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Electromagnetic turbulence suppression by marginally stable energetic particle driven modes

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R. Bilato[1], F. Jenko[1], the ASDEX Upgrade[1] and MST1 Teams, and
JET[2] contributors

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IPP JET HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

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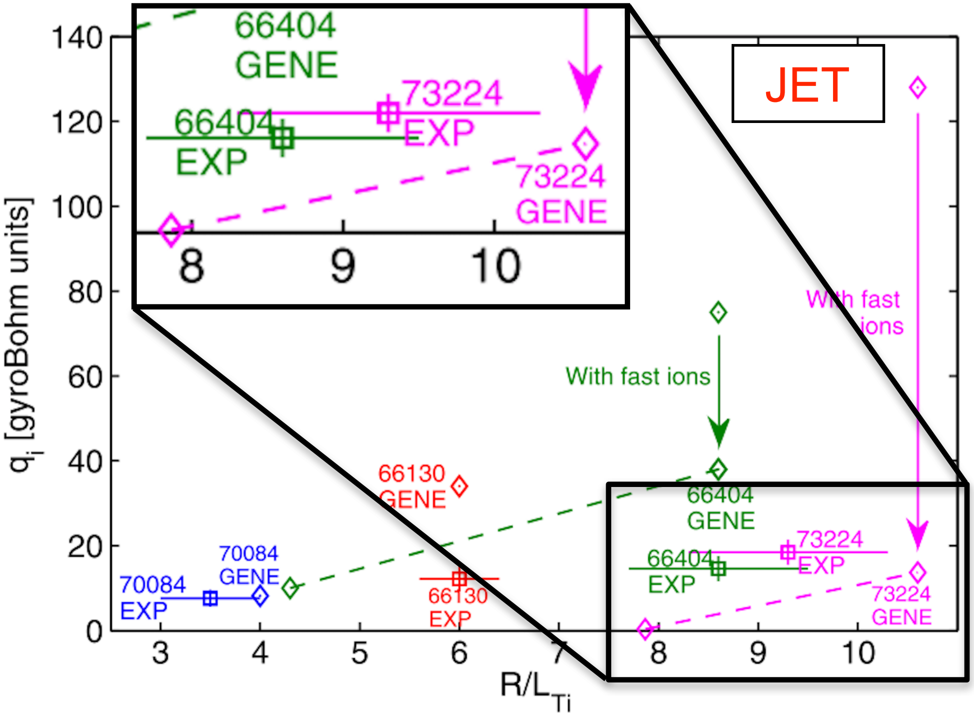
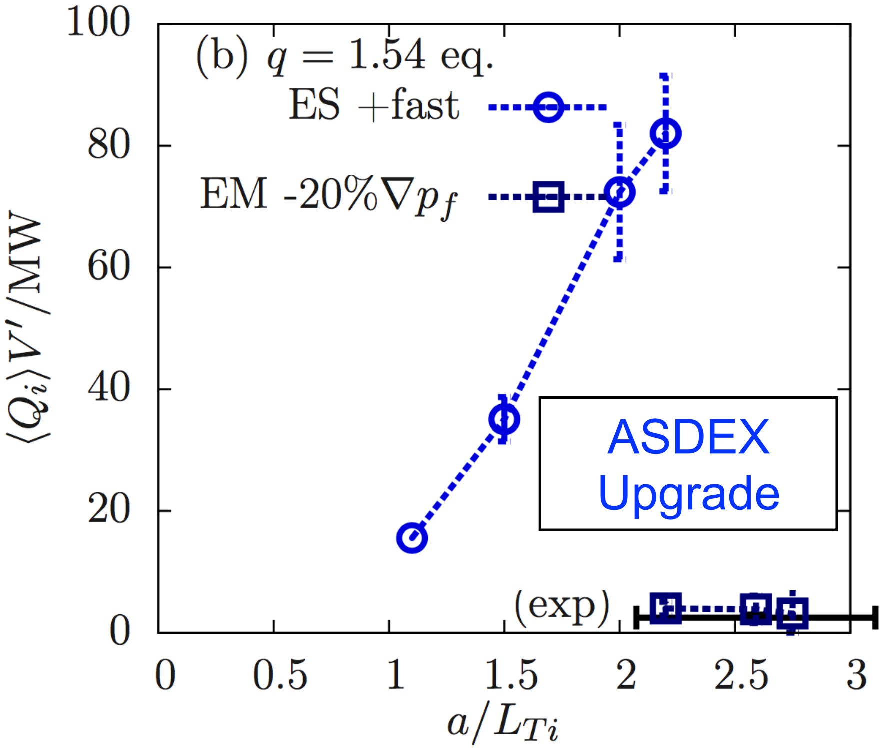
Motivation

- JET (NBI + ICRH) and ASDEX Upgrade (NBI) results predicted ITG turbulence suppression in presence of fast ions ➔ steepening of main ion temperature profile.

J. Citrin et al. PRL 2013



H. Doerk et al. NF 2017



- no theoretical model ➔ develop more detailed understanding of energetic/fast ion effects on turbulence.

Fast ion effects on plasma turbulence

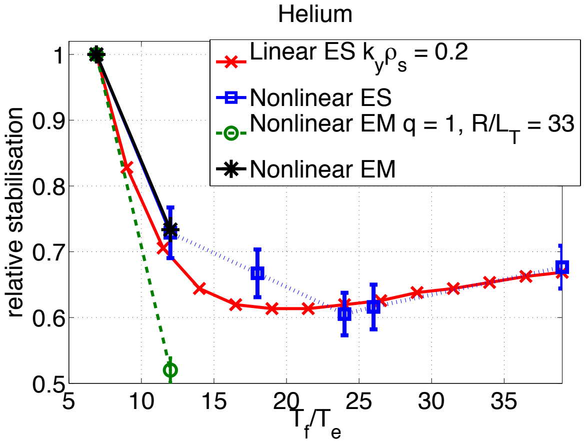
Stabilising fast ion effects

- Dilution of thermal ITG drive (Electrostatic effect).
- ITG - fast ion drift resonance (Electrostatic effect).
- Increase geometrical stabilisation through Shafranov shift (Electromagnetic effect).
- Nonlinear transport reduction (Electromagnetic effect).

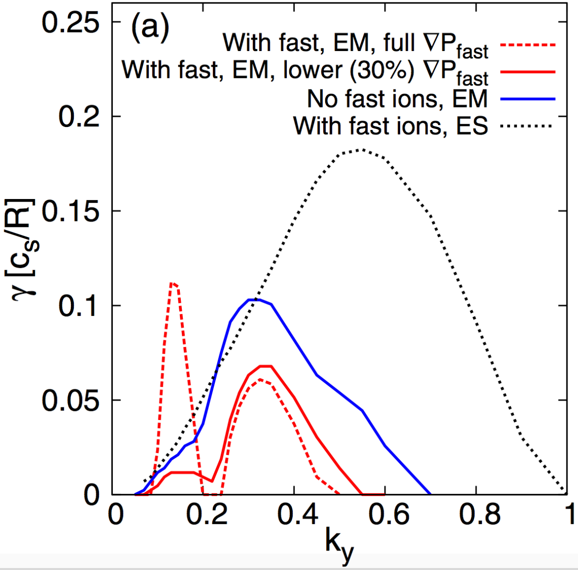
Destabilising fast ion effects

- Pressure/pressure gradients-driven fast ion modes (Electromagnetic effect).

A. Di Siena et al. NF 2018
A. Di Siena et al. PoP 2019



J. Citrin et al. PPCF 2015



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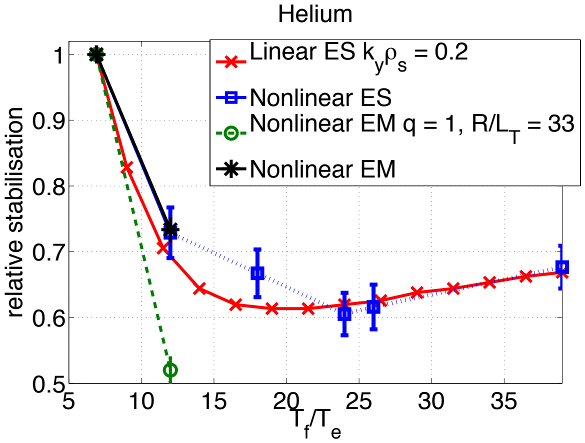

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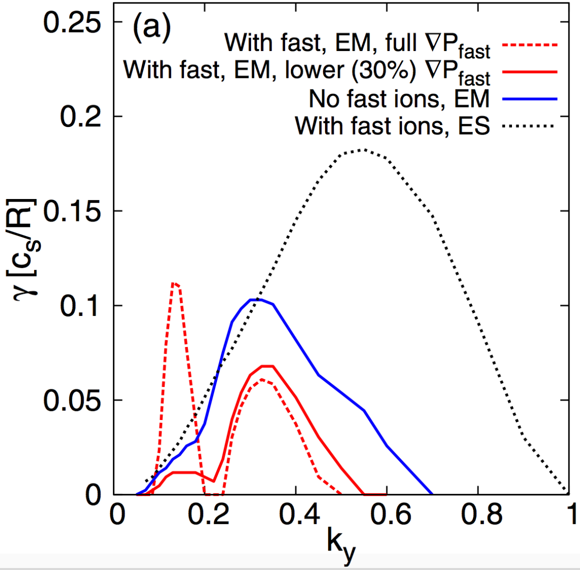
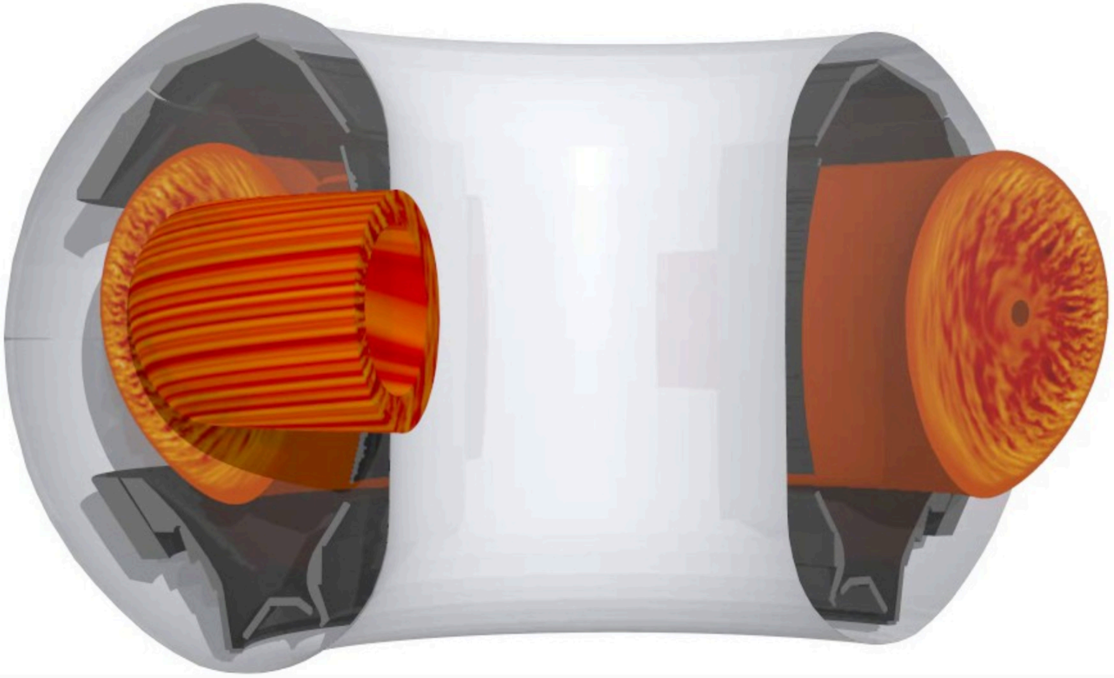


Numerical tool: gyrokinetic code GENE

GENE is a Eulerian gyrokinetic code:

- Kinetic treatment for each species
- Electromagnetic fluctuations
- Linearised Landau-Boltzmann and Sugama-type collisional operators
- External ExB shear flows
- Initial value or eigenvalue solvers
- supports local (flux-tube) and global (full-torus), gradient- and flux-driven simulations
- realistic non-Maxwellian background distributions, e.g. for fast ion studies (see **[A. Di Siena et al. PoP 2018]**, **[A. Di Siena et al. NF 2018]**)



www.genecode.org

Outlook

- Impact of fast particles on realistic JET-like plasma turbulence.

- Observation of linearly stable high-frequency (MHD-like) modes driven by EPs in nonlinear electromagnetic simulations.

- Mode-to-mode coupling between low frequency (ITG) and high-frequency instabilities.

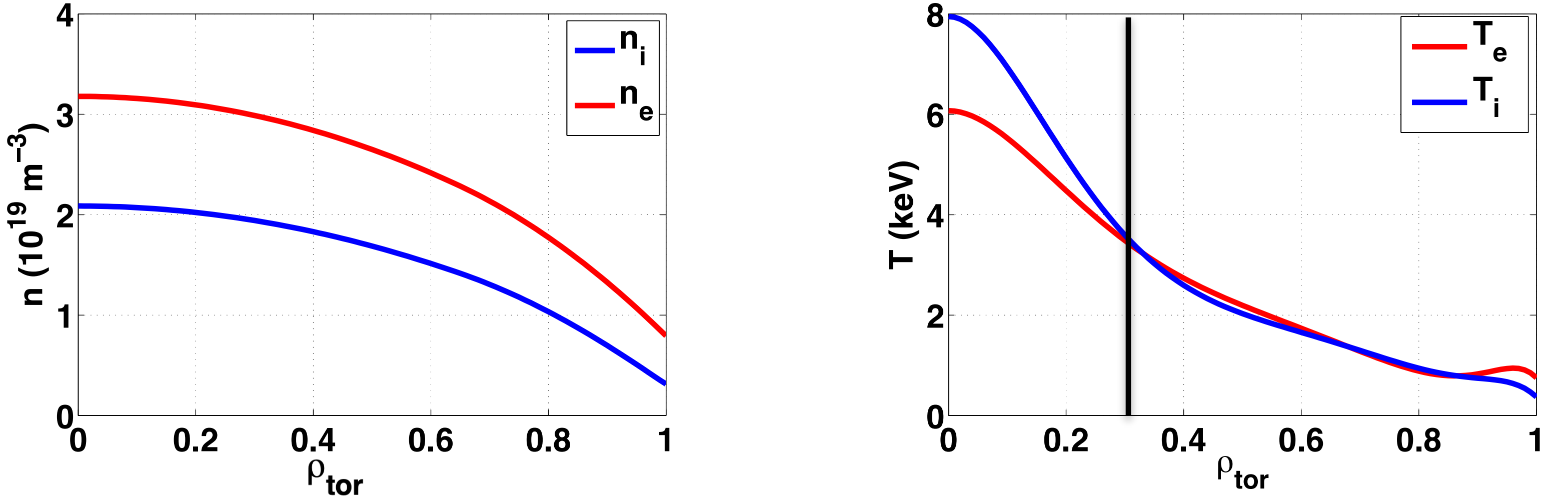
- Scaling of EP turbulence stabilisation with different plasma parameters (β_e and T_{fast}).

