Ion Stiffness Mitigation as a Key for Improved Core Ion Confinement: experimental results in JET and theoretical investigations

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Thanks to all contributors

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Outline

- **Evidence of combined role of rotation and magnetic shear in reducing ion stiffness in L-mode dedicated transport experiments**

- **Consistent evidence in high performance Hybrid, H-mode and ITB scenarios**

- **State of art of first principle simulations with regard to effect of rotational and magnetic shear on ion stiffness**

Effect of toroidal rotation

In theory, rotation reduces transport via a threshold up-shift associated to the ExB flow shear according to the quenching rule

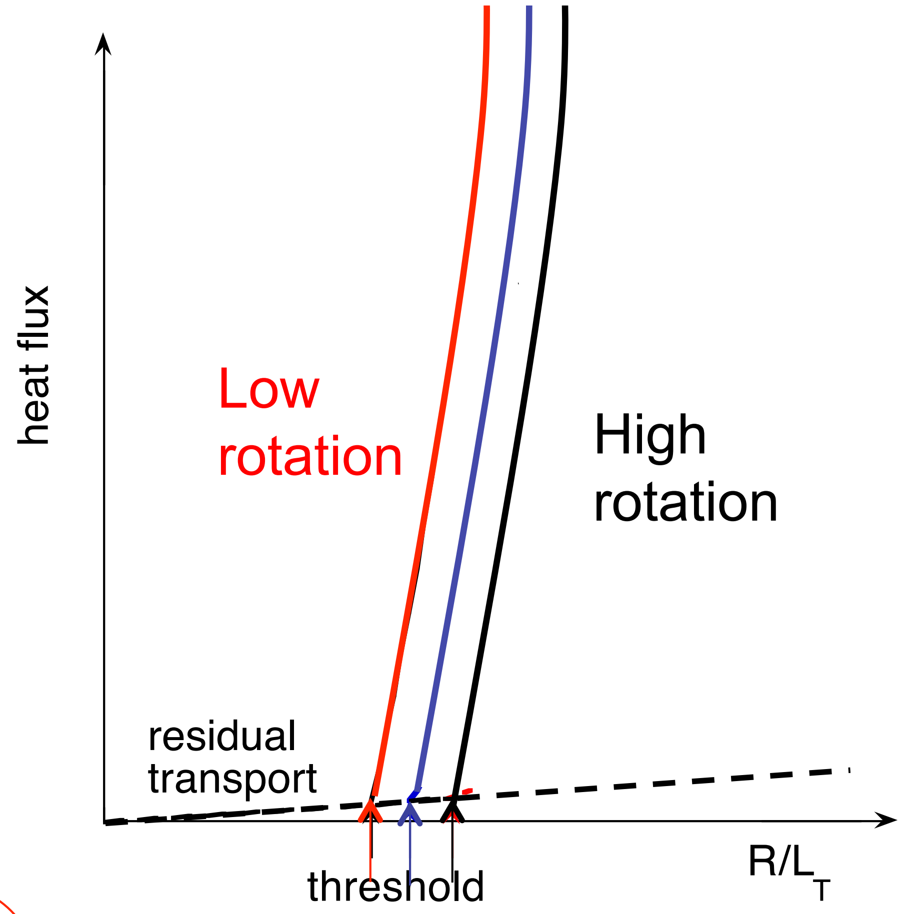
$$\gamma_{ExB} = \gamma_{noExB} - \alpha_E\ \omega_{ExB}$$

(α_E ~1) [Waltz et al., 1994]

$$\omega_{ExB} = r/q\ \ d(q\ v_{ExB}/r)\ /dr$$

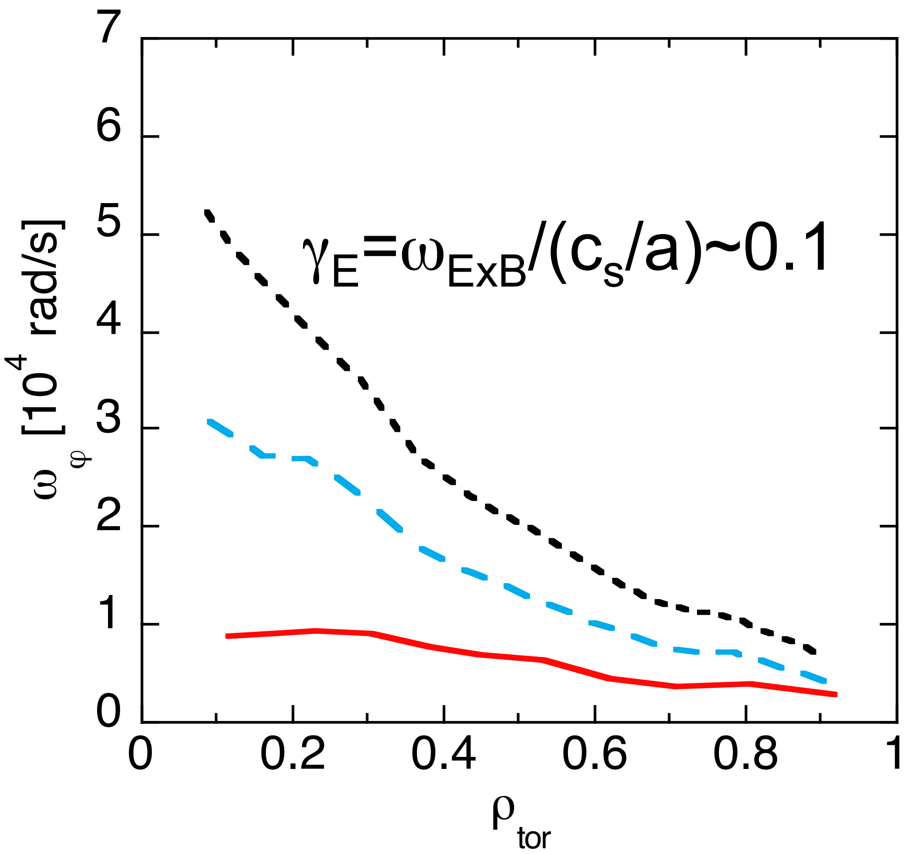
$$E_r = \frac{1}{eZ_i n_i}\frac{\partial p_i}{\partial r} - v_{\theta,i}B_\phi + v_{\phi,i}B_\theta,$$

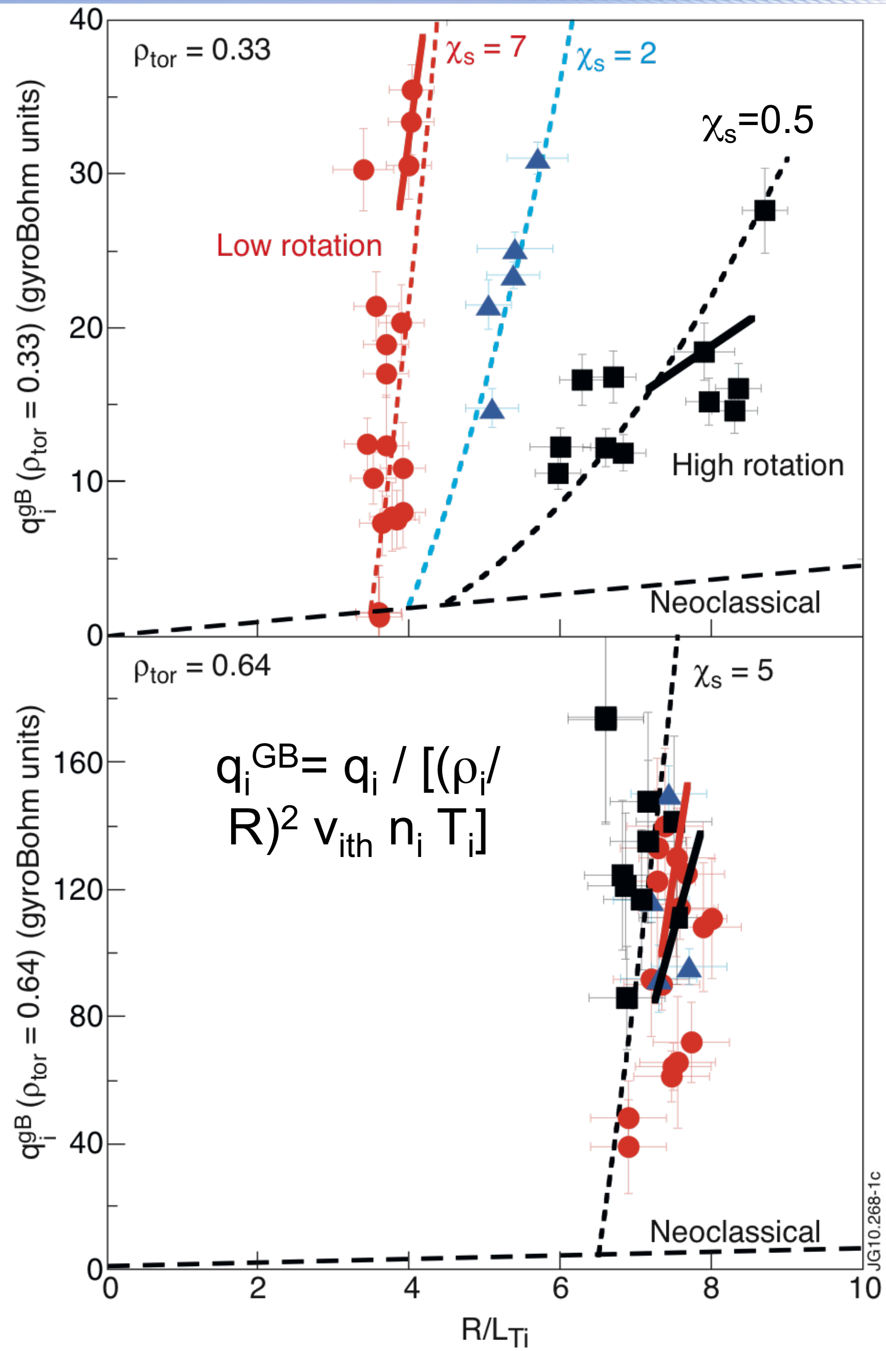
Common expectation



Stiffness mitigation by rotation in JET

3 sets of shots at different rotation





Rotation mitigates stiffness in core plasma but not in outer region.

