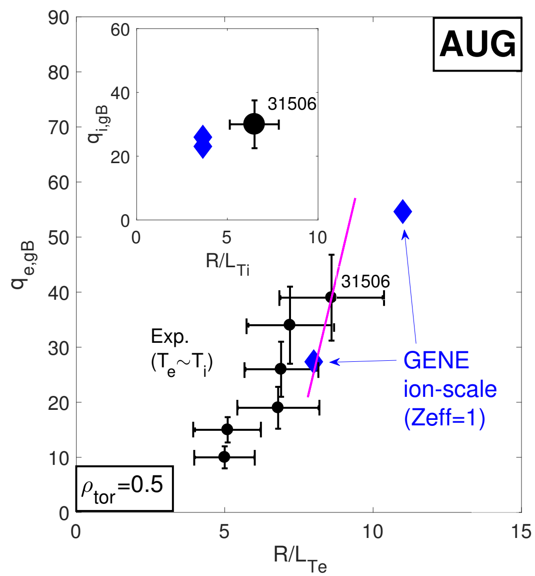

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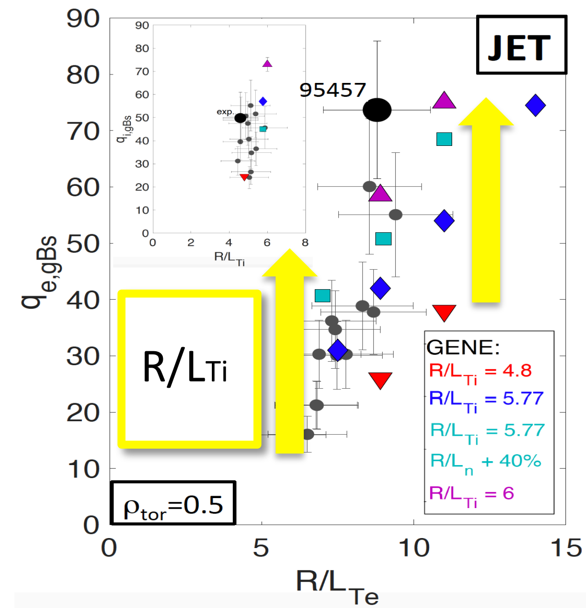

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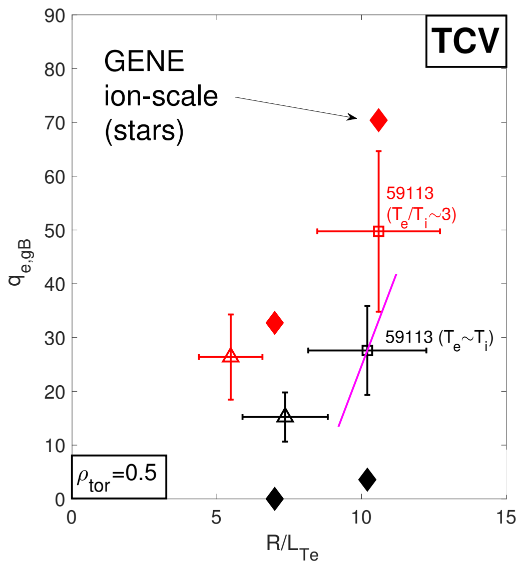
- First: q_i is matched varying R/L_{Ti}, then: two runs varying R/L_{Te};
- **GENE** slightly underpredicts the flux, but **strongly under-predicts** the stiffness from ECH modulation.

- Ions are very stiff and R/L_{Ti} also impacts q_e (similar for R/L_{ne});

Nonlinear ion-scale gyrokinetic simulations



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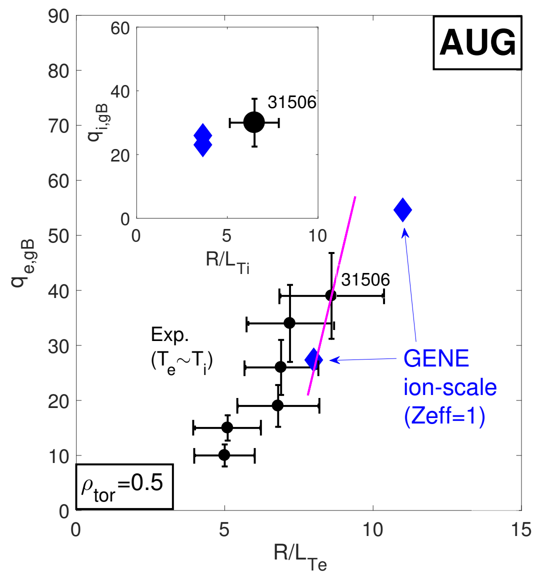

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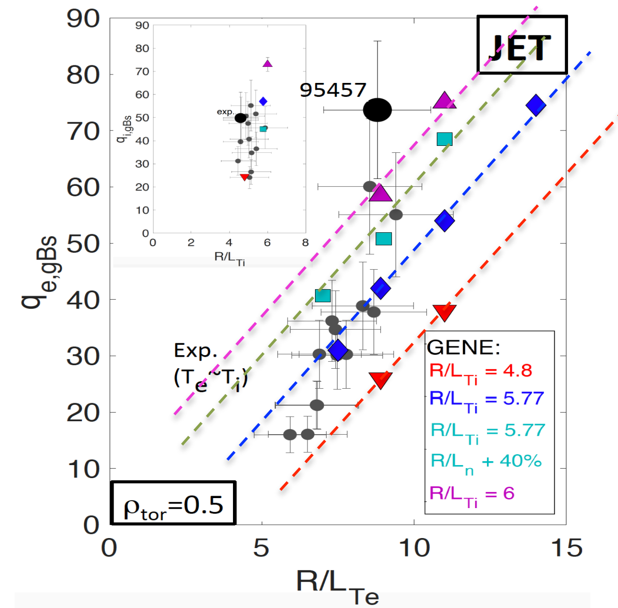