- Interaction between EP-driven high-frequency modes and zonal flow.

- Further evidences in a number of AUG and JET discharges

JET-based test case: #73224

- JET-like scenario inspired by #73224 L-mode plasma, $B_T = 3.36T, I_p = 1.8MA$, $n_{e,0} = 3.2 \cdot 10^{19} m^{-3}, P_{NBI} = 11MW, P_{ICRH}(^3He) - D = 3MW$



- GENE flux-tube simulations at $\rho_{tor} = 0.33$; EP modelled by Maxwellian distribution function.

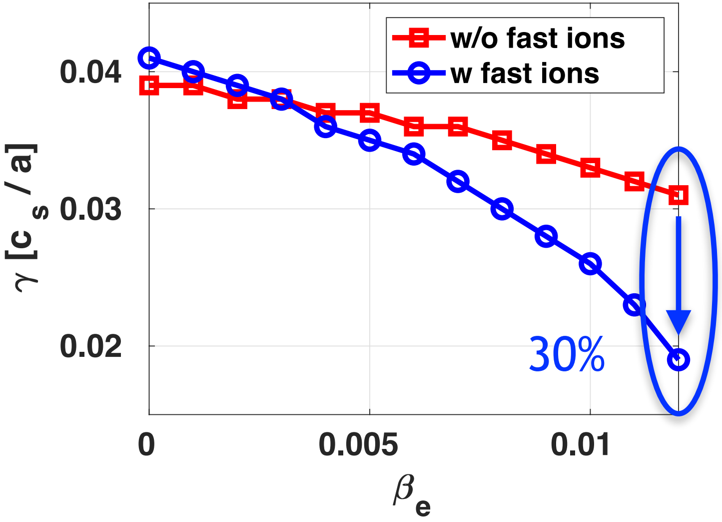
JET	L-mode	#73224				
R/a	$\hat{s}$	q	T_i/T_e	R/L_{T_i}	R/L_{T_e}	R/L_{n_i}
3.1	0.52	1.74	1.0	9.3	6.8	0.02
n_{fD}	T_{fD}/T_e	$R/L_{T_{fD}}$	$R/L_{n_{fD}}$	ρ^*_{fD}	ρ^*_i	$\beta_e(\%)$
0.06	9.8	3.2	14.8	$1/150$	$1/450$	0.33

J. Citrin et al. PRL 2013,
P. Mantica et al. PRL 2011,
P.Mantica et a. PRL 2009

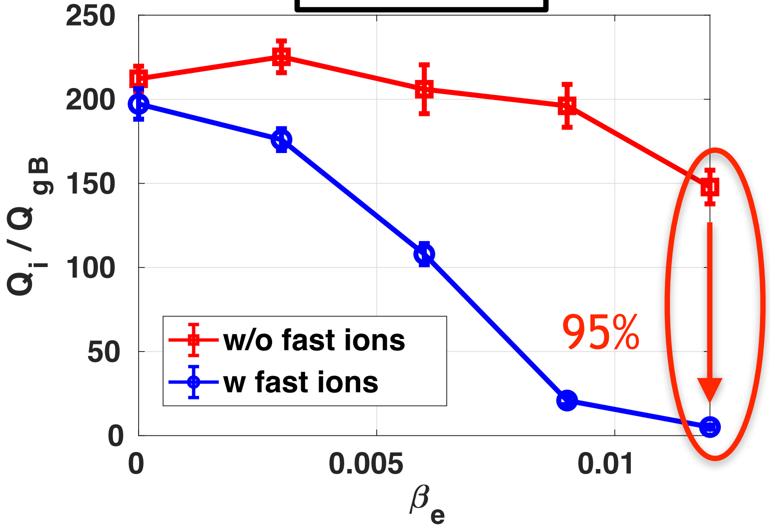
A β_e-scan for realistic JET-like scenario

- Simulation setup: $[n_x, n_y, n_z, n_v, n_\mu] = [256{,}96{,}32{,}32{,}24]$; $[L_x, L_y] = [175{,}125]\rho_i$, $k_{y,min} = 0.025\rho_i$. Safety factor q reduced to 1.2.

Linear at $k_y\rho_i = 0.1$

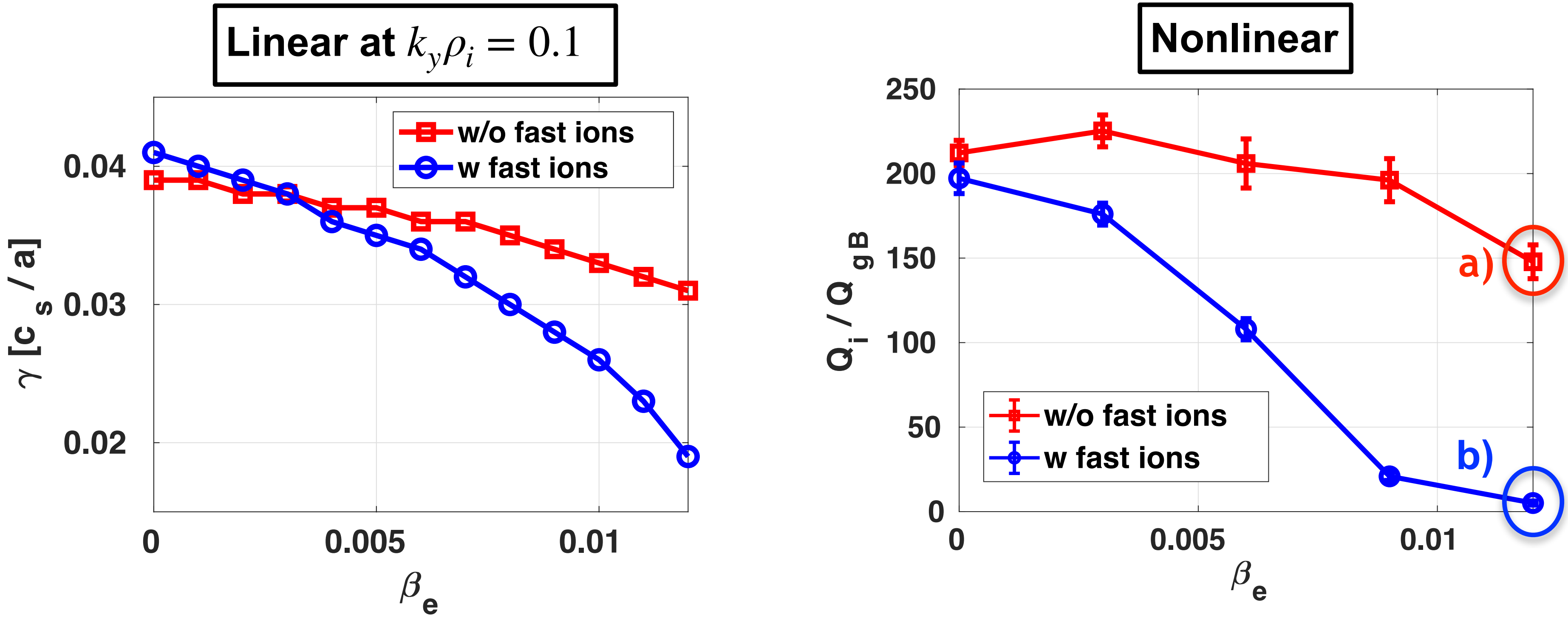


Nonlinear



- A particularly strong turbulence suppression observed only in the presence of fast particles.
- Linear/quasi-linear results cannot reproduce/explain the nonlinear findings.
- If the MHD threshold is exceed (i.e. $\beta_e > 0.013$) significantly larger fluxes are observed (not considered here).

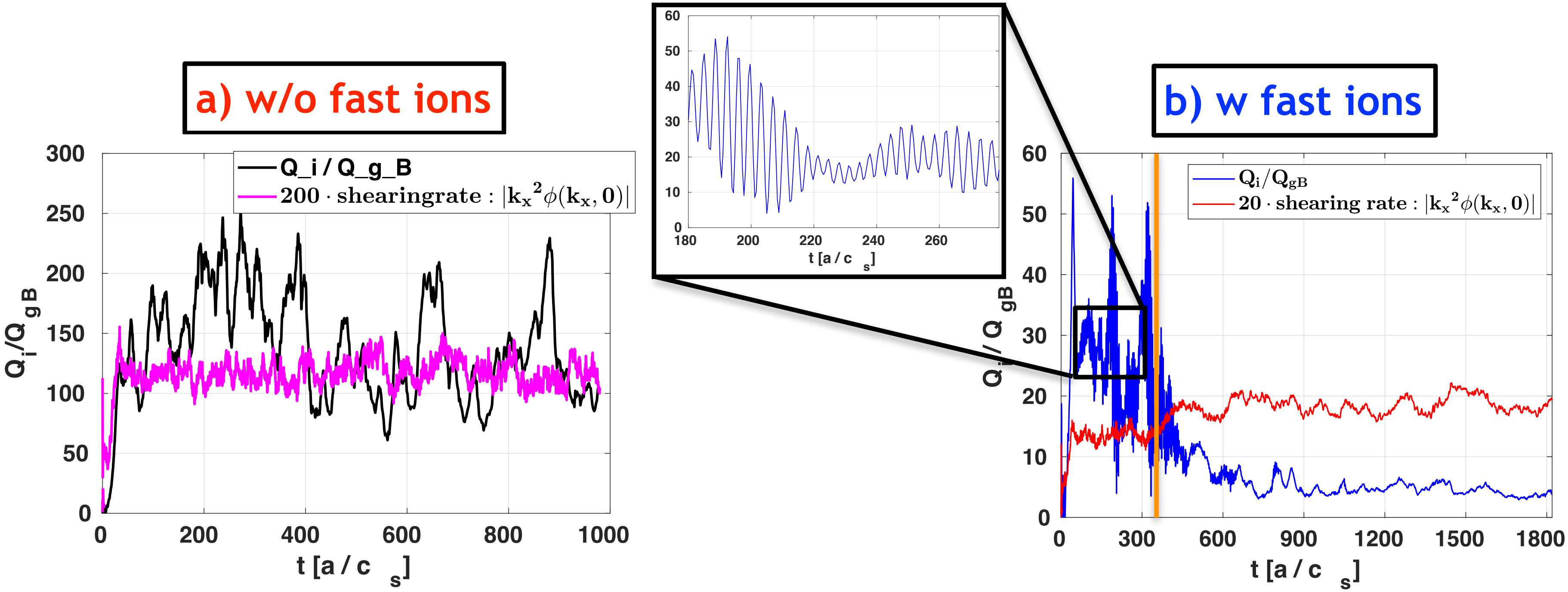
Three questions to be answered



1. What is the main role of energetic particles in this significant enhancement of turbulence suppression?
2. Why does a strong turbulence stabilization arise only in the simultaneous presence of electromagnetic and nonlinear effects?
3. How general are these findings?