Confirmed by T_i modulation

Novel empirical hypothesis

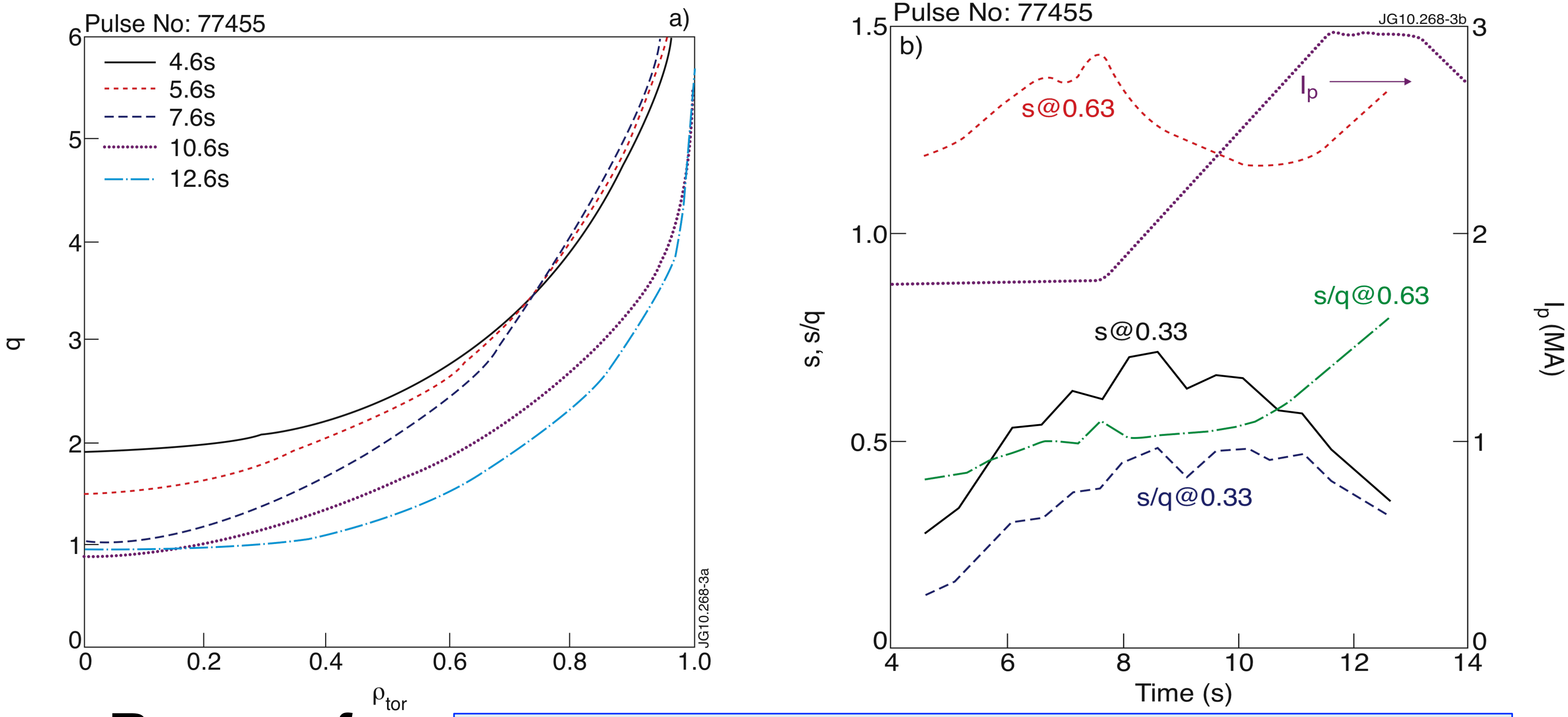
Rotation mitigates ion stiffness only in regions with low magnetic shear

Proofing the hypothesis…

Dedicated experiments of q scans both with and without rotation

-3MW ICRH(^{3}He)-D : off-axis→threshold / on-axis→stiffness at low rotation

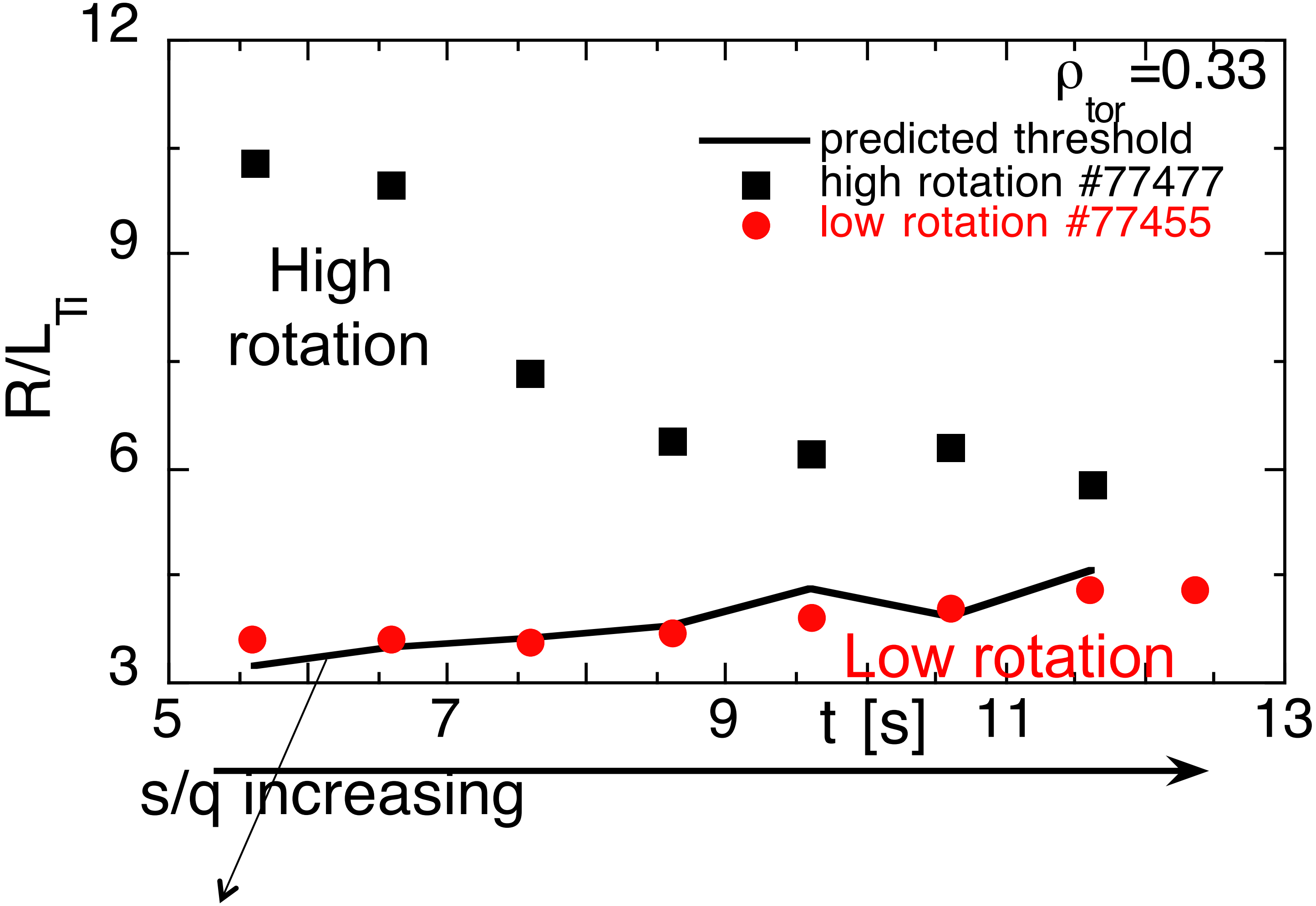
-3MW ICRH + 10-15 MW NBI →stiffness at high rotation



Range of s explored

ρ_{tor}=0.33 :	0.05<s< 0.8	0.02<s/q<0.5
ρ_{tor}=0.64 :	0.75<s<1.45	0.25<s/q<0.7

Key result



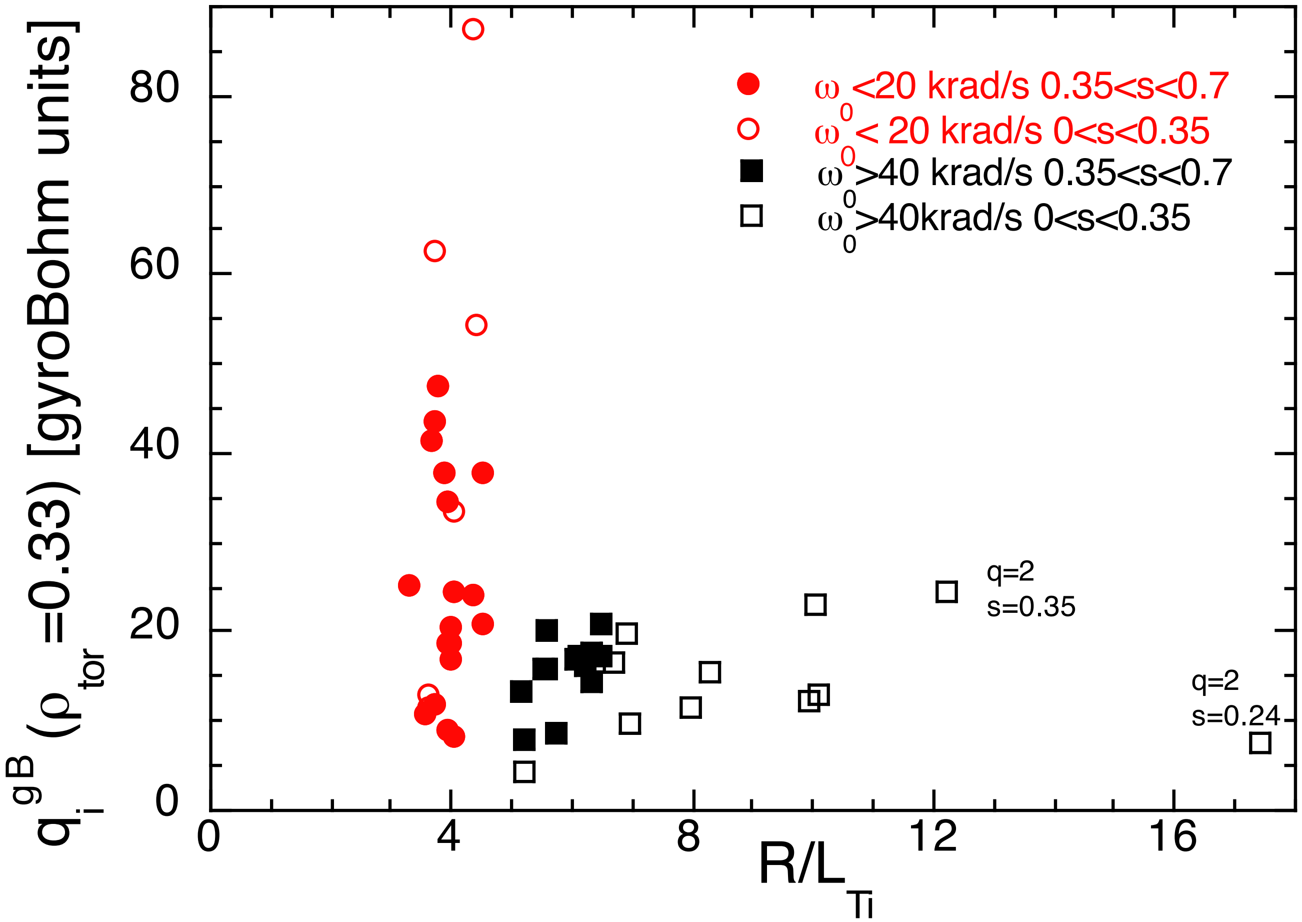
ITG threshold after
Guo, Romanelli, 1993

$$R/L_{Ti}^{\ ITG} = \frac{4}{3}\left(1+\frac{T_i}{T_e}\right)\cdot\left(1+2\frac{s}{q}\right)$$

- Threshold follows the expected behaviour with s/q
- At high rotation R/L_{Ti} well above threshold and decreasing with q profile peaking
- Consistent changes in turbulence by reflectometry

- s~0.7 appears the value for which rotation is no longer effective.