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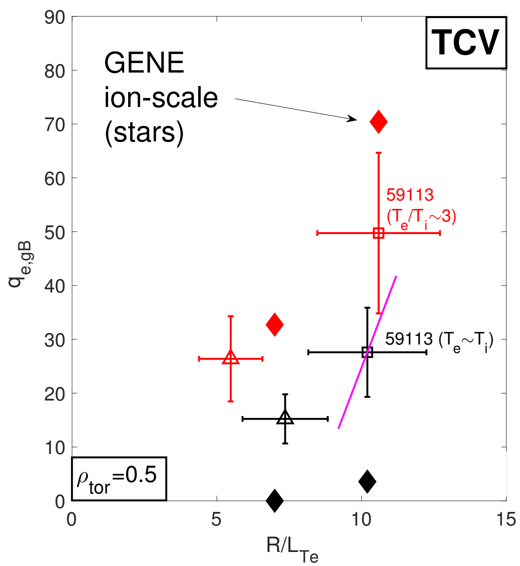
- Ions are very stiff and R/L_{Ti} also impacts q_e;
- However: they do not impact the stiffness;

Nonlinear ion-scale gyrokinetic simulations



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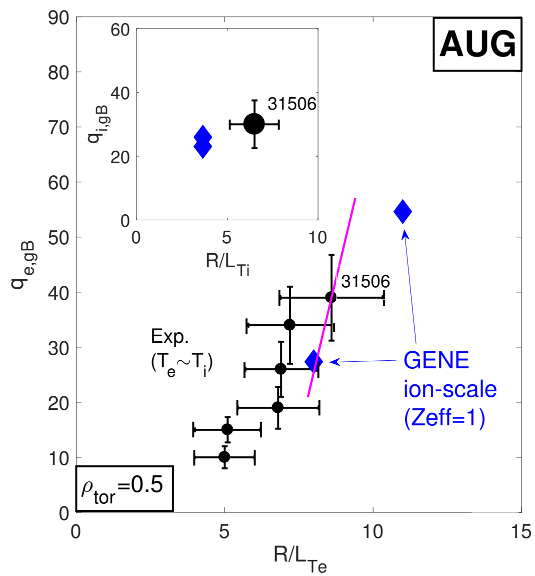
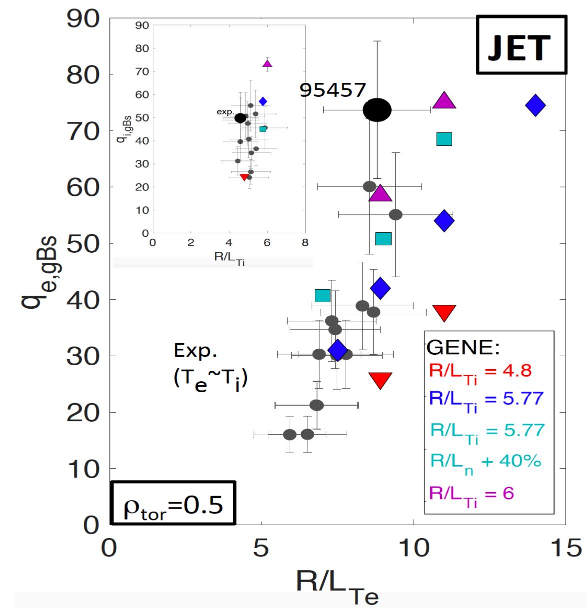


[Bonanomi N. et al., to be submitted]



Adapted from [Mantica P. et al., to be submitted]

- ECH only: flux levels and stiffness explained by ion-scales;
- **Mixed NBI-ECH**: ion-scales stabilised by a sinergy of FI and ExB: both **fluxes** and **stiffness** are **under-estimated**.

- First: q_i is matched varying R/L_{Ti}, then: two runs varying R/L_{Te};
- **GENE** slightly underpredicts the flux, but **strongly under-predicts** the stiffness from ECH modulation.

- Ions are very stiff and R/L_{Ti} also impacts q_e;
- However: they do not impact the stiffness;
- **Possible to match $q_{e,gB}$ but not the stiffness with ion-scale runs.**

Nonlinear multi-scale gyrokinetic simulations

- Cases with T_e~T_i: **ion scales** → **not sufficient** to explain both **exp. flux levels** and **stiffness**;

Nonlinear multi-scale gyrokinetic simulations

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- **Multi-scale NL GENE runs** for AUG and JET (TCV: 'global' effects could play a role and a global multi-scale run was not affordable);

JET

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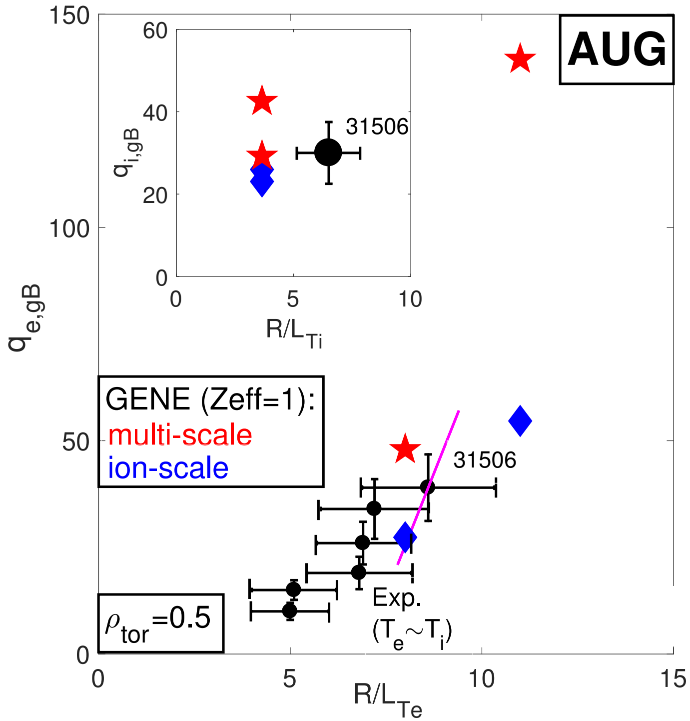
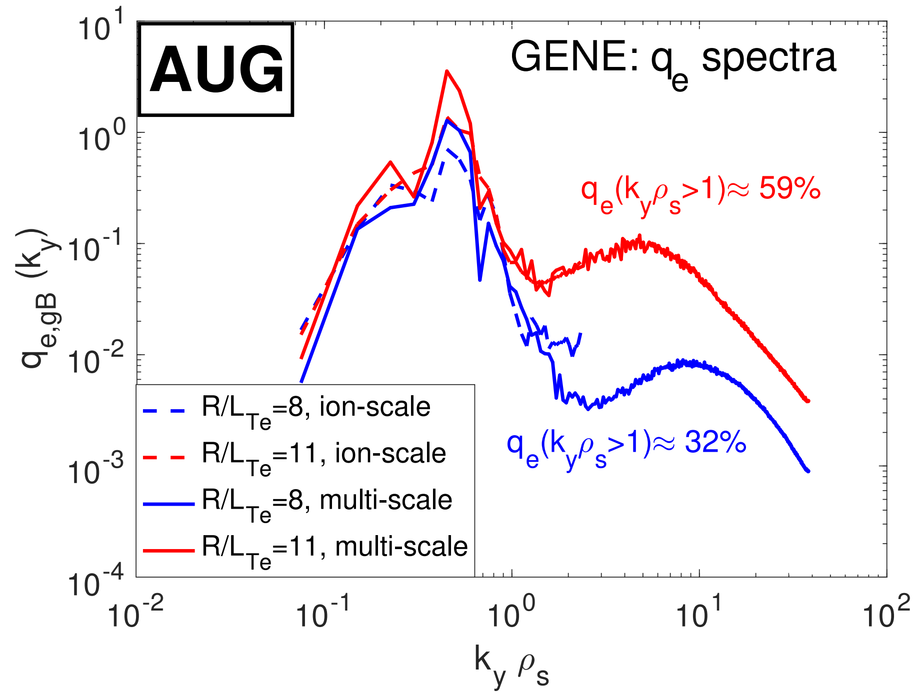
- **JET** case → impurities: taken into account.