Peculiarities of nonlinear EP simulations

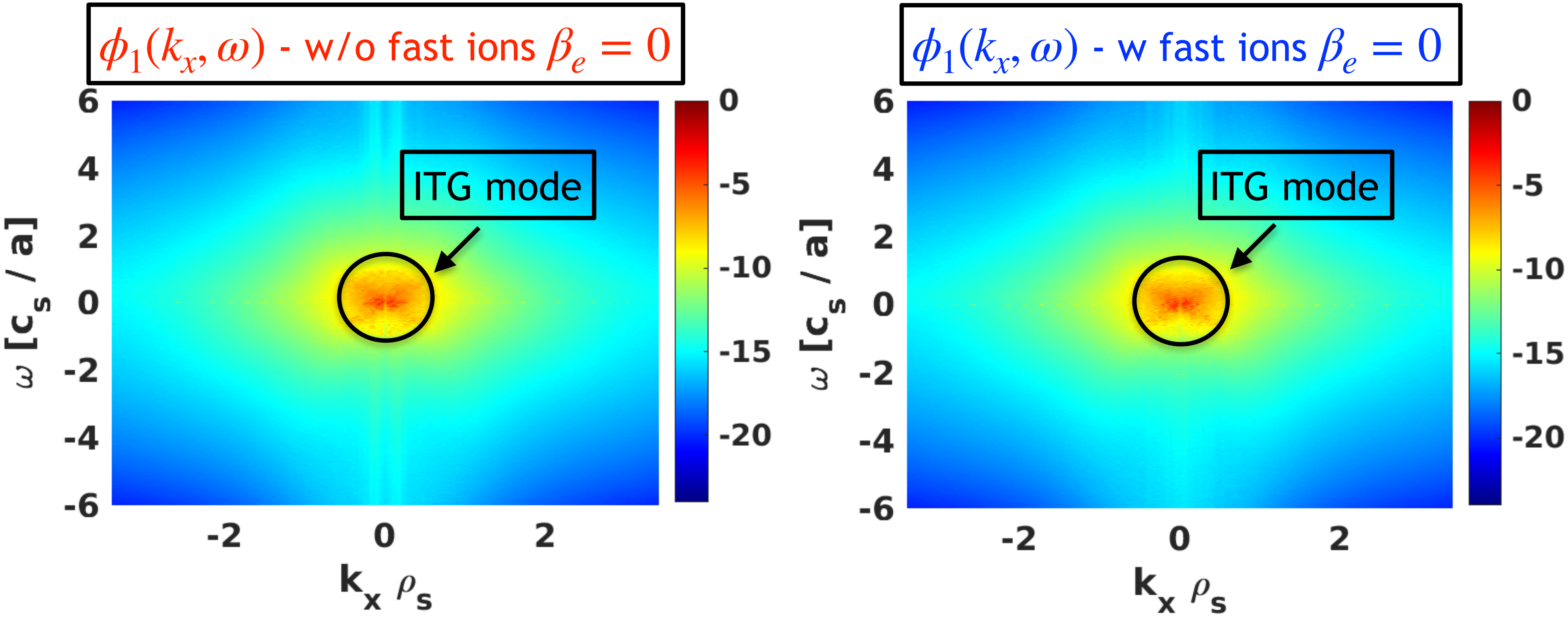
- Two different nonlinear phases are identified only in simulations with EP stabilisation.
- **Phase I:** high-frequency modulation of the main heat flux and slowly decaying transport levels.
- **Phase II:** strongly increased shearing rate levels and corresponding reduction of main ion heat flux. New stationary state reached at reduced transport levels.


a) w/o fast ions

b) w fast ions

Spectral analysis of $\phi_1(k_x\rho_i, \omega)$ at $\beta_e = 0$

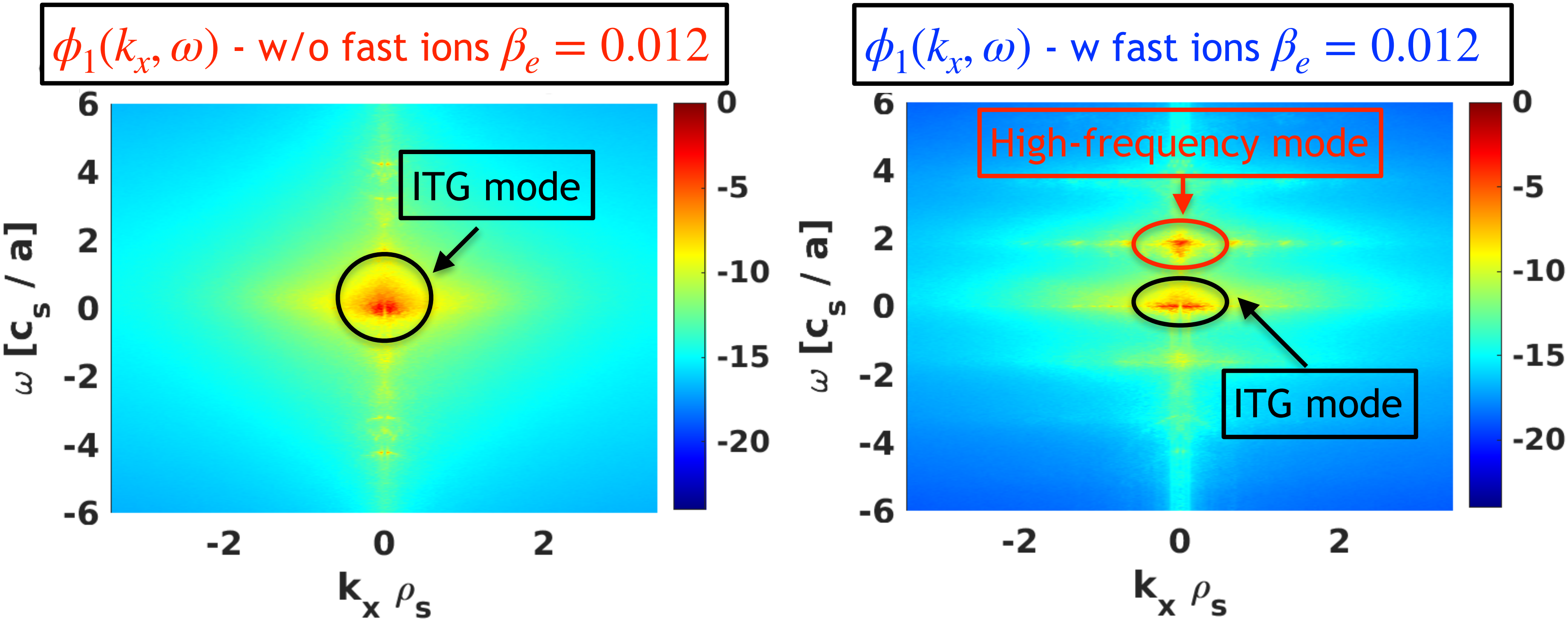
- Frequency spectra of electrostatic potential averaged over z and $k_y\rho_i$ for $t[a/c_s] = [50 - 350]$ (Phase I).



- $\phi_1(k_x\rho_i, \omega)$ hardly affected by EPs for $\beta_e = 0$.

Spectral analysis of $\phi_1(k_x\rho_i, \omega)$ at $\beta_e = 0.012$

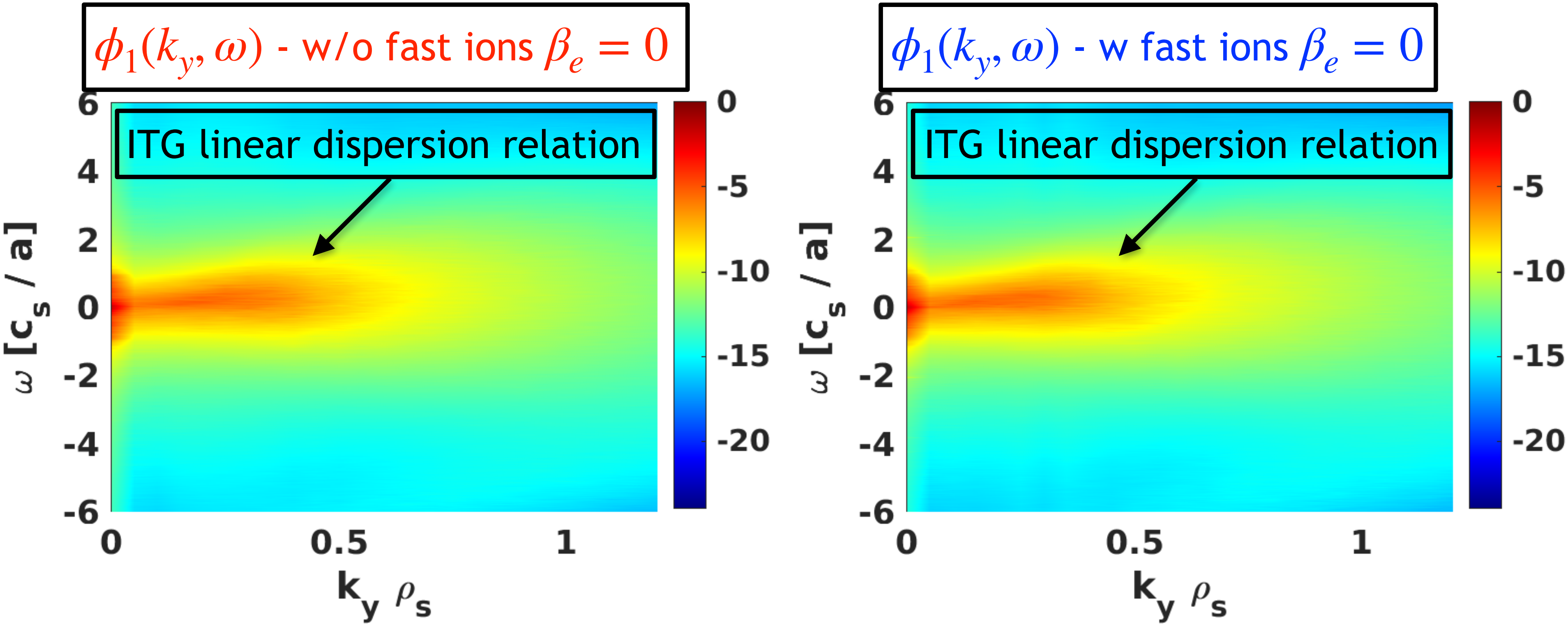
- Frequency spectra of electrostatic potential averaged over z and $k_y\rho_i$ for $t[a/c_s] = [50 - 350]$ (Phase I).



- A secondary high-frequency peak ($\omega \approx 2c_s/a$) arises in the presence of EPs at $\beta_e = 0.012$.

Spectral analysis of $\phi_1(k_y\rho_i, \omega)$ at $\beta_e = 0$

- Frequency spectra of electrostatic potential averaged over z and $k_y\rho_i$ for $t[a/c_s] = [50 - 350]$ (Phase I).



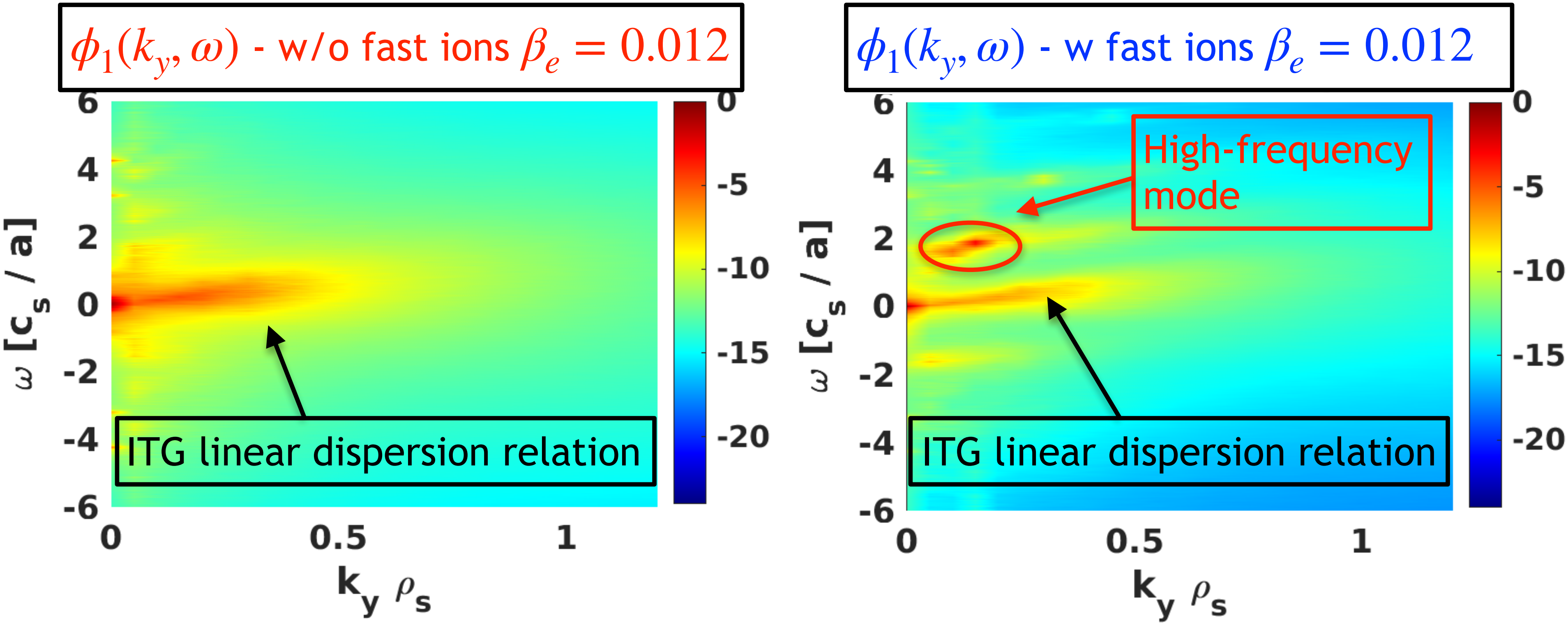
$\phi_1(k_y, \omega)$ - w/o fast ions $\beta_e = 0$

$\phi_1(k_y, \omega)$ - w fast ions $\beta_e = 0$

- $\phi_1(k_y\rho_i, \omega)$ hardly affected by EPs for $\beta_e = 0$, follows the linear ITG dispersion relation.