Summary of q scan session

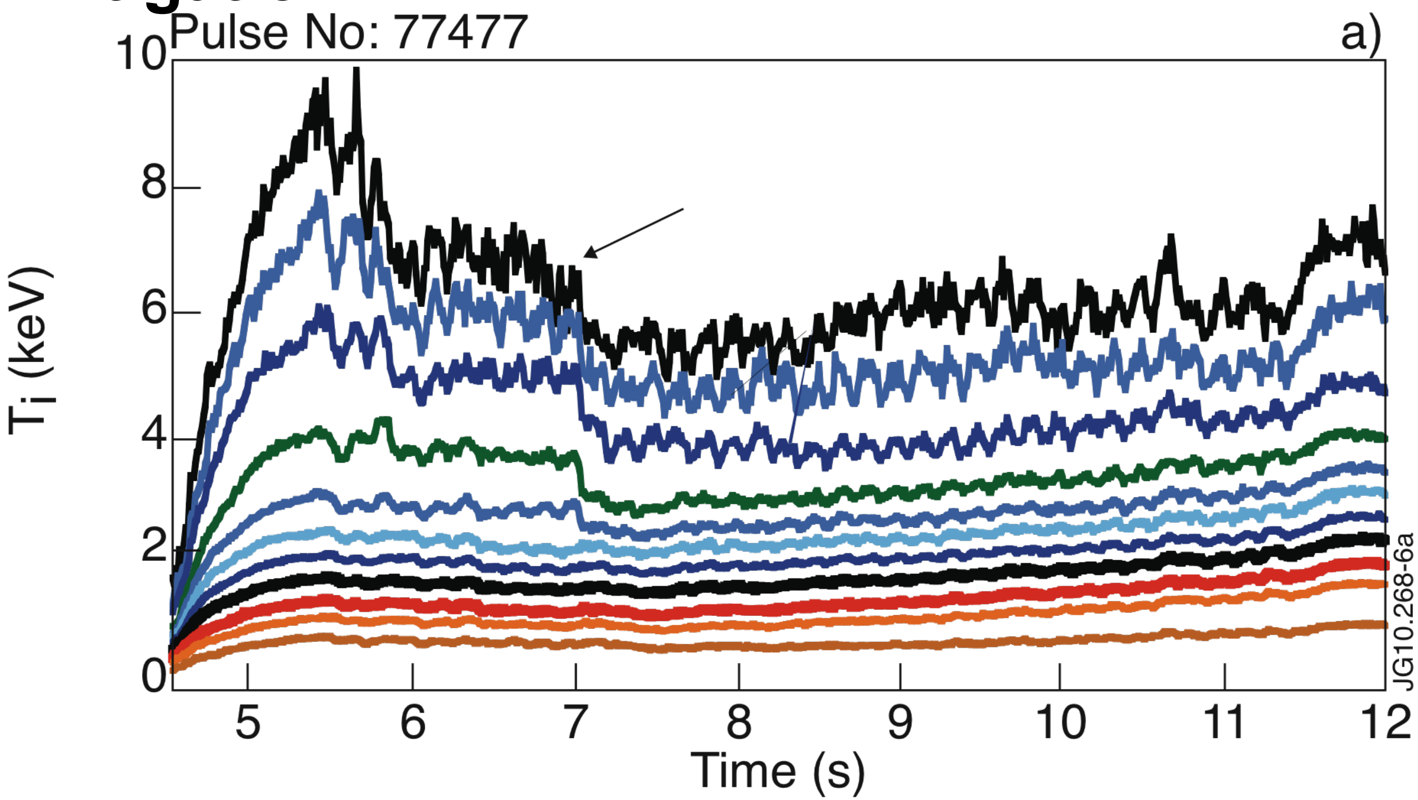


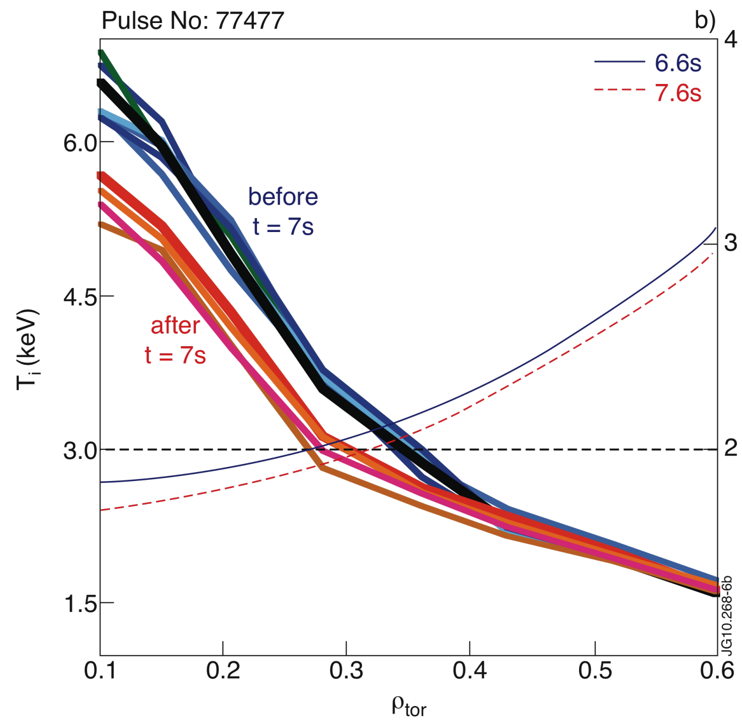
q_i calculated by PION and PENCIL

The hypothesis is confirmed by dedicated experiments

- At low rotation both low s and high s very stiff
- At high rotation, low s shots have lower stiffness
- Stiffness changes confirmed by T_i modulation
- Main rationals AND low s introduce extra improvement in R/L_{Ti}

Question: are low order rationals at low s responsible of stiffness mitigation?

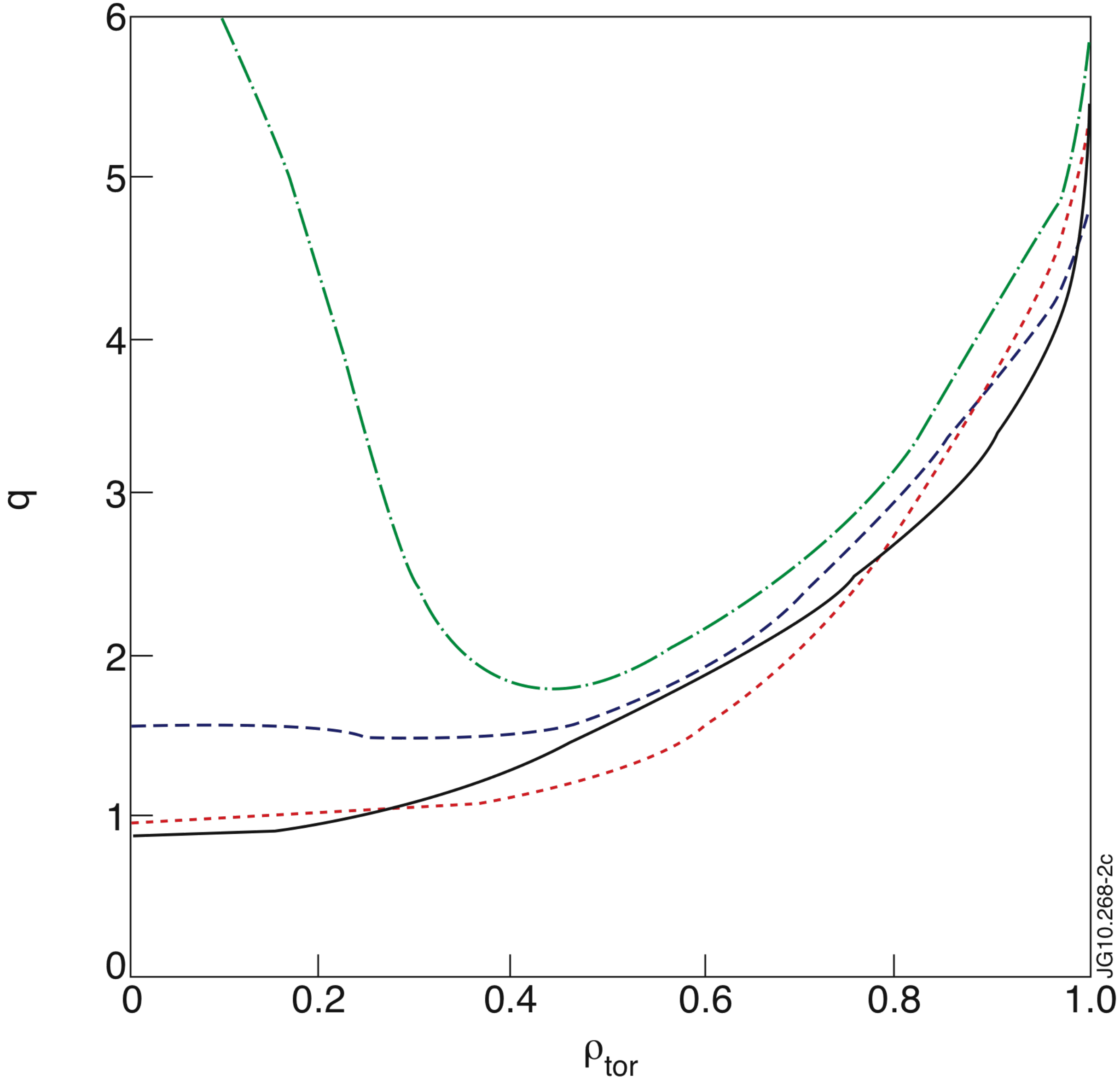




- Decrease in time of R/L_{Ti} is often abrupt. No MHD!
- It appears as a sudden shrinking of the low stiffness region
- However: 1) role of rationals reported also without rotation
  2) role of rationals reported both for ions and electrons

➔ Two separate phenomena?