AUG: nonlinear multi-scale GK simulations





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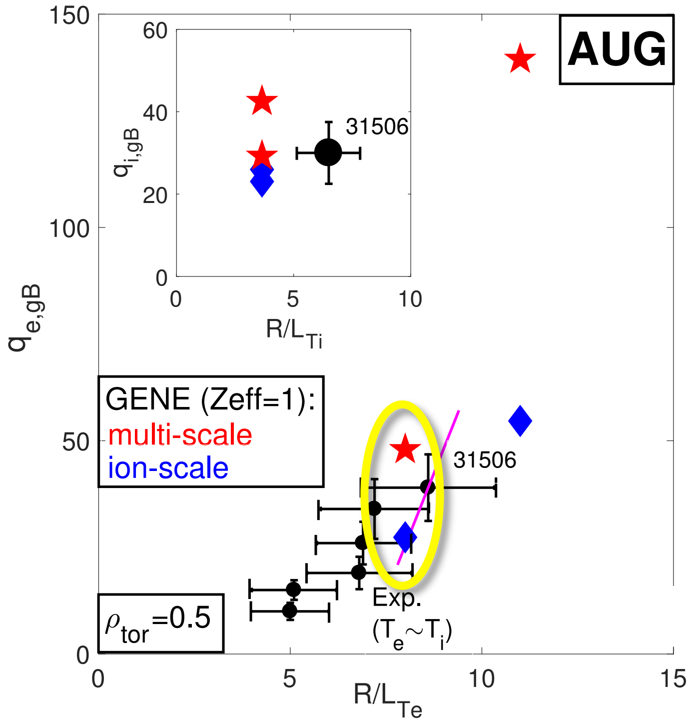

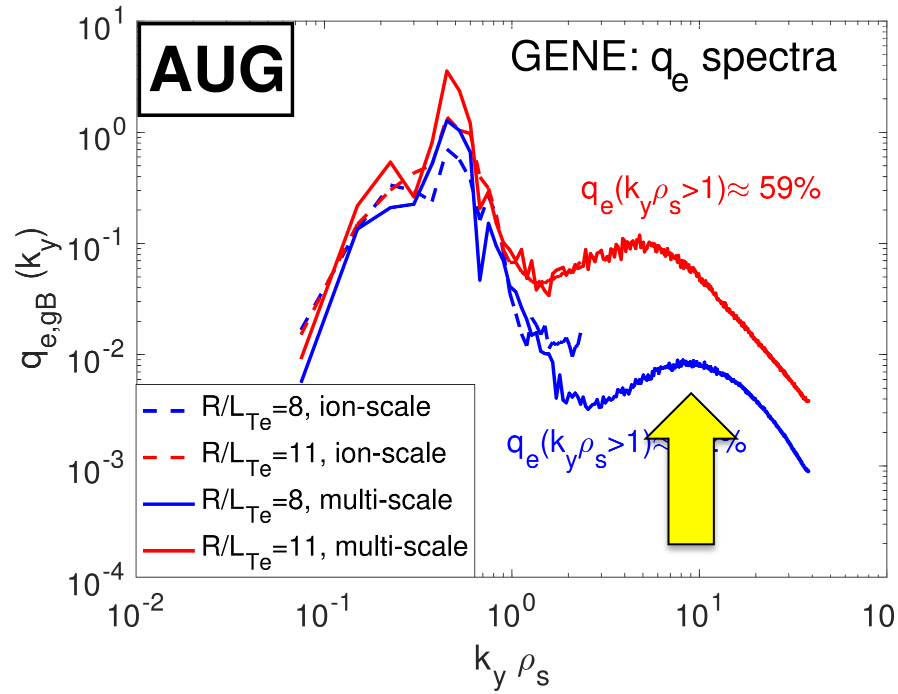

- Impact of ETGs on q_e ($k_y\rho_s>1$): increases with increasing R/L_{Te} :