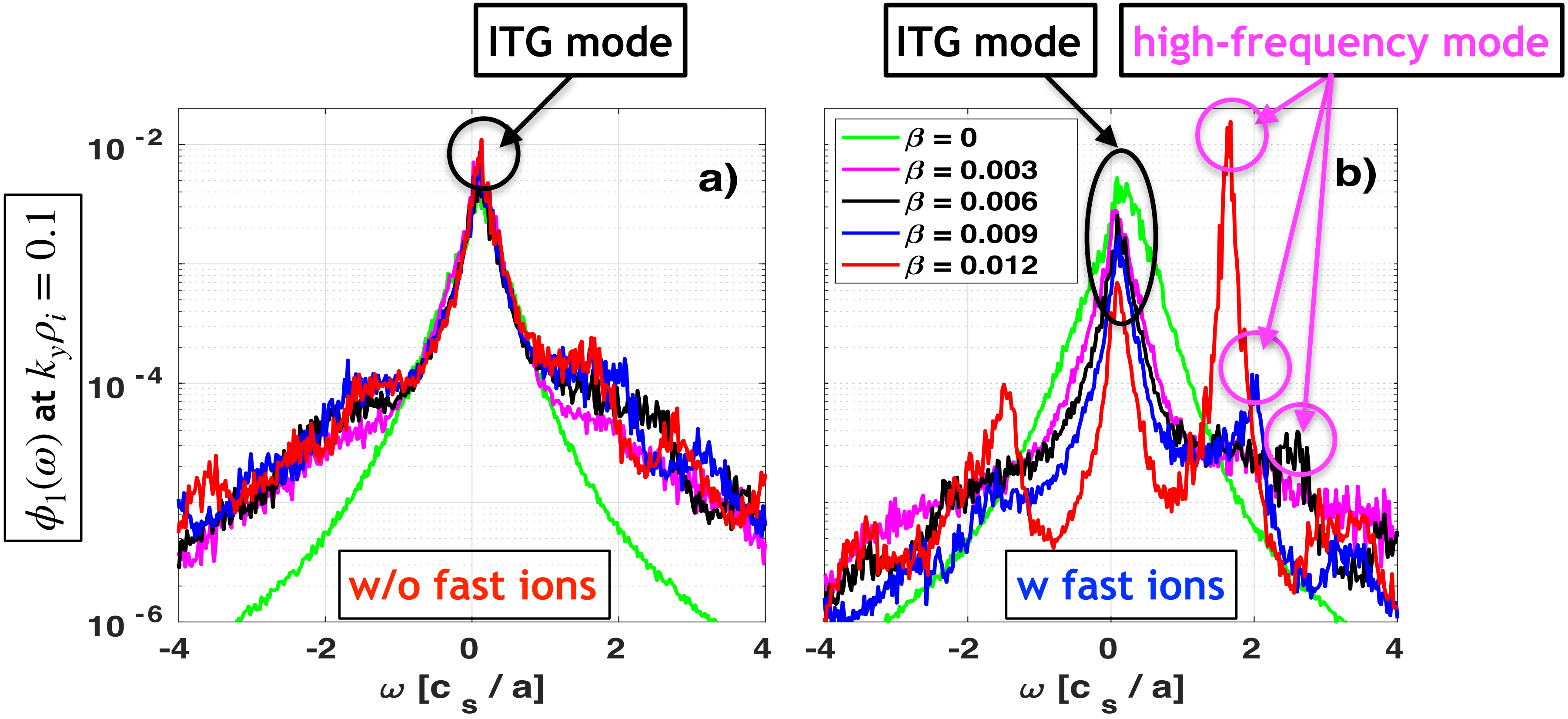
Spectral analysis of $\phi_1(k_y\rho_i, \omega)$ at $\beta_e = 0.012$

- Frequency spectra of electrostatic potential averaged over z and $k_y\rho_i$ for $t[a/c_s] = [50 - 350]$ (Phase I).



- A secondary high-frequency peak ($\omega \approx 2c_s/a$) arises w fast ions at $\beta_e = 0.012$ - significantly smaller amplitude w/o fast ions.

Impact of β_e on electrostatic potential ϕ_1



- Progressive destabilisation of high-frequency mode ($\omega \sim 1.8[c_s/a]$) with $\beta_e = \beta_i \cdot \sqrt{T_e n_e/(T_i n_i)}$ (here at $k_y\rho_i = 0.1$) observed only w fast ions.
- Reduction of ITG frequency peak ($\omega_{ITG} \sim 0.1[c_s/a]$) as the high-frequency mode increases in amplitude.

Free energy balance (a brief introduction)

- The complex nonlinear dynamics can be investigated by studying the time evolution of the system's free energy

Kinetic contribution

Field contribution

$$E_{FE} = \sum_s \int d^3x d^3v T_{0,s} \frac{f_{1,s}^2}{2F_{0,s}} + \int d^3x \frac{E^2 + B^2}{8\pi}$$

- Its time derivative (free energy balance equation) determines the energy flow during the whole simulation. In the gyrokinetic formalism, it reads [**A. Banòn Navarro PRL 2011**]:

$$\xi_{1,s} = \phi_{1,s} - v_{th,s} v_\parallel A_{1,\parallel}$$

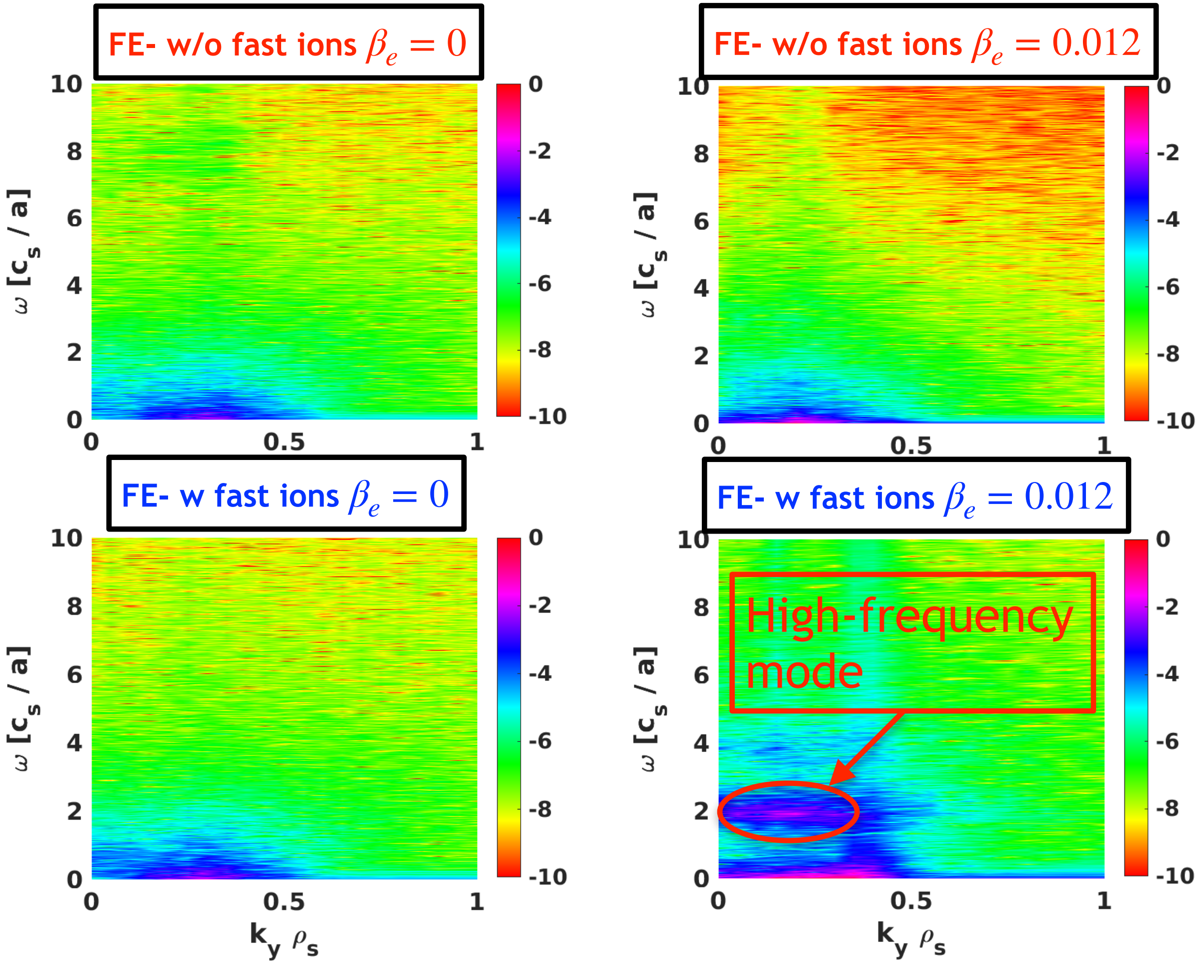
$$\frac{\partial E_{FE}}{\partial t} = \sum_s \int d\mu dv_\parallel \frac{\pi}{2} B_0 n_{0,s} \left(\frac{T_{0,s} g_{1,s}^*}{F_{0,s}} + q_s \xi_{1,s}^* \right) \frac{\partial g_{1,s}}{\partial t}$$

$$g_{1,s} = f_{1,s} + v_{th,s} v_\parallel \frac{q_s}{T_{0,s}} F_{0,s} A_{1,\parallel}$$

- Through the Vlasov equation (**of each species s**) the parallel advection, gradient-drive, curvature and nonlinear term contributions to the total free energy can be identified.

Energy redistribution from low- to high-frequencies

- Free energy spectra averaged over $k_x\rho_i$ and z for $t[a/c_s] = [50 - 350]$ (Phase I).



FE- w/o fast ions $\beta_e = 0$

FE- w/o fast ions $\beta_e = 0.012$

FE- w fast ions $\beta_e = 0$

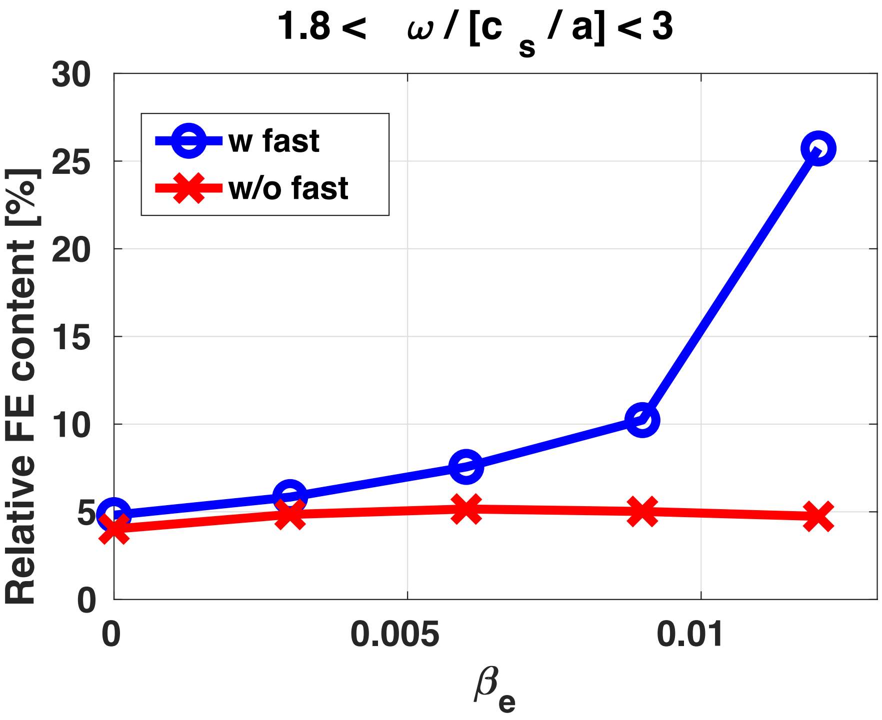
FE- w fast ions $\beta_e = 0.012$

High-frequency mode

- Significant energy redistribution from ITG to high-frequency modes enhanced by energetic particles and nonlinear effects.

Energy redistribution from low- to high-frequencies

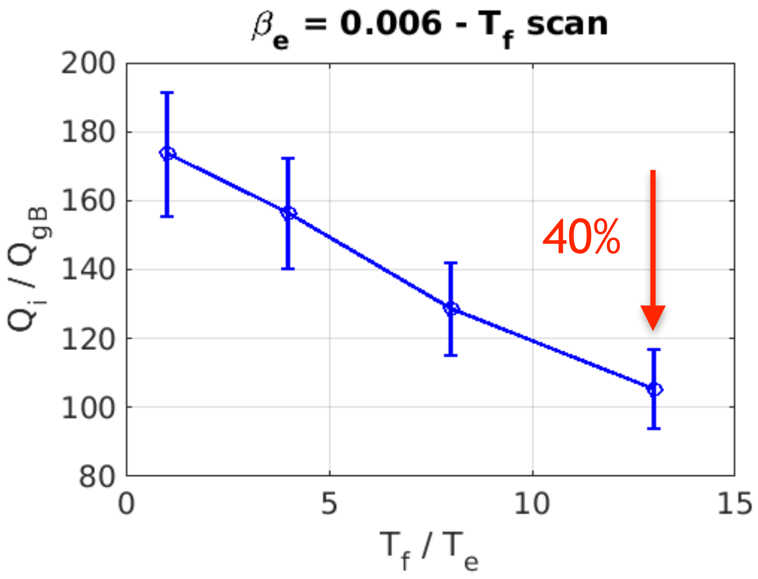
- Energy enclosed in in the high-frequency range ($1.8 < \omega/[c_s/a] < 3$) increases up to 30% at $\beta_e = 0.012$ ➡ reduction in the ITG free energy content.
- Consistent with progressive stabilisation on turbulent fluxes observed in Phase I.

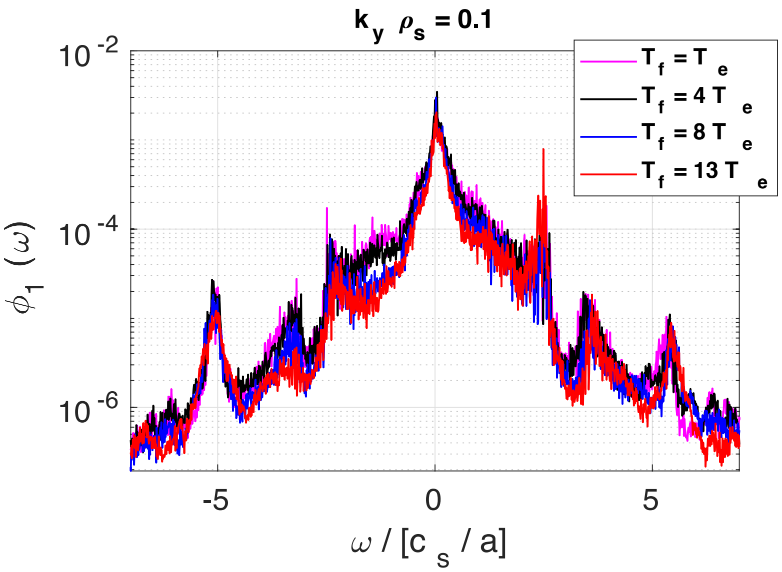


- No visible difference in the absence of fast ions.

EP temperature scan for realistic JET-like scenario

- Nonlinear flux-tube simulations at $\beta_e = 0.006$ show a substantial reduction of main ion heat flux as T_{fast} is increased (stabilisation of $\sim 40\,\%$ at $T_{fast} = 13T_e$).