Some implications for scenarios



4 scenarios with different q profile:

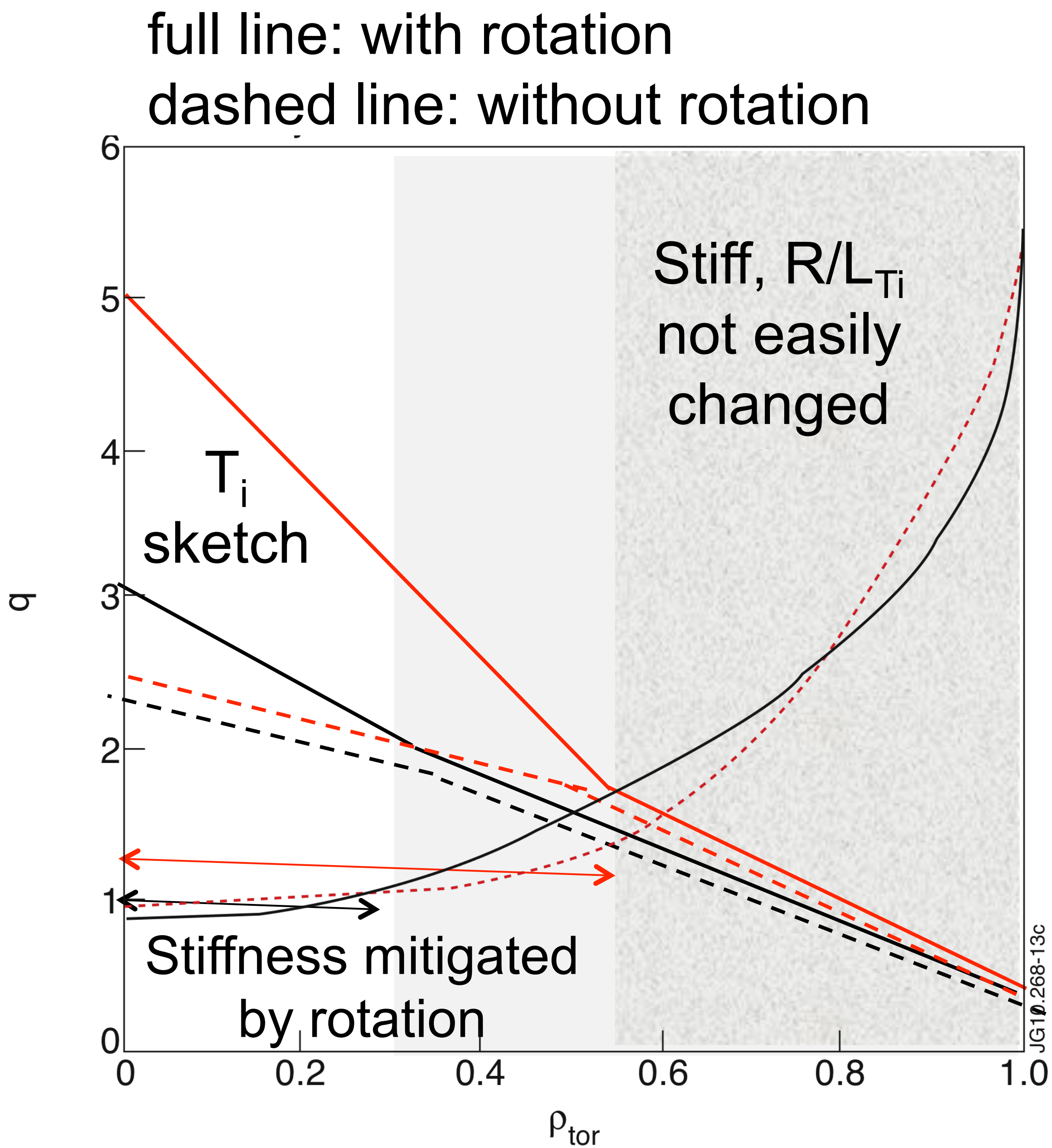
Fully diffused H-mode

Hybrid

Ion ITBs with OS

Ion ITBs with NS

Some implications



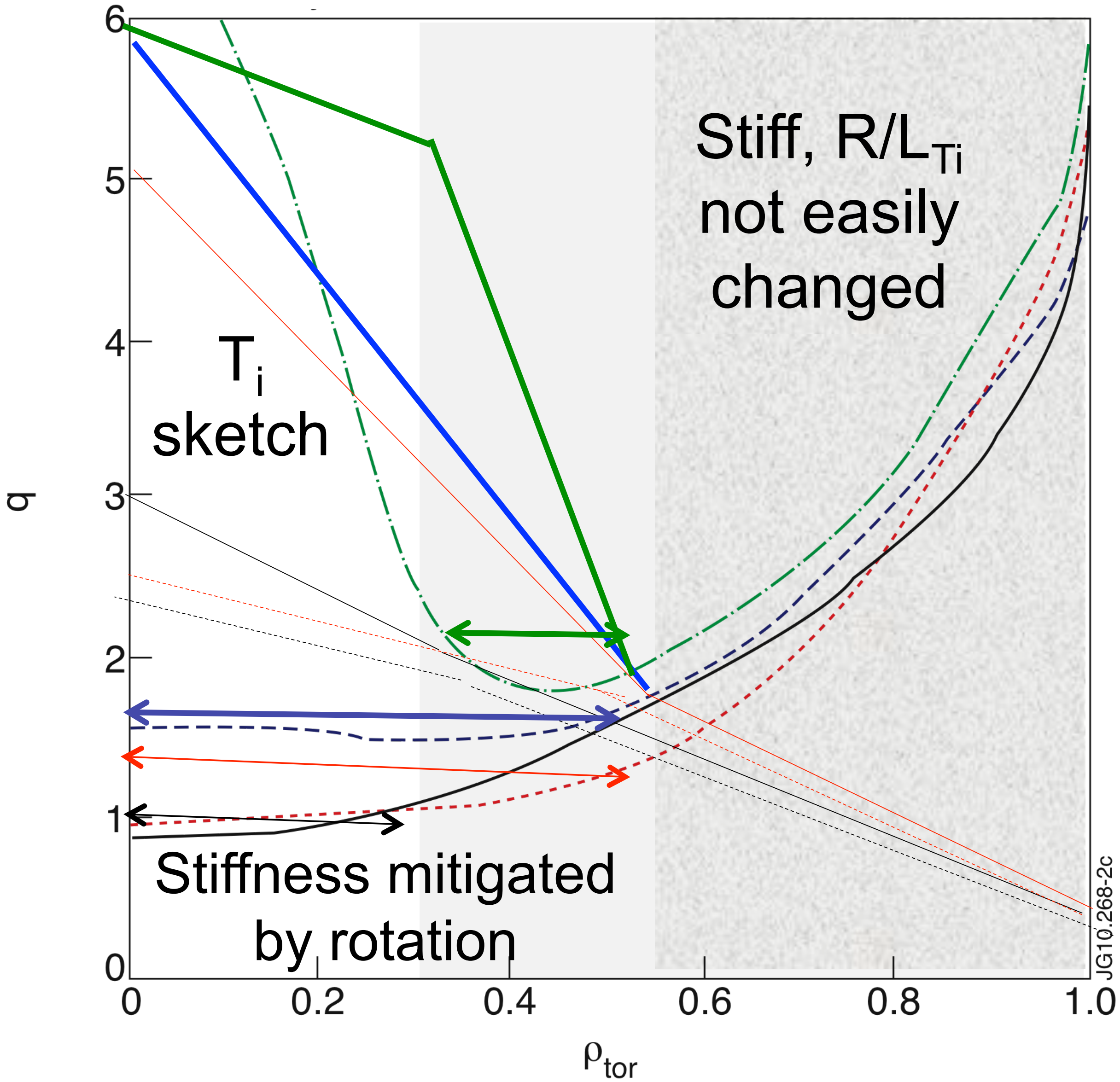
How improved core ion confinement originates in hybrid

Fully diffused H-mode

Hybrid

Some implications

full line: with rotation
dashed line: without rotation



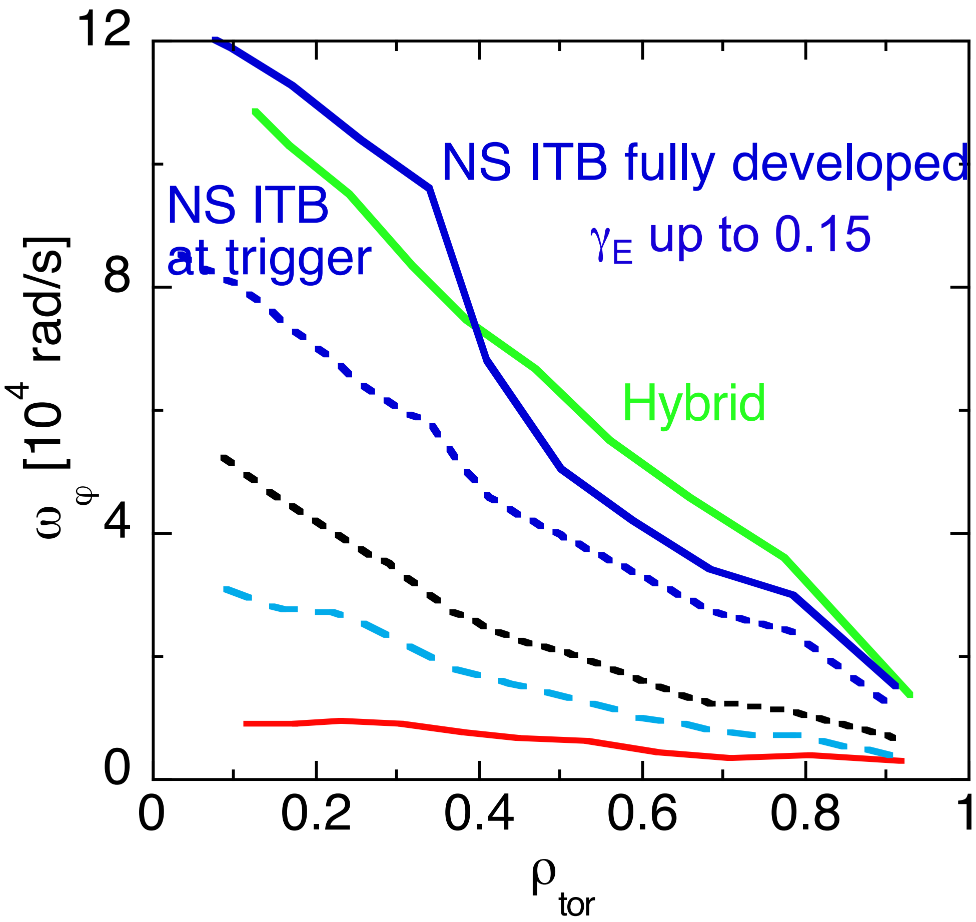
The same mechanism could explain all 4 scenarios

Fully diffused H-mode
Hybrid
Ion ITBs with OS
Ion ITBs with NS

Enhanced core confinement was lost at reduced rotation in JET and DIII-D hybrids and ITBs