moderate/large (~32%) at **exp. R/L_{Te}=8**

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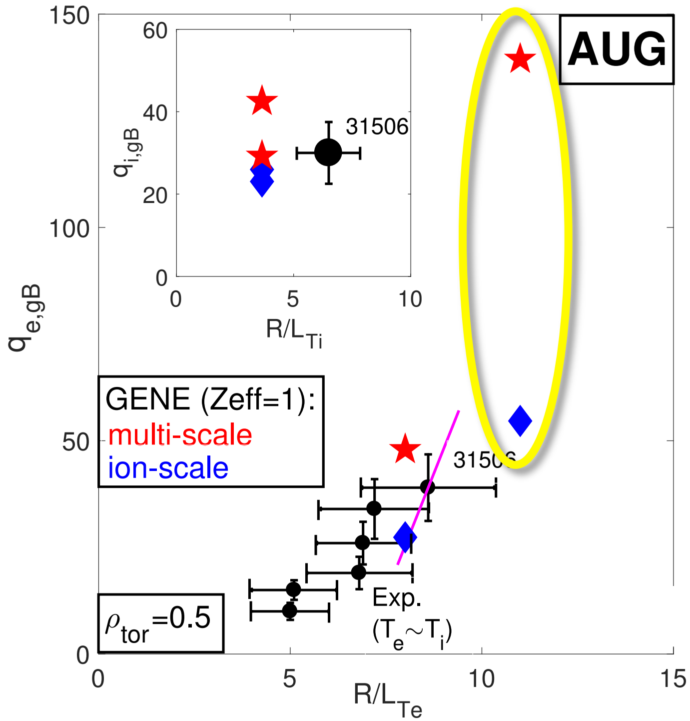

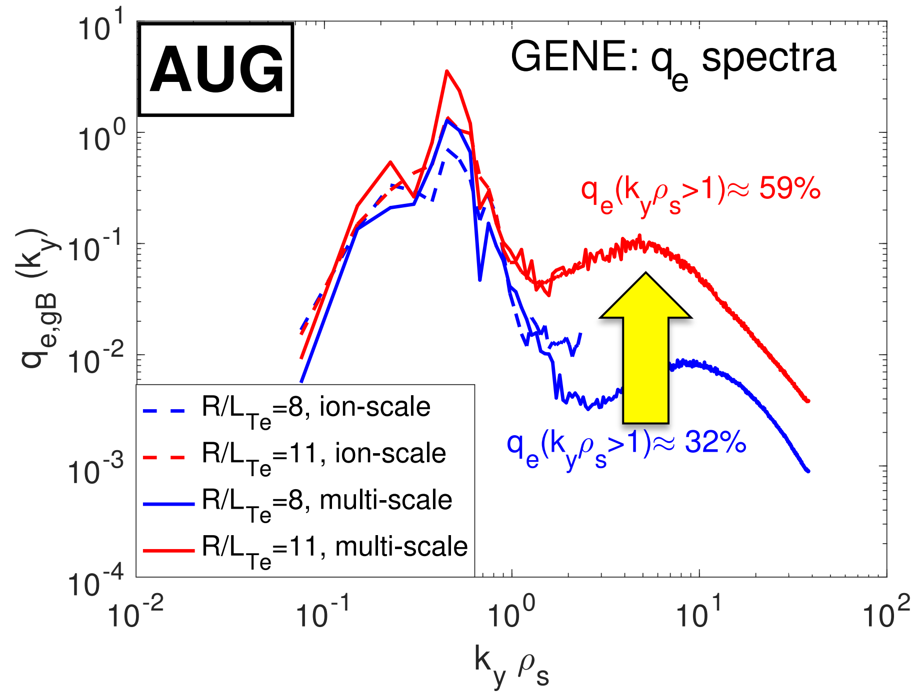

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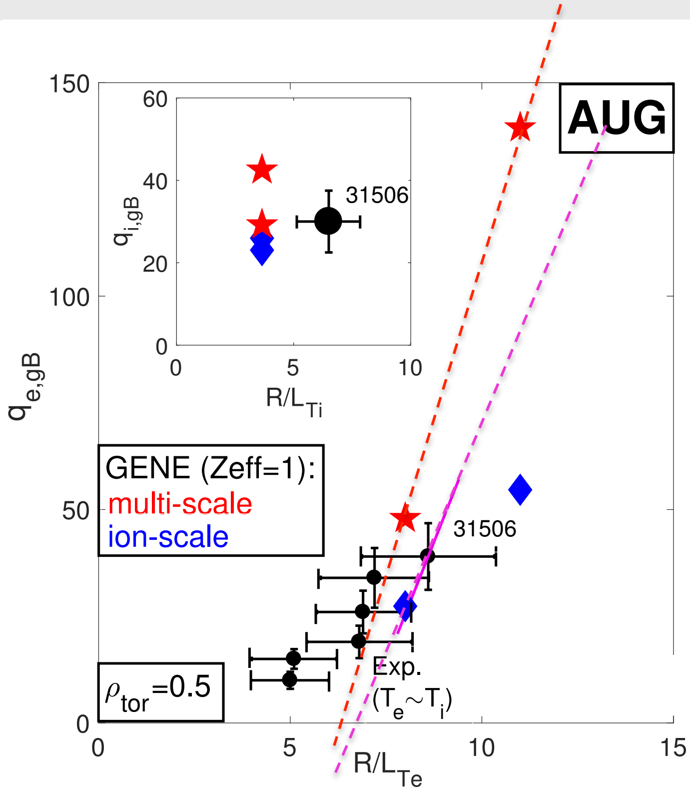