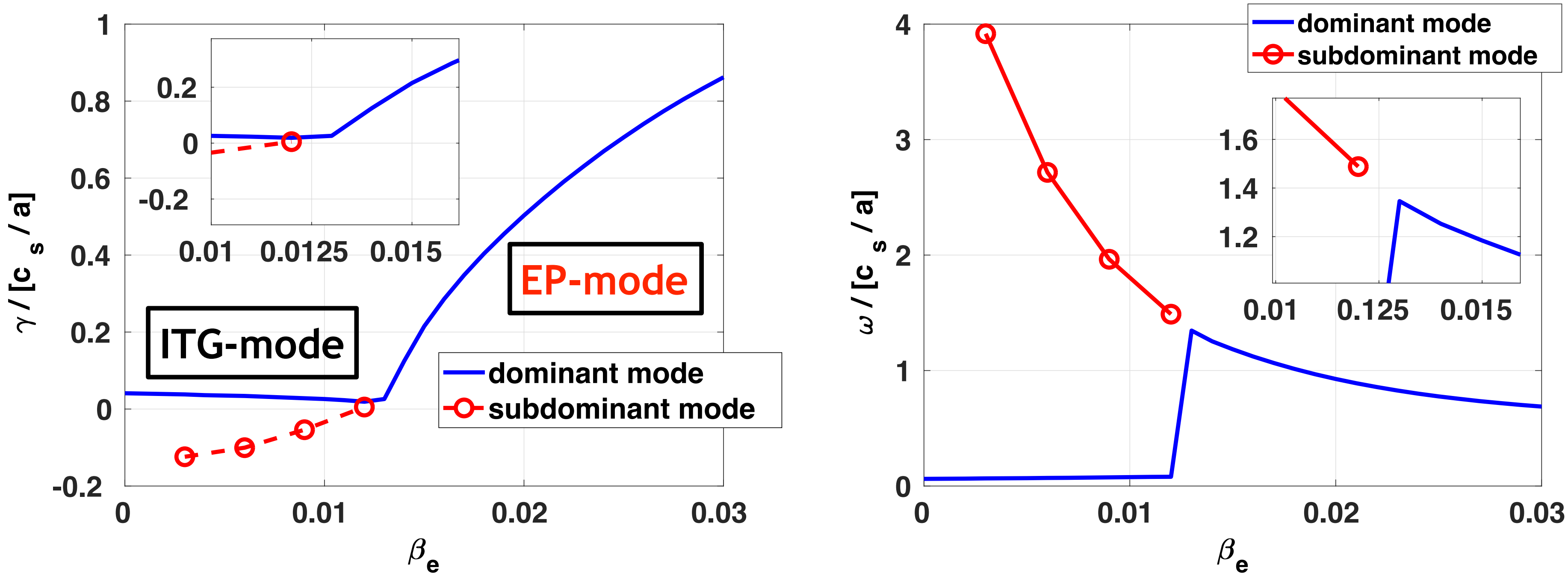


- Progressive destabilisation of high-frequency modes at $k_y\rho_i = 0.1$; increase in the mode amplitude, no frequency dependence with T_{fast}.
- Only mild fast particle effects on shearing rate levels observed.
- Energy enclosed in $1.8 < \omega/[c_s/a] < 3$ increases with T_{fast} up to $\sim 10\,\%$.

What is the nature of this EP-driven mode?

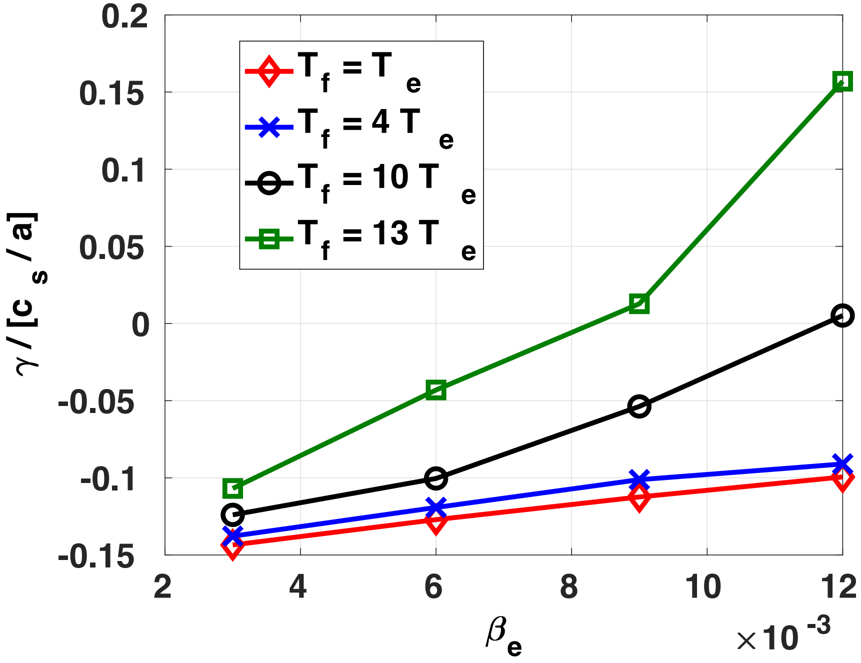
Mode identification: linear (β_e/T_{fast})-scans

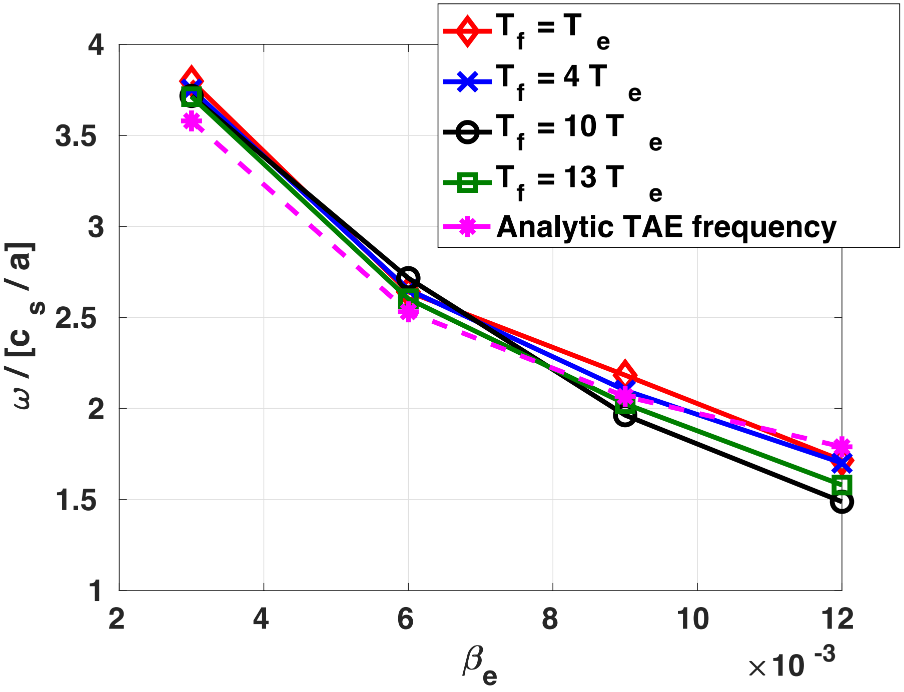
- Linear simulations for $k_y\rho_i = 0.1$ (i.e. $n = 17$) reveal that the high-frequency mode is linearly (*marginally*) stable for $\beta_e < 0.013$ ➡ linear damping decreases with β_e.
- Sub-dominant mode frequencies/growth rates extracted by filtering (in post-processing) the low-frequency (ITG) components and by fitting the time trace of high-frequency electrostatic field.



Mode identification: linear (β_e/T_{fast})-scans

- High-frequency mode ω not affected by T_{fast} (consistently with nonlinear results) but T_{fast} increases the mode drive → impact on the linear threshold.
- Dominant poloidal mode numbers are $m = 20$ and $m = 21$ → $k_{\parallel} = 1/2qR$. It lies at the center of the TAE gap and exhibit the TAE frequency $\omega_{TAE}/[c_s/a] = v_{th,i}/(2qR_0\sqrt{\beta_i})$.

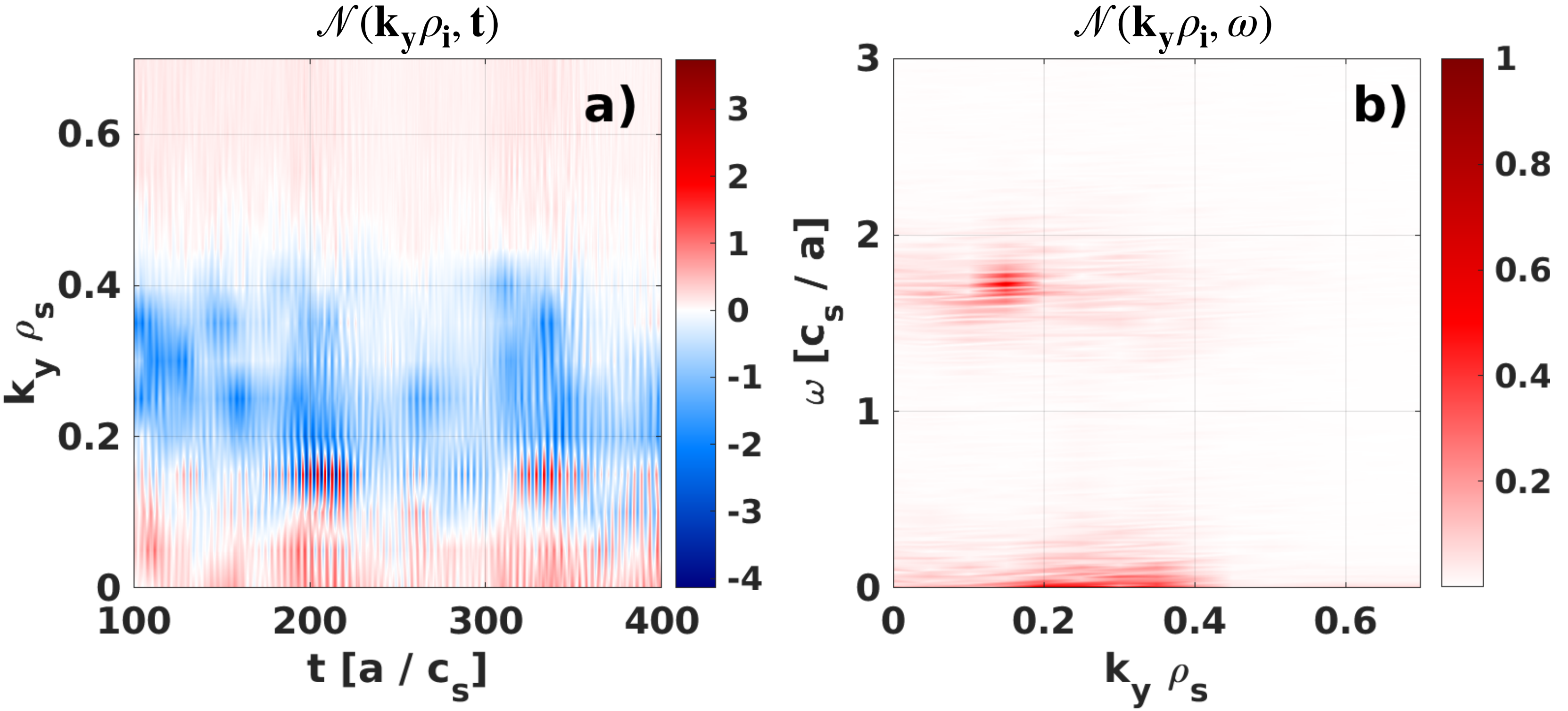




How does turbulence destabilise marginally stable TAEs?

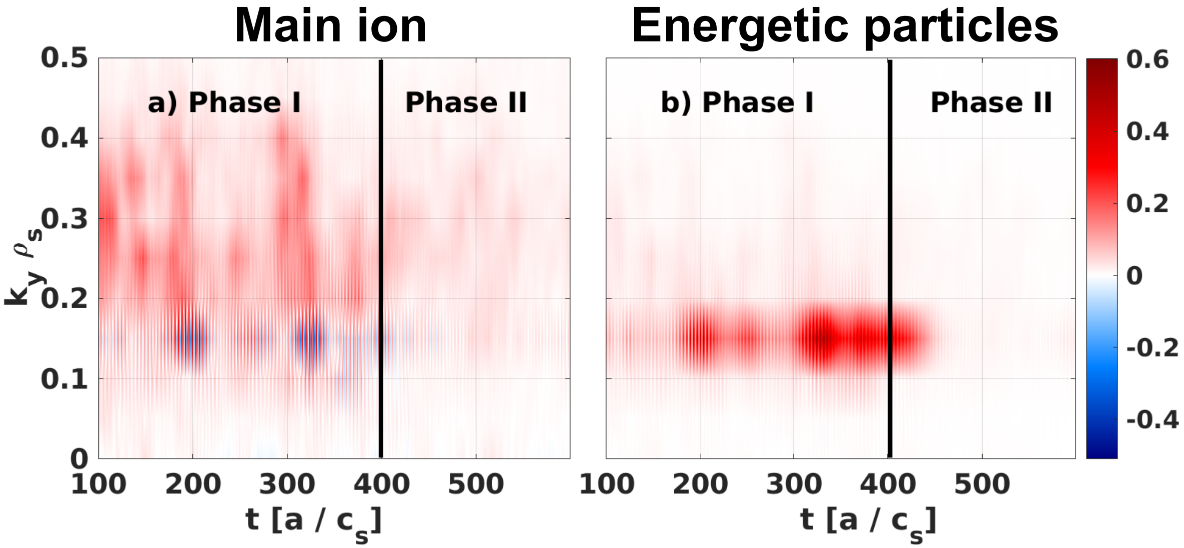
Nonlinear destabilisation of stable TAE modes

- Nonlinear term averaged over $k_x \rho_i$ and z in Phase I for $\beta_e = 0.012$.
- Positive and negative values indicate that a given wave-vector is receiving or losing energy through nonlinear coupling.
- Significant energy transfer from ITGs $(0.2 < k_y \rho_i < 0.45)$ to TAEs $(0.05 < k_y \rho_i < 0.175)$ relevant scales modulated at the TAE frequency.