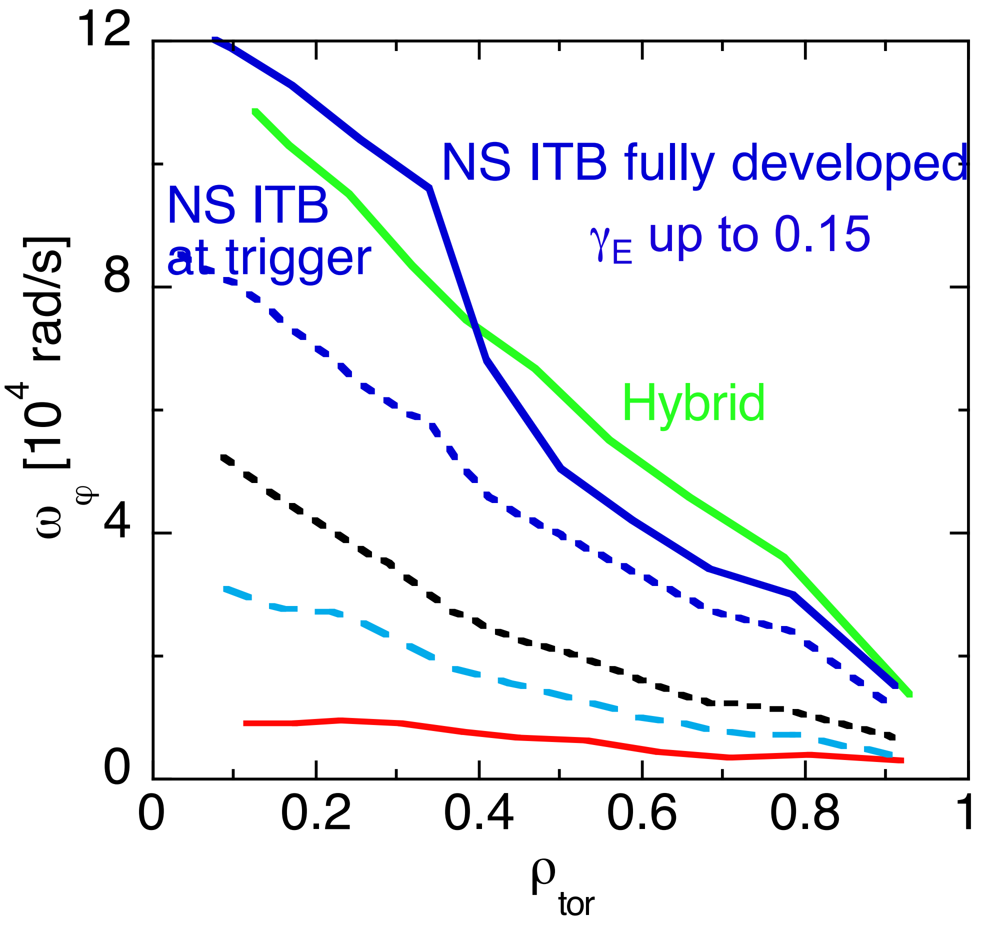
DE VRIES,P.C.,et al,Nucl.Fusion **49**(2009)075007
POLITZER,P.A.et al,Nucl.Fusion**48** (2008)075001

JET Hybrids and ITBs are characterized by high rotation



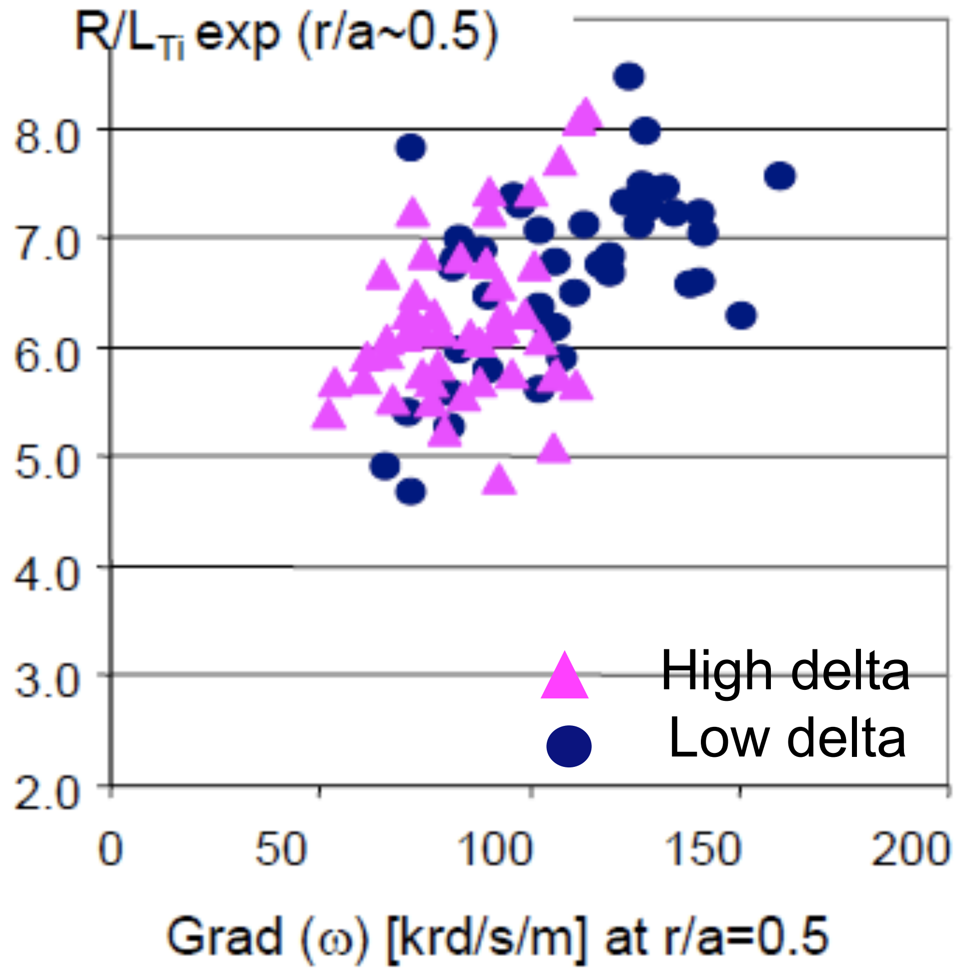
Evidence in Hybrids and ITBs

JET Hybrids and ITBs are characterized by high rotation



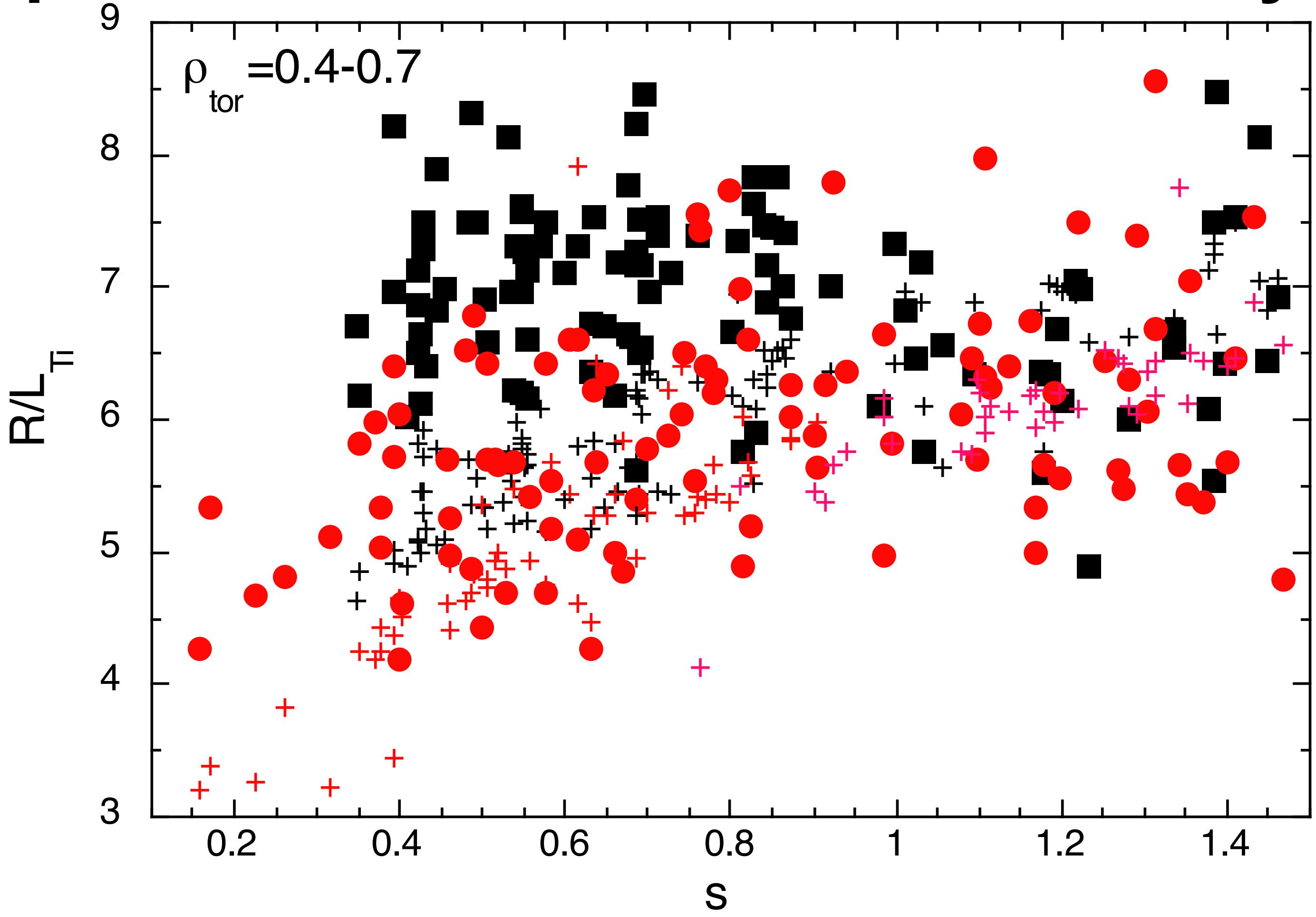
Correlation is found between R/L_{Ti} and rotation gradient

Hybrid database



E.Joffrin, EX/1-1, IAEA 2010

Dependence on s and rotation from Hybrid/Hmode database



s from EFIT with magnetic signals, pressure and polarimeter measurements constraints