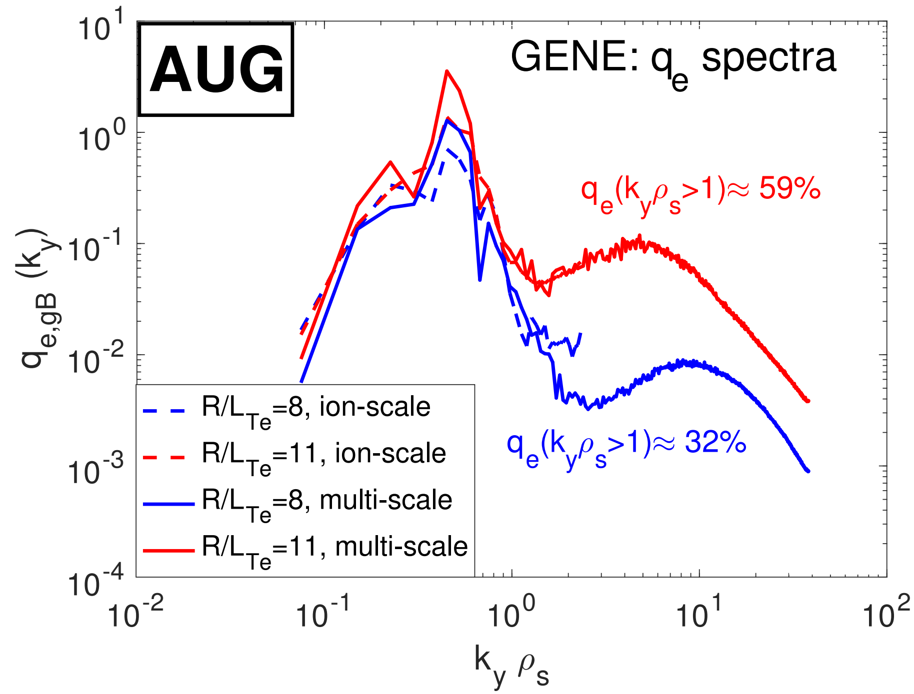

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moderate/large (~32%) at **exp. R/L_{Te}=8** → large (~59%) at R/L_{Te}=11;

- Multi-scale stiffness: **high** ← well aligned with the ECH modulation result;

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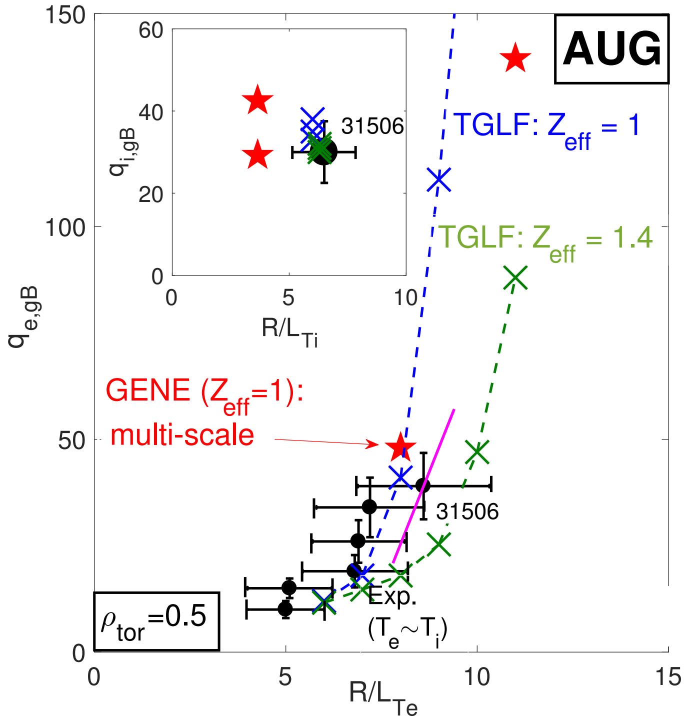
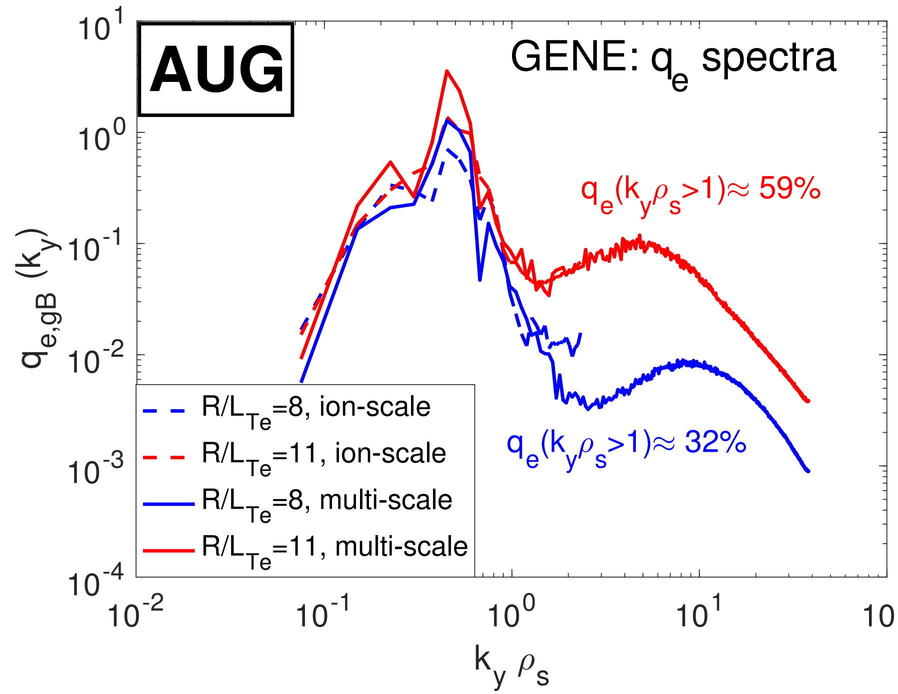
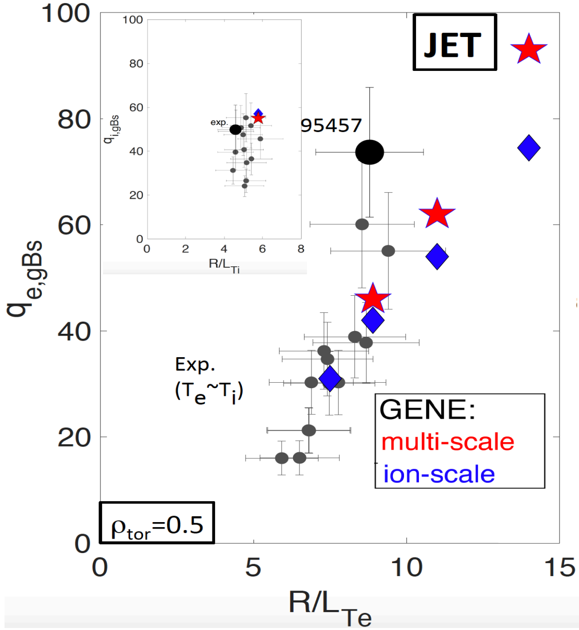