Fast ions drive the high-frequency modes

Curvature term averaged over $k_x\rho_i$ and z for $\beta_e = 0.012.$



Phase I:

- EP provide the dominant contribution to the TAE → EP curvature term is peaked at the TAE-scale and the energy is modulated at the TAE frequency.

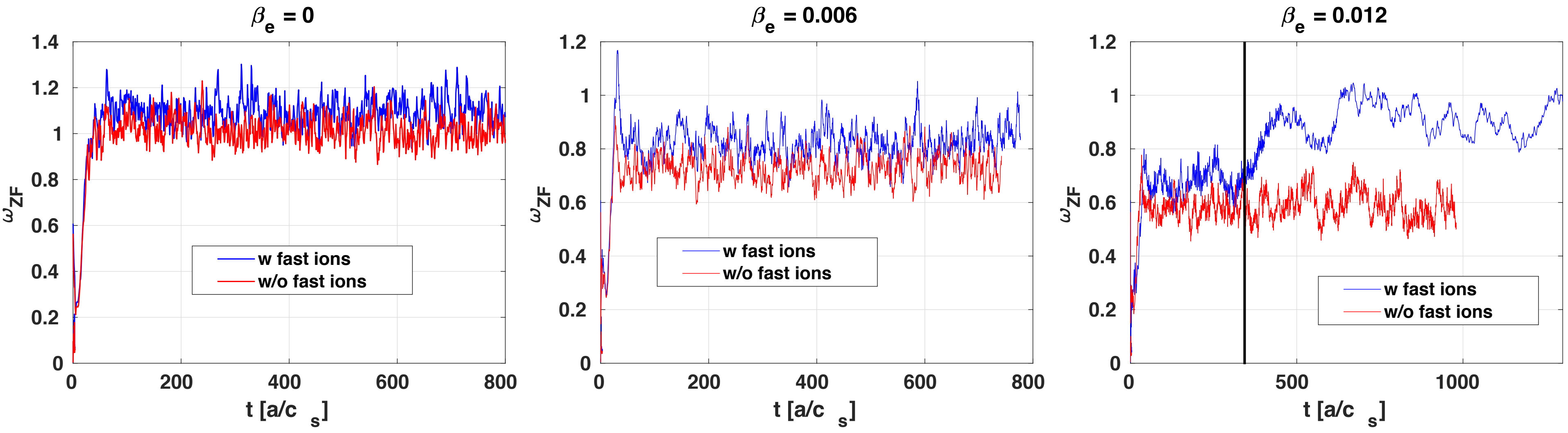
Phase II:

- Amplitude of main ion curvature term decreases significantly.
- EP contribution drops at a later time → lack of cross-scale transferred energy from main ions

Is the transition between Phase I and Phase II triggered by zonal flows?

Fast ion impact on $k_y\rho_i = 0$ (zonal flow)

- Minor EP impact ($\sim 10\,\%$) on shearing rate $\omega_{ZF} = \langle k_x^2 \phi_1(k_y = 0)\rangle_{rms}$ in weak EM case.
- For $\beta_e > 0.006$ a significant increase in ω_{ZF} is observed in correspondence with Phase II transition.
- In deep Phase II the simulation reaches a new stationary state with substantially reduced turbulent transport and increased zonal levels.



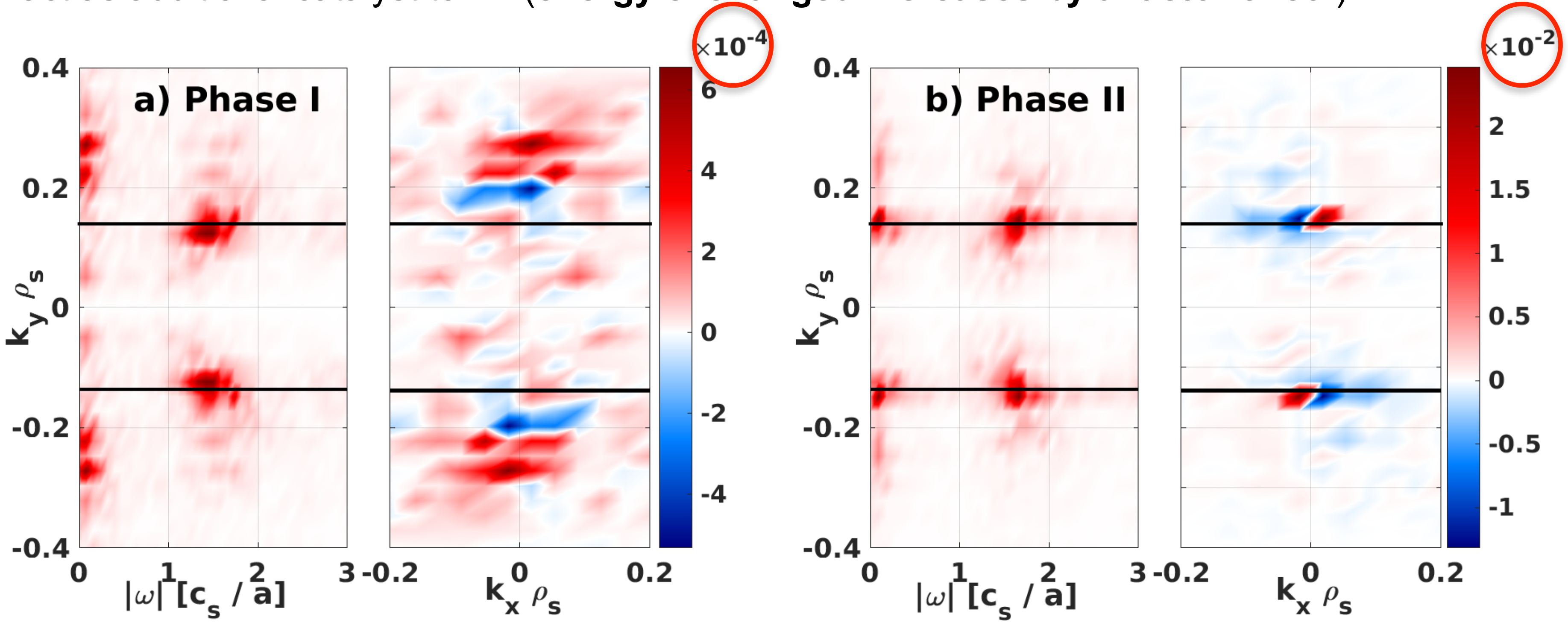
Triad transfer to zonal component $(k_x, k_y)\rho_i = (0.04{,}0)$

Phase I:

- ZF is interacting mainly with ITG scales (i.e. $0.2 < k_y\rho_i < 0.4$) ➡ negligible energy transfer at TAE frequency.

Phase II:

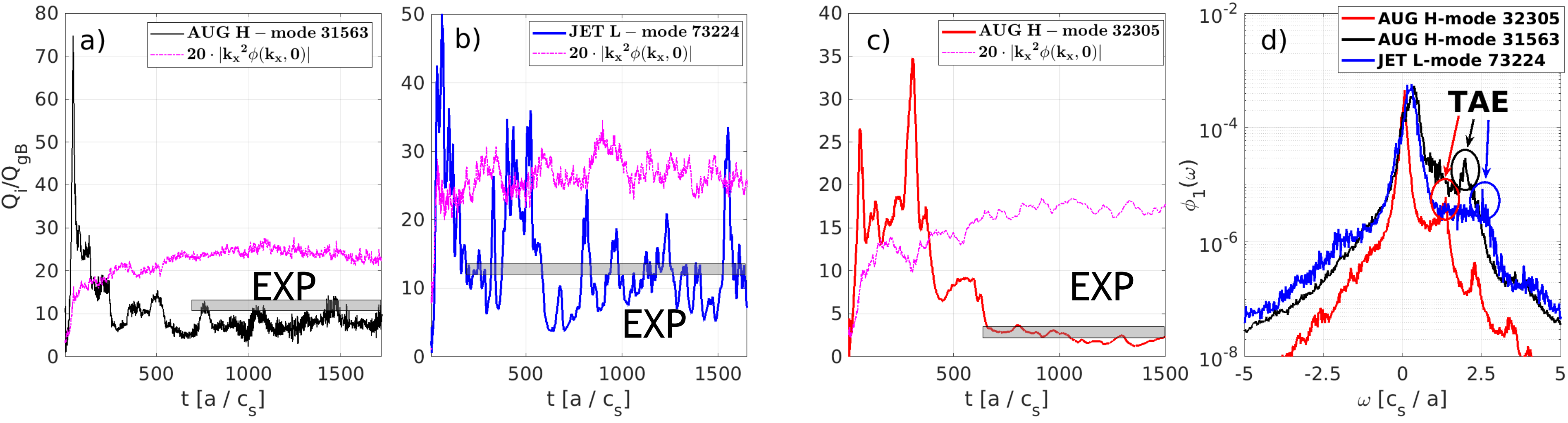
- Energy is transferred mainly from wave-vector $k_y\rho_i = 0.15$ (where TAE is dominant). TAEs act as additional catalyst to ZF (**energy exchanged increases by a factor of 30!**).



How general are these findings?

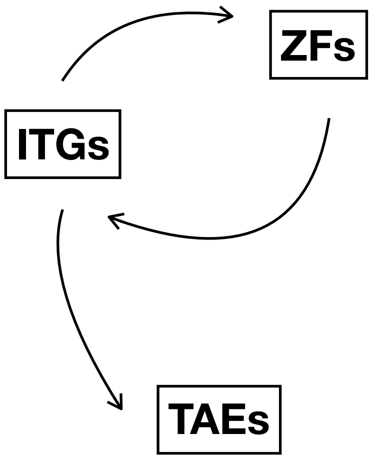
Similarities of different discharges

- Similar results are observed in an increasing number of experimental scenarios in which a substantial turbulent stabilisation is attributed to energetic particle nonlinear electromagnetic effects:
  - JET L-mode #73224 with both NBI and ICRH.
  - AUG H-mode #31563 with ICRH.
  - AUG H-mode #32305 with NBI.



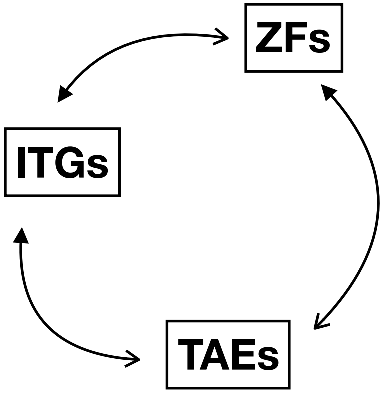
Conclusions

Phase I:



- Fast particles provide linearly stable TAE-like modes destabilised nonlinearly.
- Energy redistribution from ITGs to TAEs.
- Depleting the energy content of the turbulence.

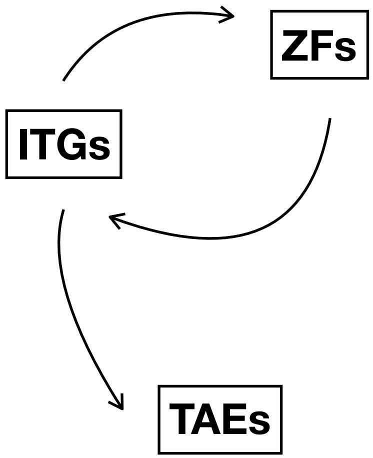
Phase II:



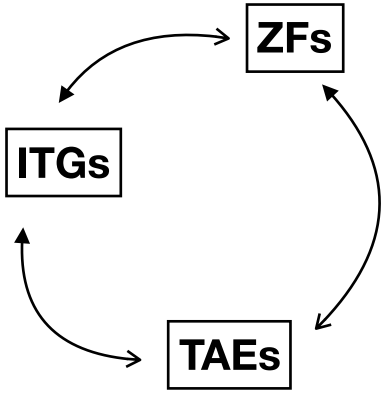
- If β_e is sufficiently large, fast particles interact with ZF.
- Increase in energy transfer to ZF and scattering to larger $k_x\rho_i$ mode numbers.
- Direct impact of ZF on ITGs, strongly suppressing heat/particle fluxes.

Conclusions

Phase I:



Phase II:

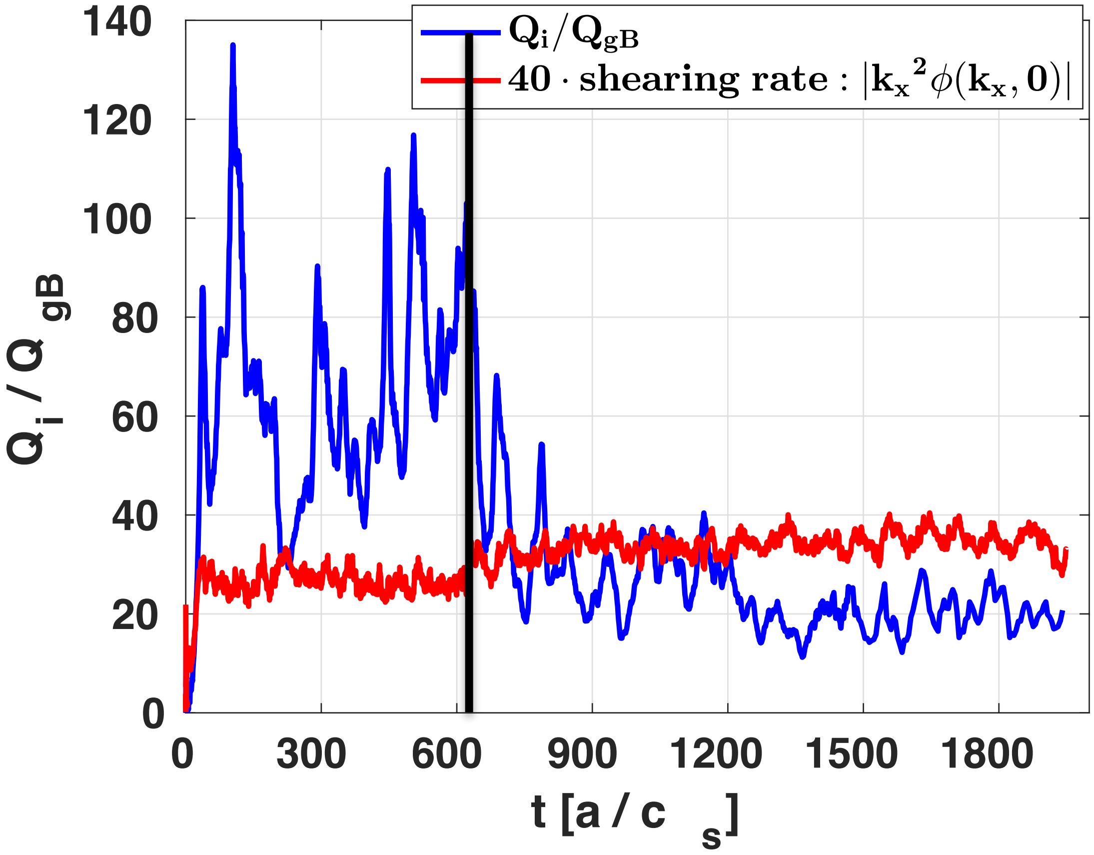


A. Di Siena et al. accepted NF 2019

Thanks for your attention!