Black : high rotation dv/dr>400 krad/s

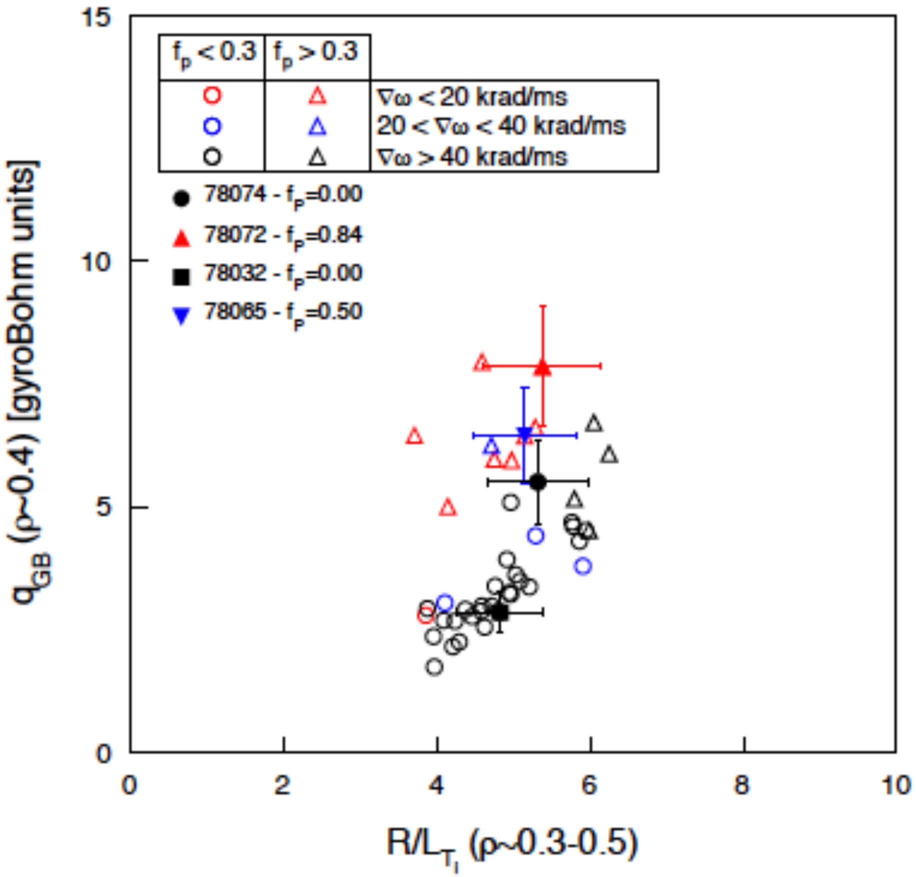
red : low rotation dv/dr<130 krad/s

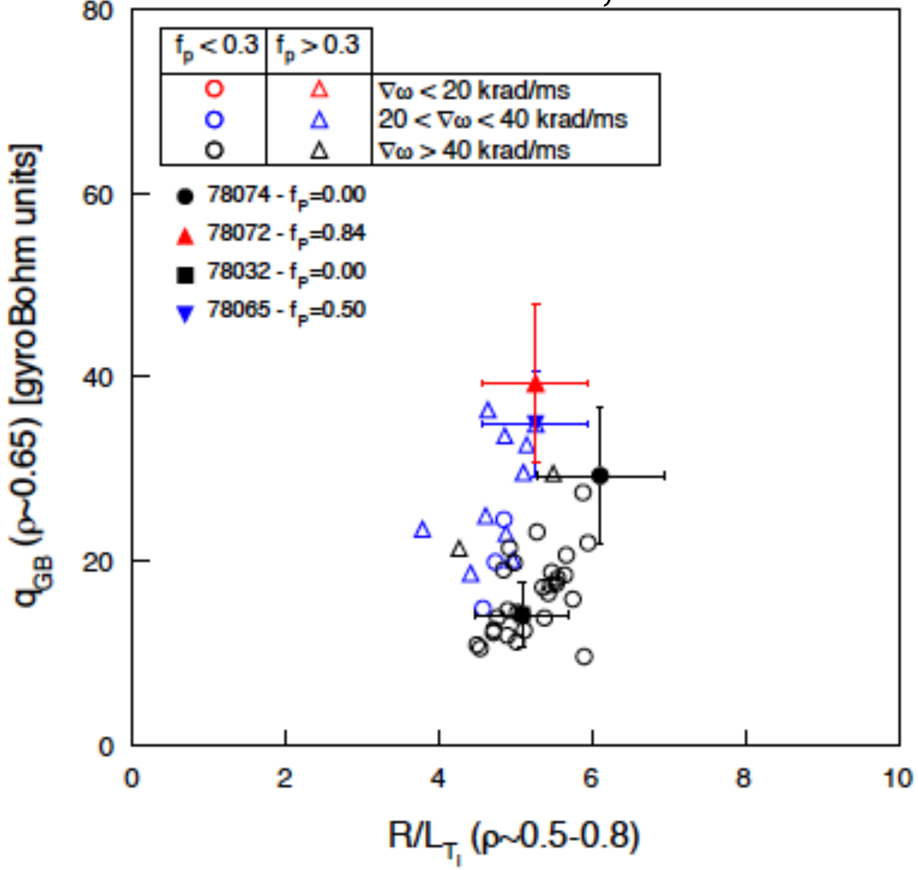
+,+ : threshold after F.Romanelli et al.

High scatter due to the fact that s and rotation are not the only players (q_i and T_e/T_i dependences are embedded in data) . Still, results from scenario database also indicate improved R/L$_{Ti}$ with rotation only at low s.

Substituting NBI with ICRH in H-mode

T.Versloot, submitted to NF

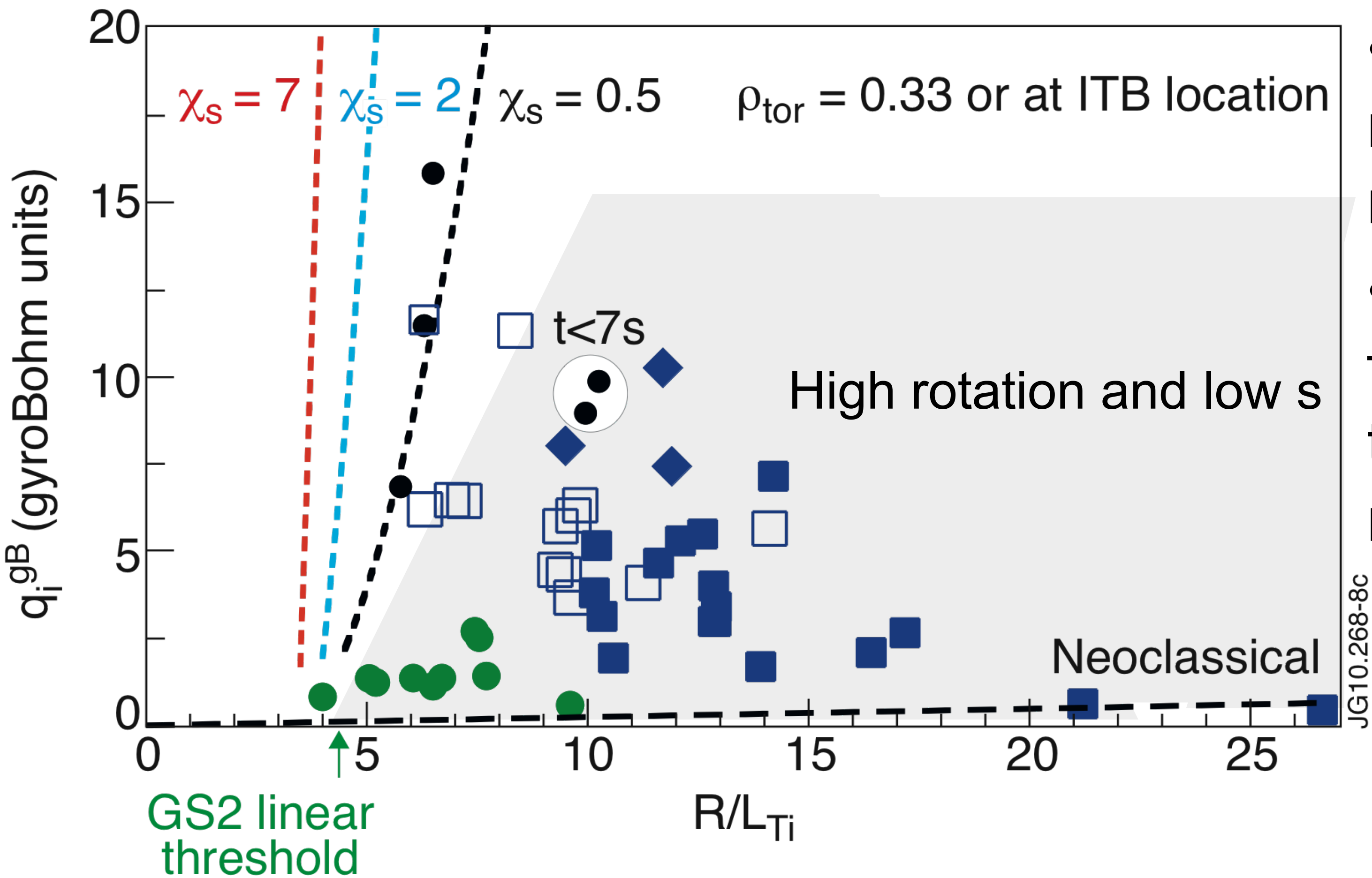




Same effect on core R/L_{Ti} as seen in transport experiments. But effect smaller due to 1) Higher s in H-mode 2) Smaller region of low s 3) Compensation between change of stiffness and of power deposition

Doing the same in ITB plasmas leads to ITB loss → effect always present but major consequences of losing rotation in low s conditions

Evidence in Hybrids and ITBs



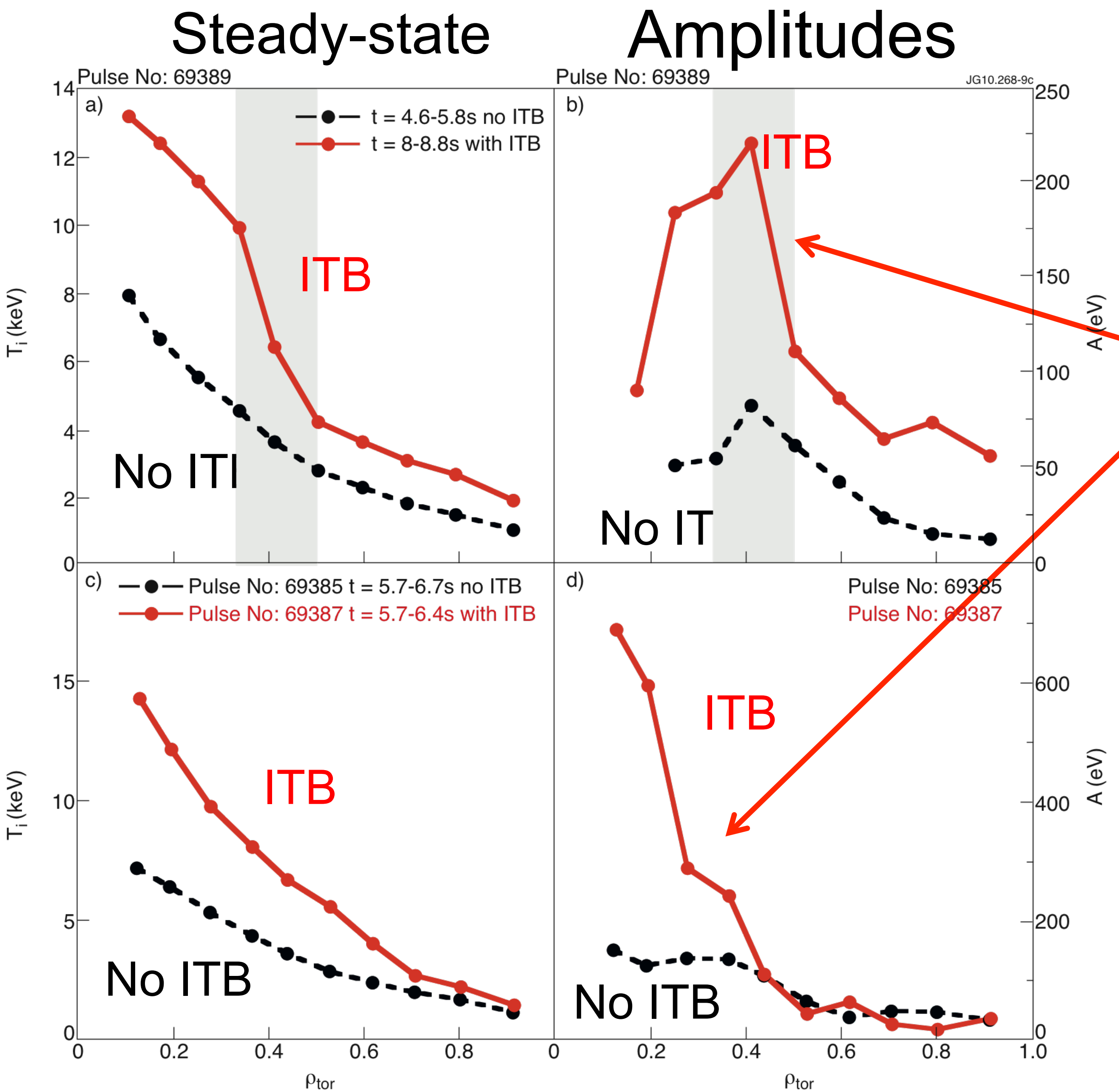
- Linear threshold does not vary much from H-mode to Hybrid
- ω_{ExB} <4 10^4 s^{-1} apart from strong ITBs→ threshold up-shift alone not enough