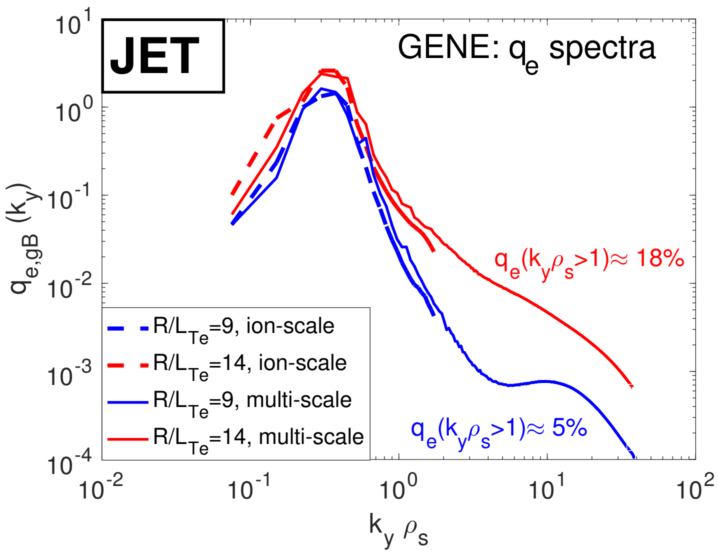
- TGLF [Staebler G.M. *et al.* PoP 2007] standalone R/L_{Te} scans **with** and **without** impurities

→ test the effect of Z_{eff} on the 'ETG wall' position: **non-negligible**.

JET: nonlinear multi-scale GK simulations



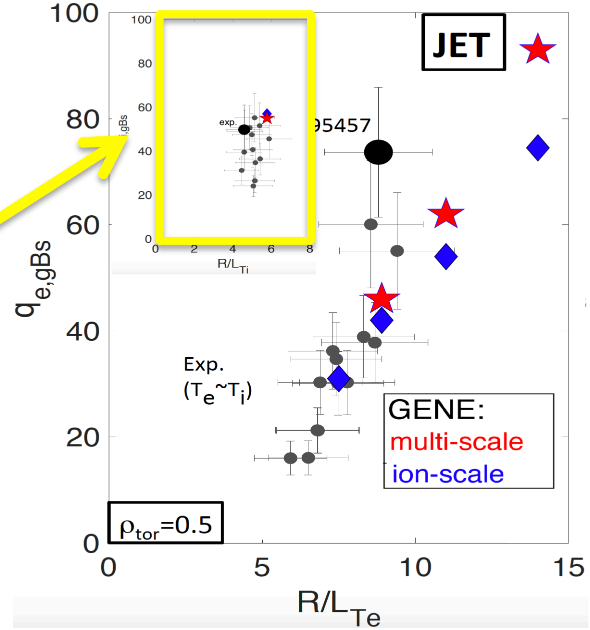
Adapted from [Mantica P. et al., to be submitted]



[Mantica P. et al., to be submitted]

JET: nonlinear multi-scale GK simulations

R/LTi=5.77
(qi at the upper end of the exp. error bar)



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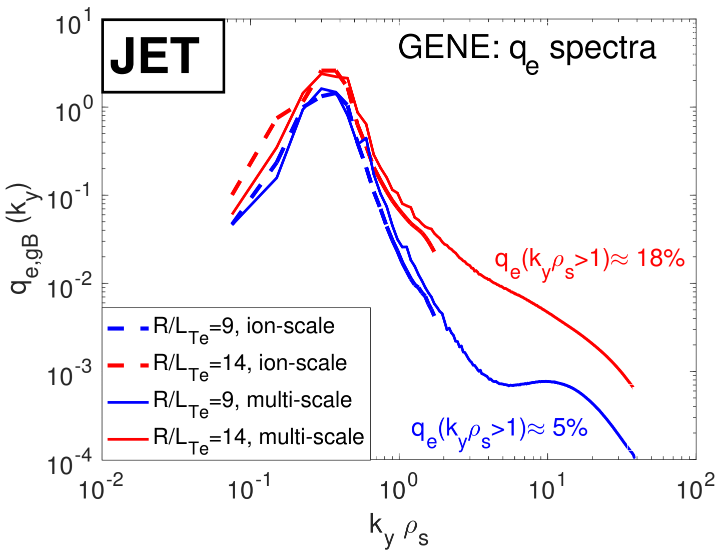

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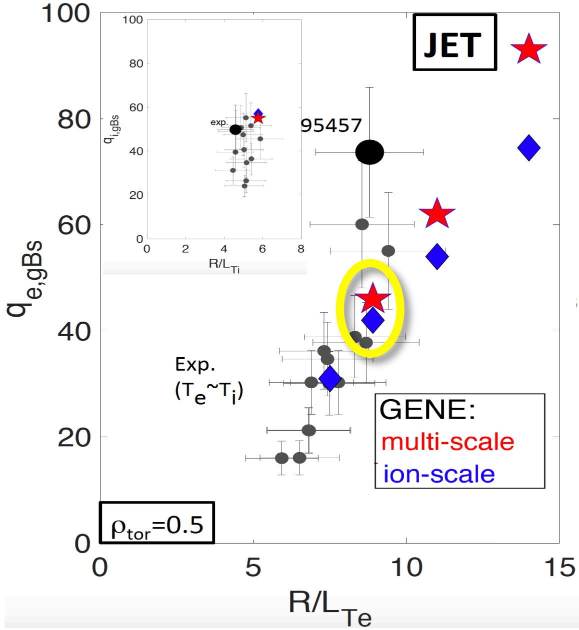