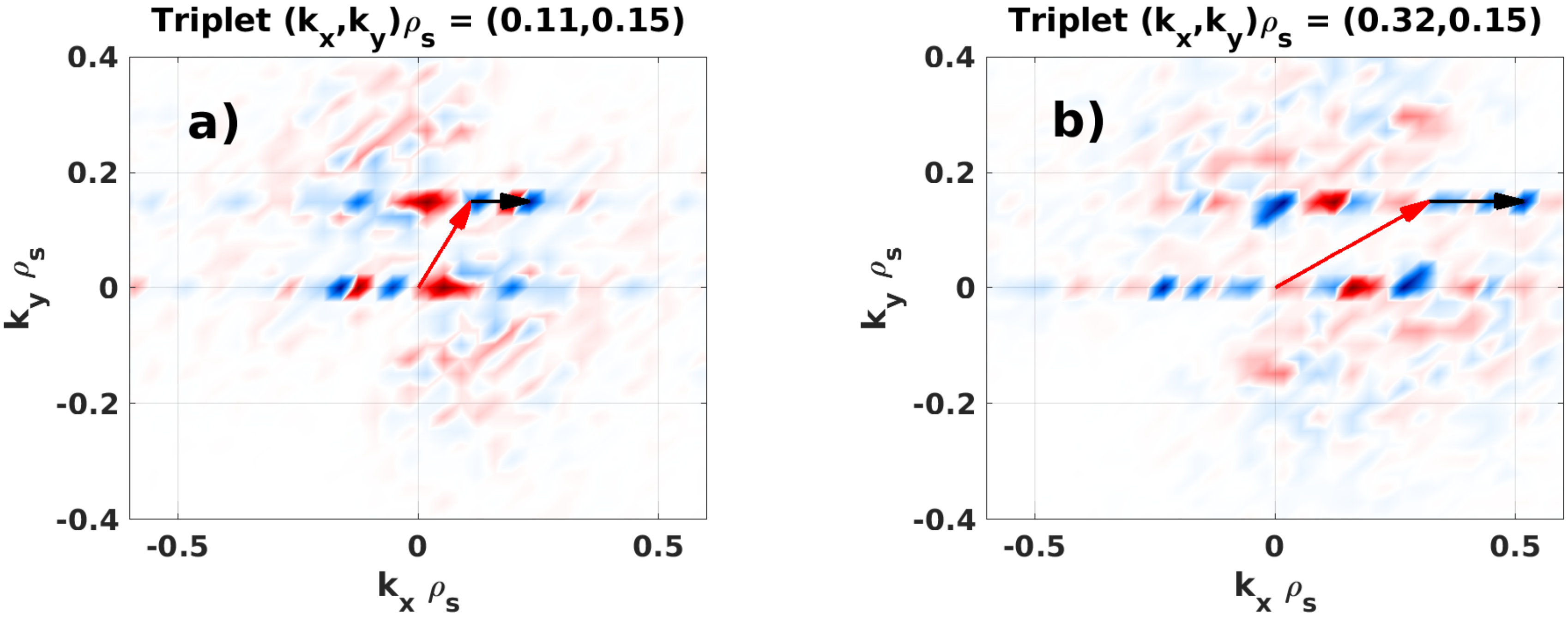
Backup slides

Nonlinear simulation at $\beta_e = 0.009$

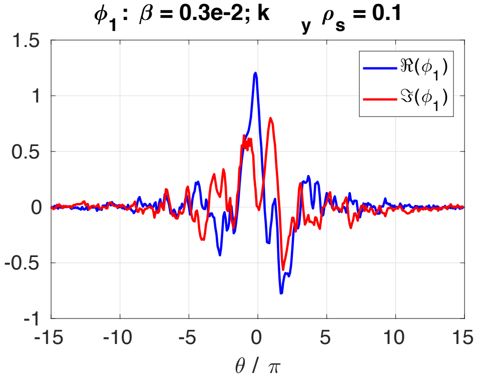


Scattering to larger $k_x\rho_i$ mode numbers

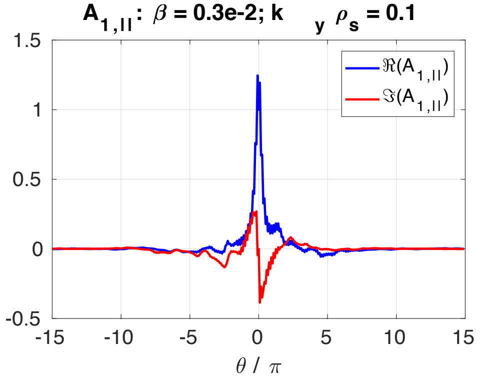
- Time averaged ($t = [470 - 550]a/c_s$) triad transfer to $(k_x, k_y)\rho_i = (0.11{,}0.15)$ and $(k_x, k_y)\rho_i = (0.32{,}0.15)$.
- By increasing the radial component of the triplet (marked in red), energy is successfully transferred to modes at the same $k_y\rho_i$ but with larger $k_x\rho_i$ (**black**) → larger damping due to gyroradius effects: **turbulence stabilisation**.
- This process is enhanced by EP.



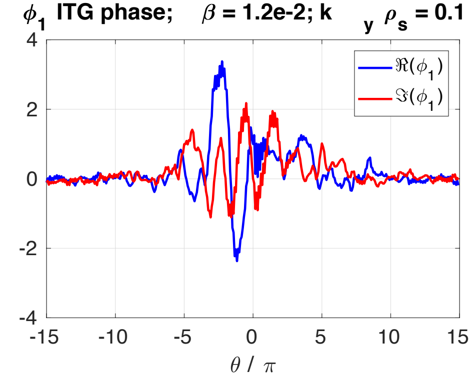
Nonlinear ballooning mode structure



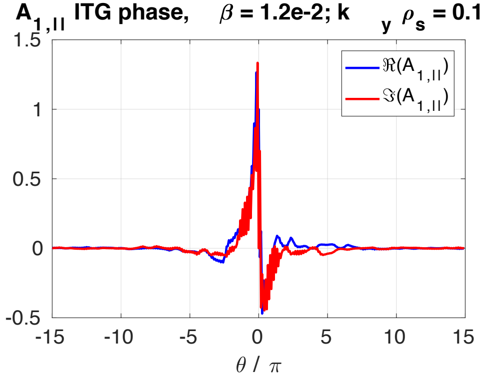
ϕ_1: β = 0.3e-2; $k_y \rho_s$ = 0.1



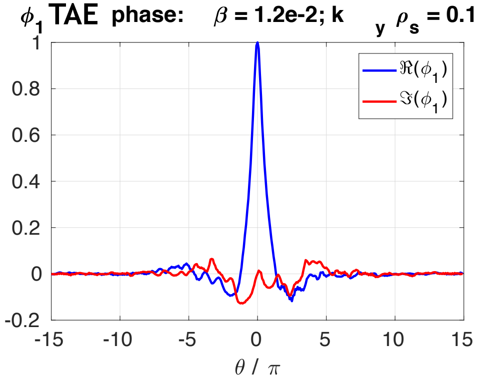
$A_{1,||}$: β = 0.3e-2; $k_y \rho_s$ = 0.1



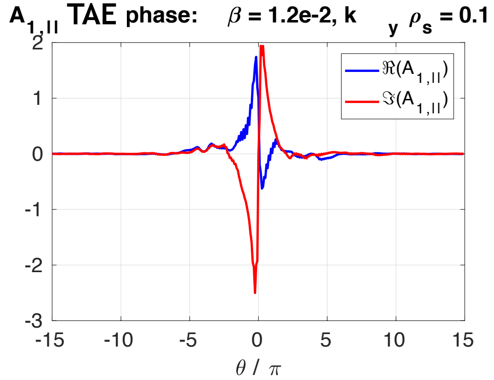
ϕ_1 ITG phase; β = 1.2e-2; $k_y \rho_s$ = 0.1



$A_{1,||}$ ITG phase, β = 1.2e-2; $k_y \rho_s$ = 0.1

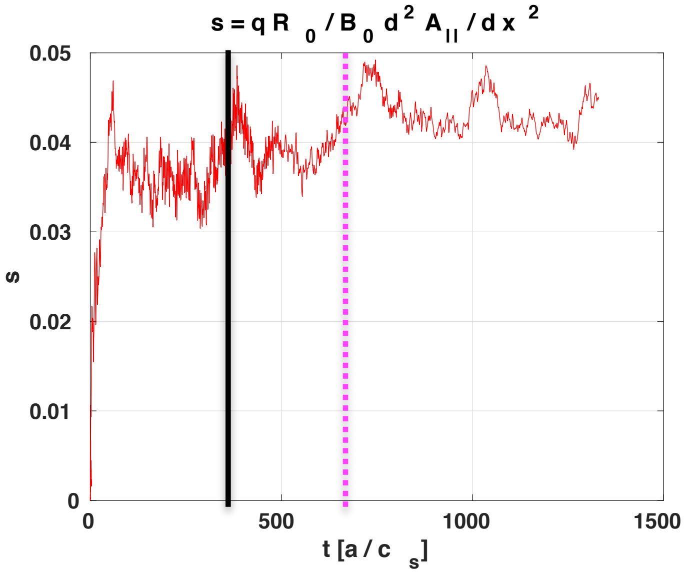


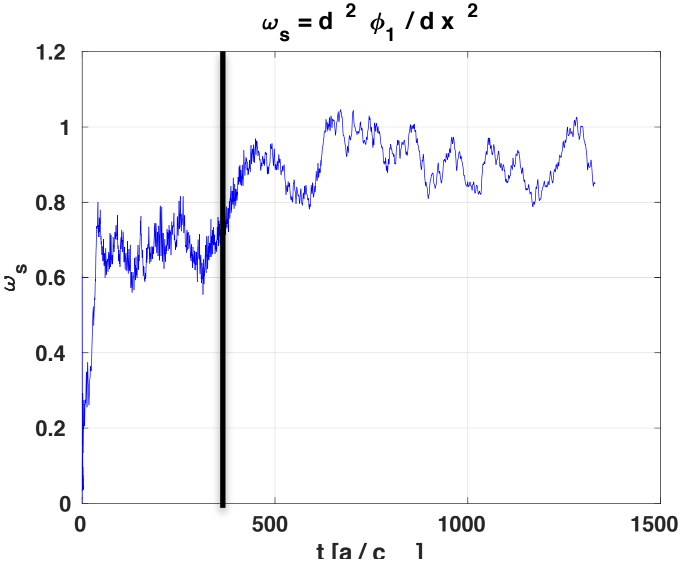
ϕ_1 TAE phase: β = 1.2e-2; $k_y \rho_s$ = 0.1