ITBs and Hybrid fill the very low stiffness region

Ion stiffness mitigation contributes to achieve high H_{98} together with improved pedestal and absence of NTMs

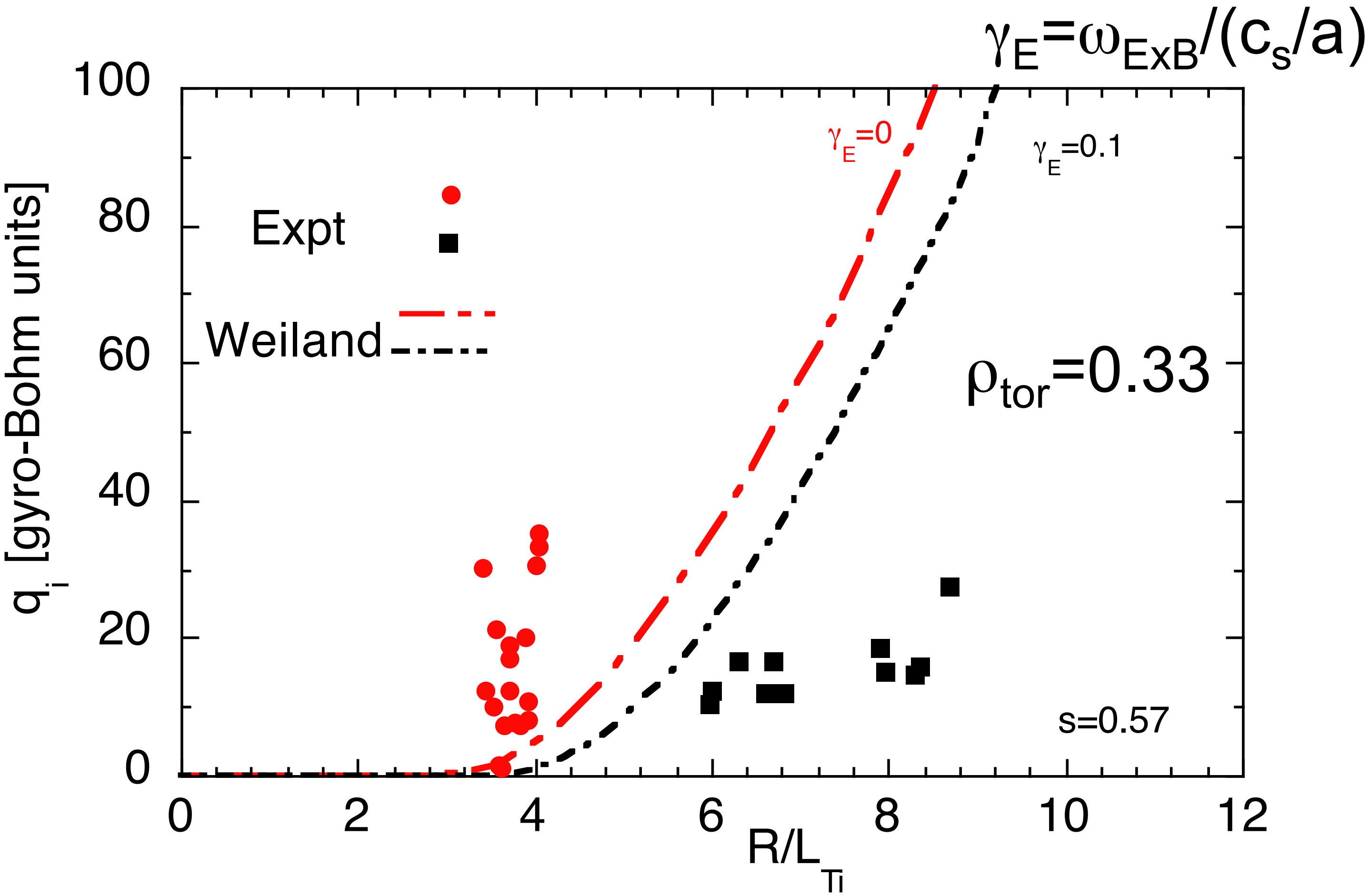
In Hybrids it can contribute up to ΔH_{98} = 0.2, more in ITBs

T_i modulation



- ICRH modulation in (^3He)-D
- Large gradients in modulation amplitude in the ITB region indicate low stiffness.
- Similar evidence in Hybrid core by T_i modulation using NBI.

Theory predictions

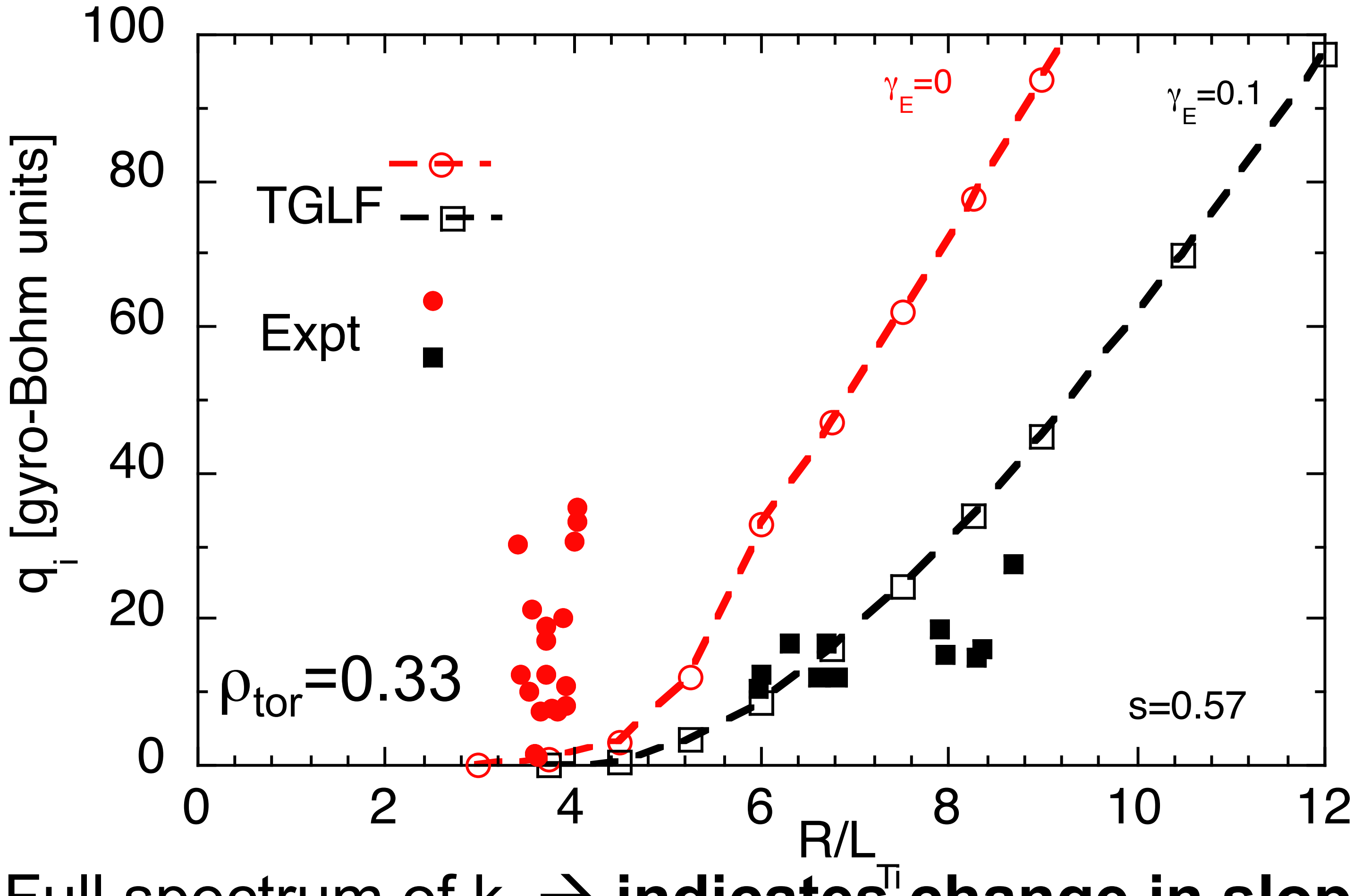


Weiland model

Simulations made by J.Weiland

One k_Θ only and Waltz rule applied after solving dispersion relation → only threshold up-shift

Theory predictions



TGLF

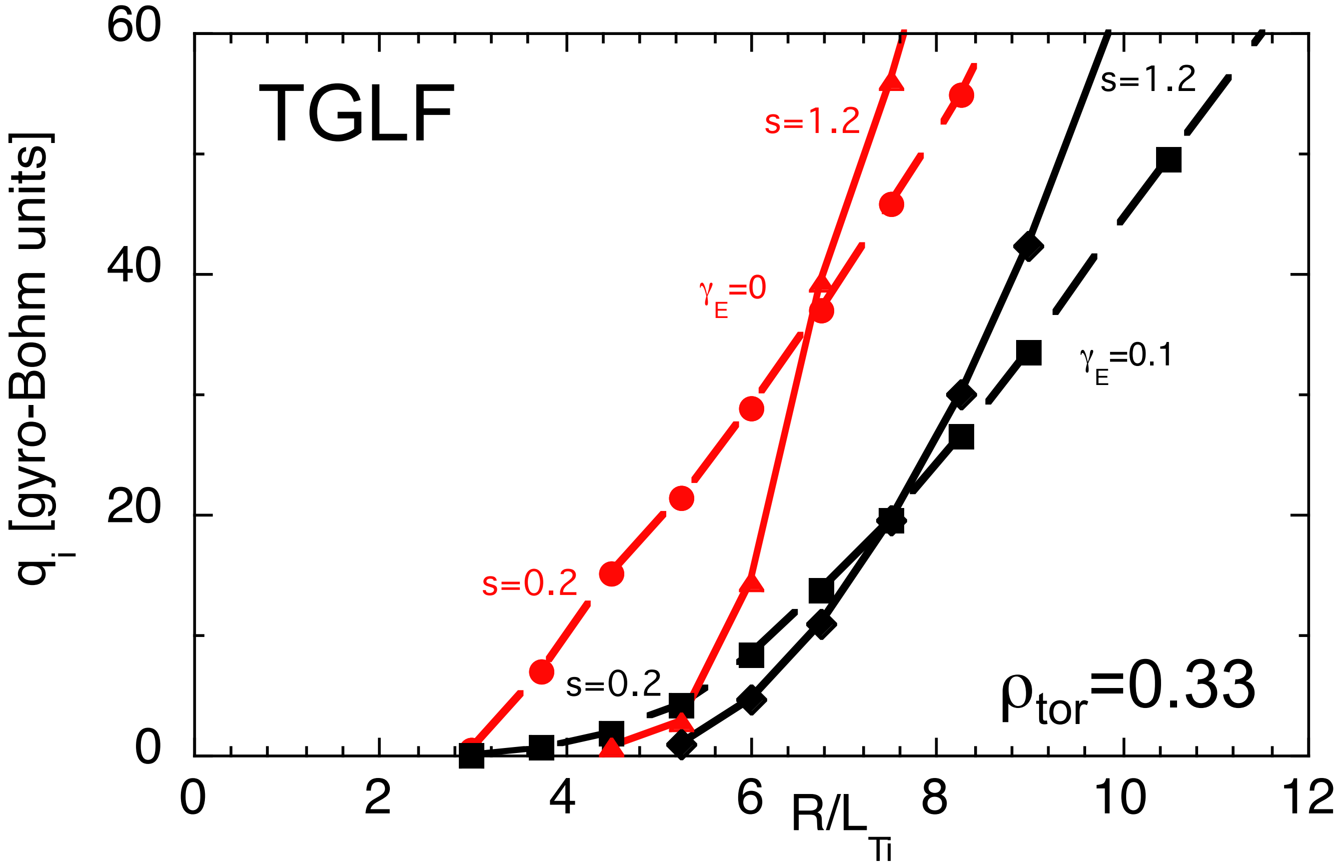
Scan in R/L_{Ti} (with R/L_{Te} in prescribed ratio) using the parameters of one low rotation shot and increasing γ_E (and dv_{tor}/dr) progressively