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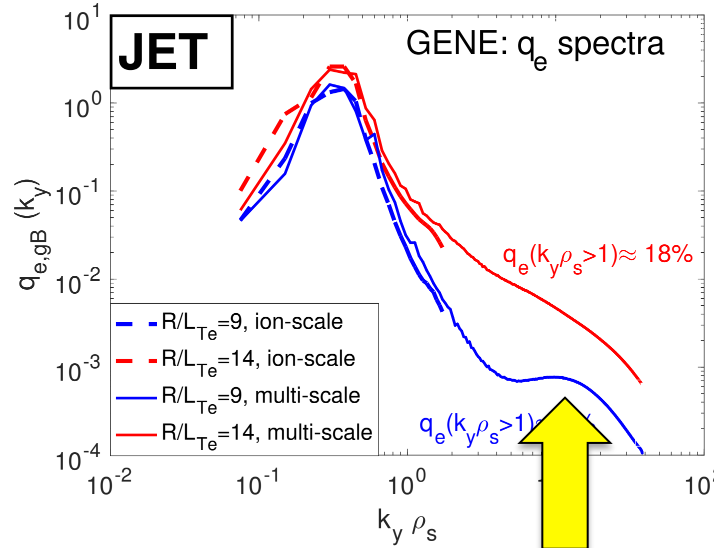
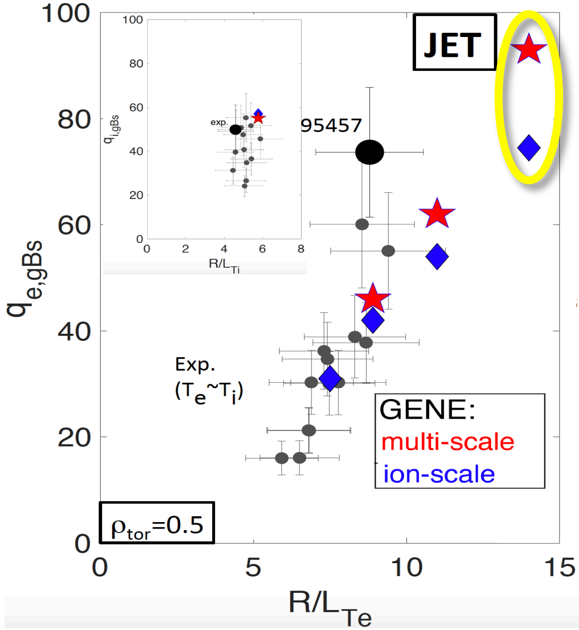


[Mantica P. et al., to be submitted]

- Impact of ETGs on q_e: negligible (~5%) at exp. R/L_{Te}=9

JET: nonlinear multi-scale GK simulations

R/L_{Ti}=5.77 (q_i at the upper end of the exp. error bar)



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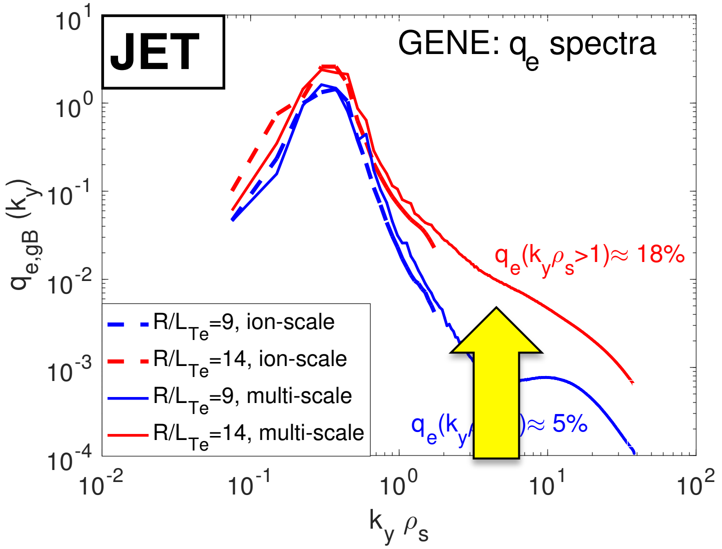

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- Impact of ETGs on q_e: negligible (~5%) at exp. R/L_{Te}=9 ⟶ **moderate** (~18%) at **R/L_{Te}=14**;

JET: nonlinear multi-scale GK simulations

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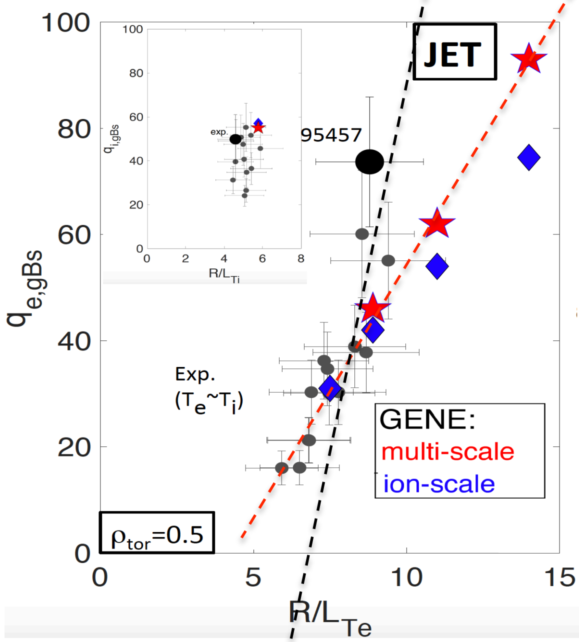

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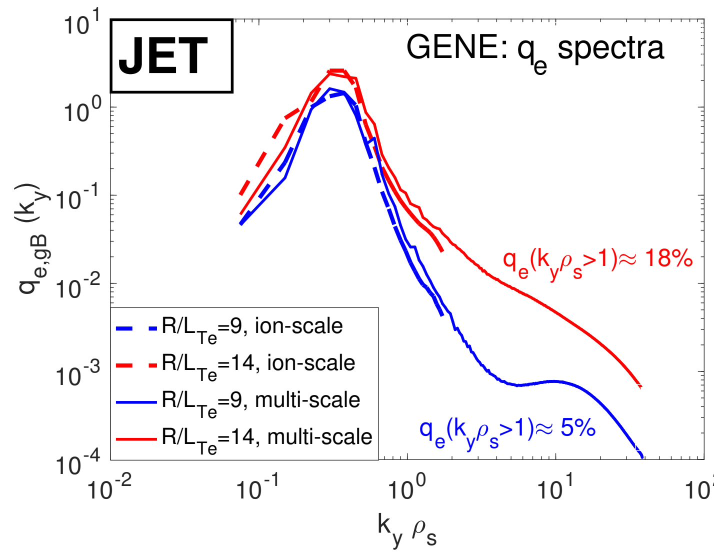

[Mantica P. et al., to be submitted]

- Impact of ETGs on q_e: negligible (~5%) at exp. R/L_{Te}=9 ⟶ **moderate** (~18%) at **R/L_{Te}=14**;
- Multi-scale stiffness: **moderate**, it **still does not explain the exp. stiffness** (run at R/L_{Te}=11 with reduced R/L_{Ti}: ongoing);

Conclusions

- Comparison: experimental data ⟷ gyrokinetic simulations of dedicated pulses of TCV, AUG and JET is presented ⟶ impact of ETG modes on the electron heat transport;

JET

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- Need of exp. measurements of density and temperature fluctuations at electron scales.