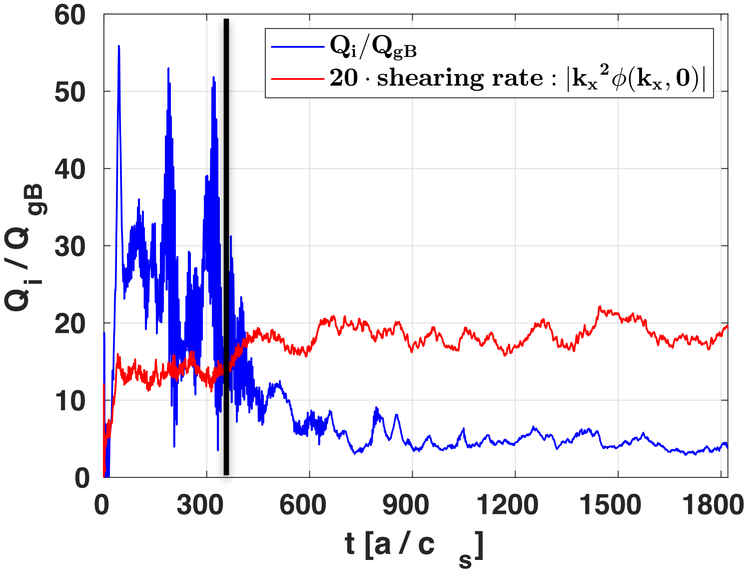


$A_{1,||}$ TAE phase: β = 1.2e-2, $k_y \rho_s$ = 0.1

EP impact on $A_{1,\|}$

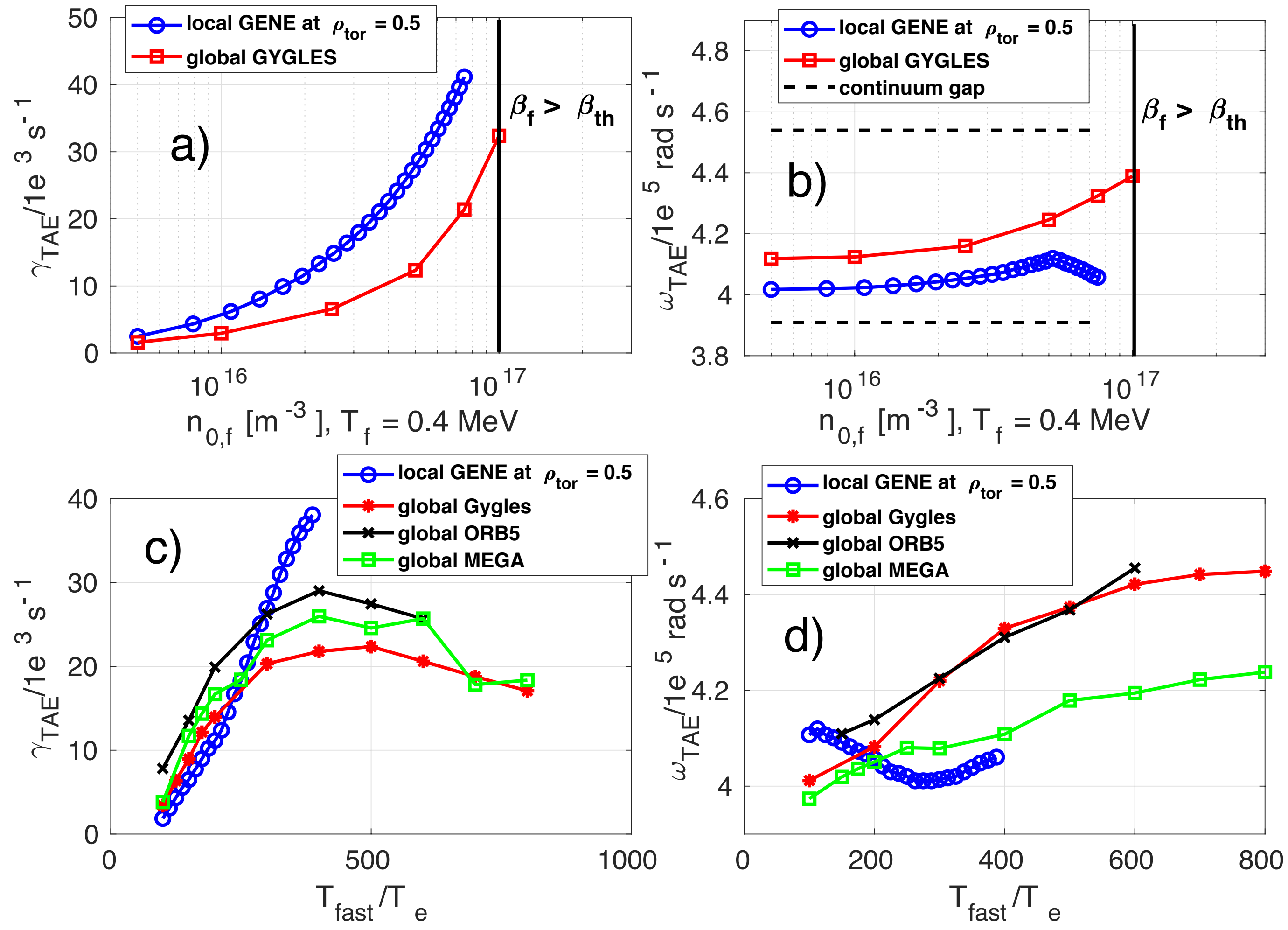






Flux-tube approximation of EP-driven modes

Comparison between flux-tube (at $\rho_{tor} = 0.5$) and global TAE results for the ITPA-benchmark case (see **[A. Mishchenko et al. PoP 2009]** and [**A. Könies et al. NF 2019]**)

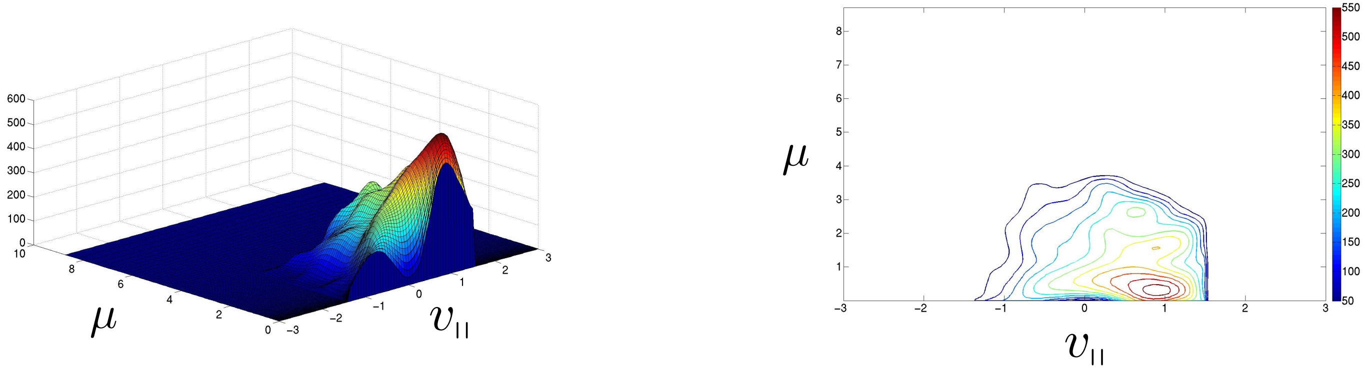


‘High realism’ study: JET #73224

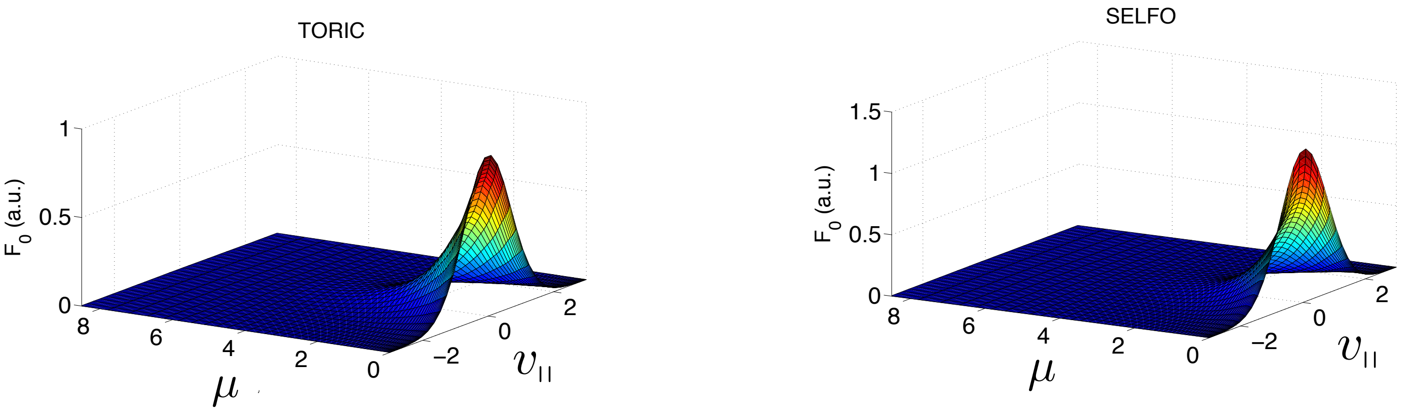
- GENE has been extended to support arbitrary backgrounds [A. Di Siena et. al PoP 2018].
- Bulk plasma: Deuterium, electron, Carbon impurities; fast particles: fast Deuterium and ^{3}He.

Numerical distribution functions

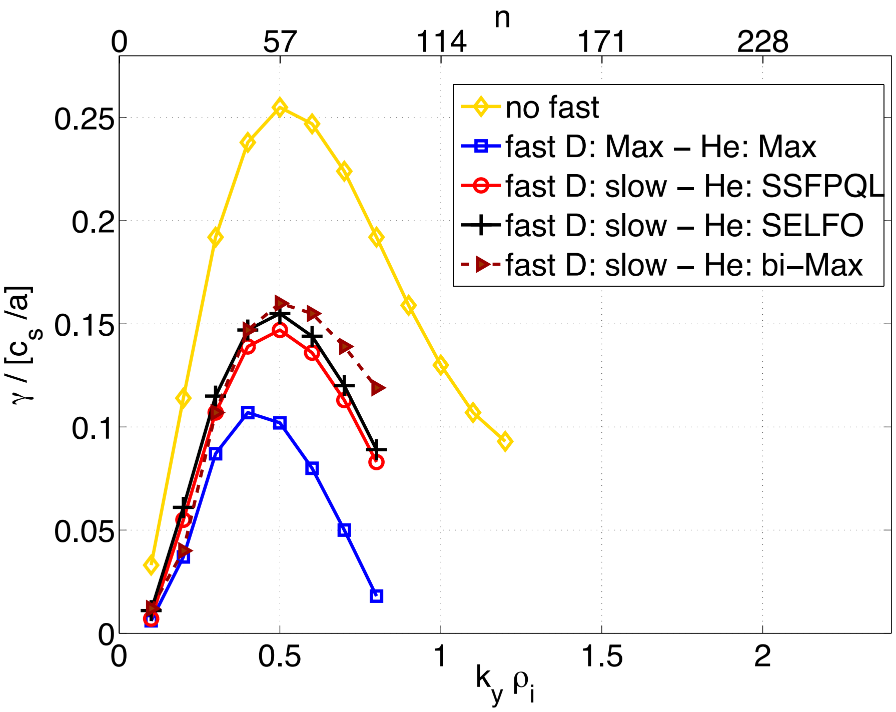
- Fast Deuterium NB-heated distribution function: SPOT simulation with 4191 test particles.

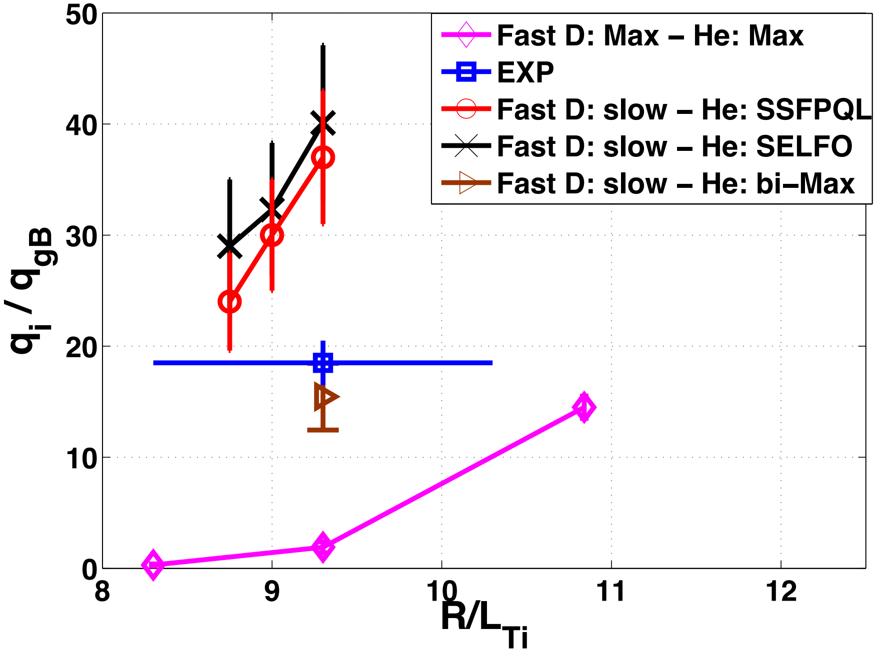


- ICRH ^{3}He distribution function: TORIC/SSFPQL and SELFO/PION+LION.



‘High realism’ study: JET #73224 - ICRH



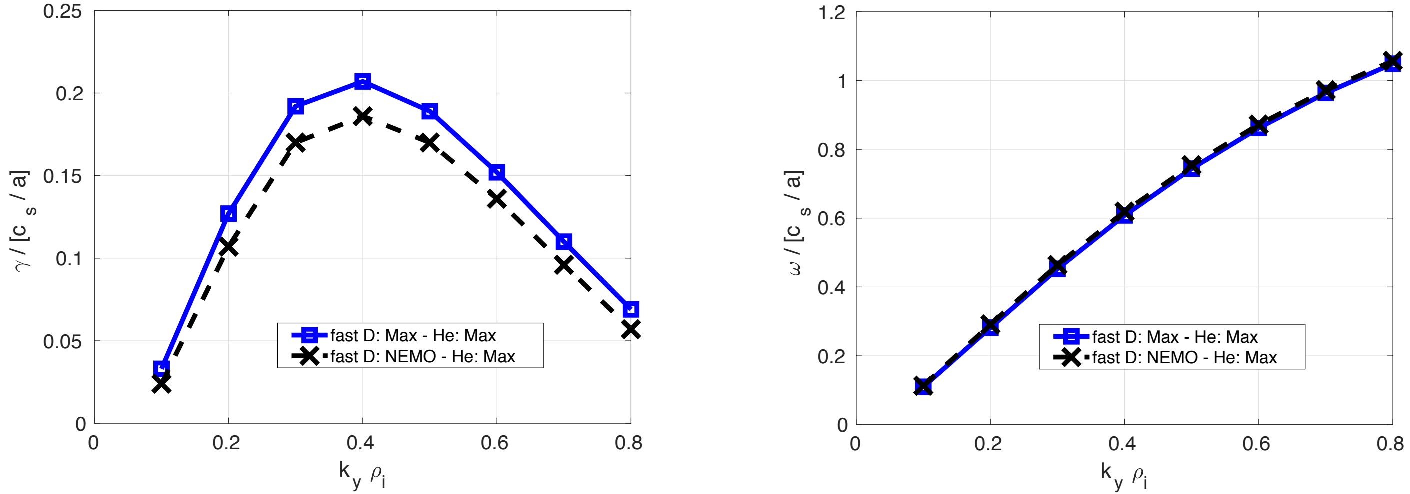


- Substantial but weaker fast ion stabilisation.
- The experimental fluxes are matched inside error bars.
- Excellent agreement between TORIC and SELFO nonlinear results.

Improved agreement with EXP value!

‘High realism’ study: JET #73224 - NBI

Linear simulations



Nonlinear simulations