Simulations made by G.Colyer and G.Staebler

Full spectrum of k_Θ → **indicates change in slope in particular in the "knee"** region near marginality

Differential suppression of low (stiff) and high (less stiff) k_Θ yields the effect of changing slope

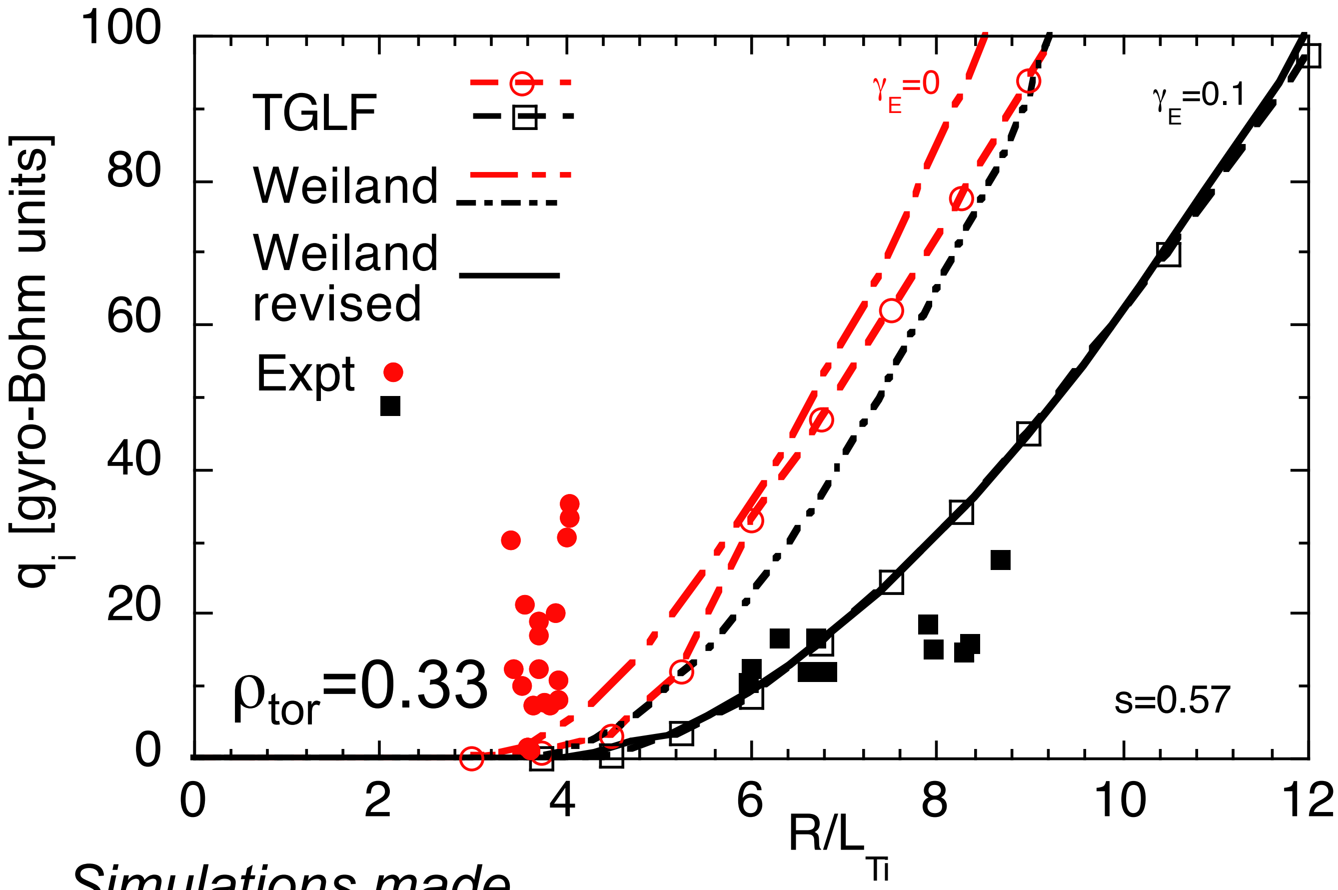
Theory predictions – s dependence



- Stiffness is lower at low s than at high s without and with rotation
- **Relative change in stiffness in the knee region from without to with rotation is enhanced at low s**

Simulations made by G.Colyer and G.Staebler

- According to TGLF, experimental observations may find explanation in the complex behaviour of turbulence in the transition region between fully developed turbulence and zonal flows quenching
- This region is difficult to address numerically but is also the operational region of the core of high performance devices.



Simulations made by J.Weiland

Revised Weiland model

Main idea:
maximize the growth rate with respect to mode number with rotation included

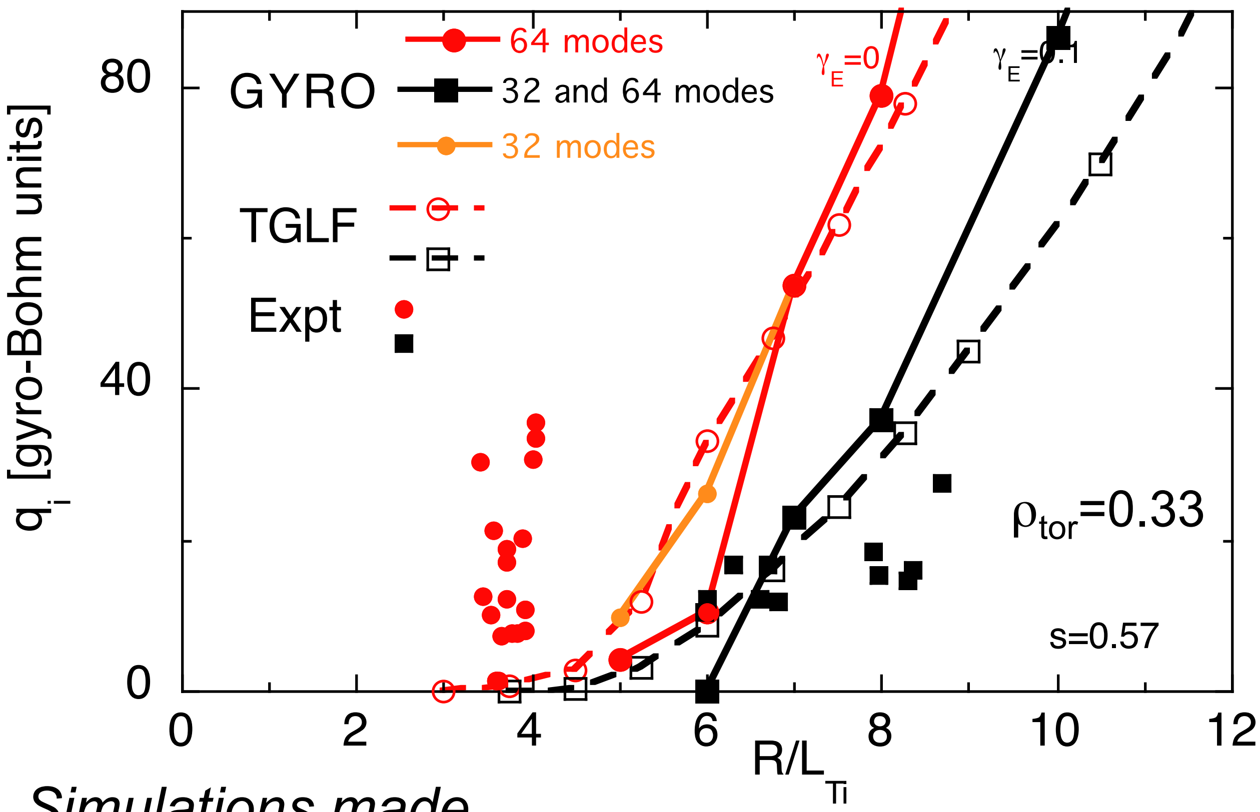
Flow shear is subtracted inside the linear solver

=> Mode number of fastest growing mode changes with rotation

Result: stiffness changes significantly with rotation at low s and not at high s. The curve overlaps with TGLF.

Theory predictions

GYRO ρ^*_{expt} <1/700



Simulations made by C.Angioni

non-linear, electrostatic, flux-tube, electron collisions.
16, 32 and 64 toroidal modes, box size properly adjusted.
All simulations give same results at high flux.
However **simulations in the knee region are difficult**. 64 modes leads to stronger ZF activity, with consequent reduction of transport.

Overall GYRO yields a larger effect on threshold than on stiffness

Open issue: the high stiffness observed without rotation has not been reproduced. May require global simulations and turbulence spreading.

Conclusions

- JET experiments show that ion stiffness is reduced by the combined effect of low magnetic shear and high rotational shear
- Ion stiffness mitigation seems at the basis of enhanced ion core confinement, such as in Hybrid and ITB scenarios
- AT scenarios in ITER should seek for maximum rotational shear compatible with the available heating systems and minimum magnetic shear in the broadest region
- The effect of rotation on stiffness is observed in numerical simulations with TGLF especially in the “knee” region. Here low magnetic shear enhances the effect of rotation on stiffness. However properly resolved GYRO runs yield mainly an effect on threshold and not on stiffness → experimental result still unexplained.
- The role of low order rationals seems an independent phenomenon.
- Another open issue: the high stiffness observed without rotation has not yet been reproduced in modelling. Global simulations?