Backup slide: simulations input parameters

TABLE 1. Main plasma parameters for the analised pulses at $\rho_{tor} = 0.5$

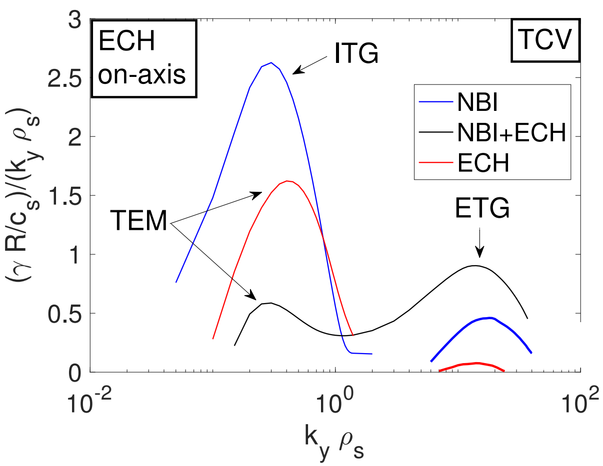
	TCV ECH (59113)	TCV ECH+NBI (59113)	TCV NBI (59113)	AUG (31506)	JET (95457)
T_e/T_i	3.04	~1	1.16	~1	~1
Z_{eff}	2.50	2.80	2.80	1.4	1.5
R/L_{Te}	10.59	10.20	8.71	8	9
R/L_{Ti}	5.94	5.55	15.07	6.5	4.59
R/L_{n_e}	3.69	4.85	6.07	0.91	3.12
q	1.65	1.34	1.42	2.07	1.82
$\hat{s}$	0.99	1.19	1.14	6.85	1.05
β_e $[10^{-3}]$	2.01	2.37	1.54	5	1.12
ν_c $[10^{-3}]$	0.91	1.33	1.77	1.87	0.57
γ_E $[c_s/R]$	~0	0.14	0.34	0.04	~0

JET

Backup slide: Linear multi-scale GK simulations

TCV

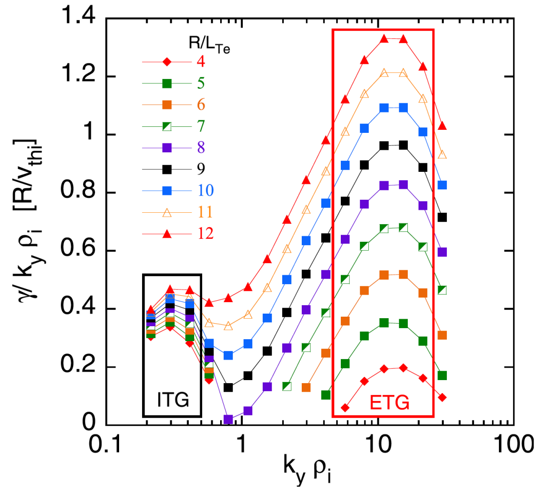
All cases with ECH on-axis and NBI only case:



Adapted from [Mariani A. et al., NF (2019)]

AUG (GKW)

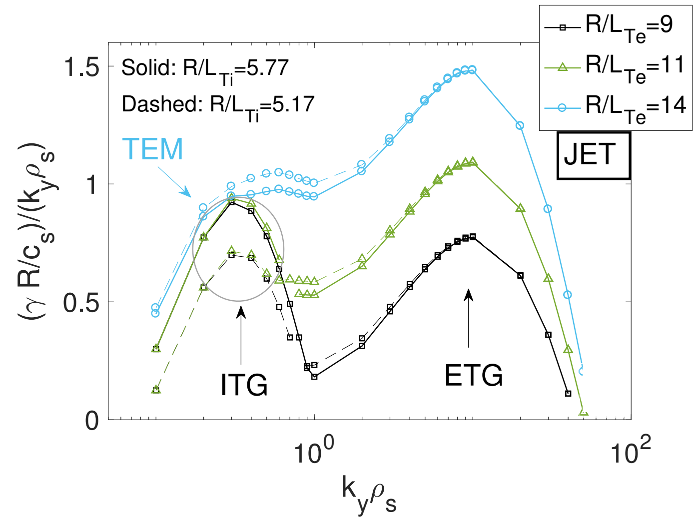
Exp. case with largest $q_{e,gB}$: R/L_{Te} scan (Z_{eff}=1):



[Ryter F. et al., NF (2019)]

JET

Exp. case with largest $q_{e,gB}$: R/L_{Te} scan also varying R/L_{Ti}:



Adapted from [Mantica P. et al., to be submitted]

Ion scales: ITG-dominant (all cases except TCV when ECH is injected: TEM-dominant), electron scales: ETGs

Simple criterion: ETGs impact q_e if γ/k_y is larger at electron scales (ETGs) [Staebler, G.M. et al., NF (2017)] :

- **ETG impact: mixed NBI-ECH case (T_e~T_i);**
- Due to **FI stabilising** TEMs at **ion scales**.

- **ETG role** for **R/L_{Te}>6** ;
- (lower boundary since Z_{eff}=1<1.4=$Z_{eff,exp.}$ in the simulations).

- **ETG role: R/L_{Te}>11** when R/L_{Ti}=5.77, **R/L_{Te}>9** when R/L_{Ti}=5.17.