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Measurements and modelling of turbulent transport on Tore Supra

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Acknowledgements: J. Abiteboul, P. Angelino[1], S. Benkadda[2], C. Bourdelle, A. Casati[1], F. Clairet, G. Falchetto, C. Fenzi, S. Futatani[2], T. Gerbaud[3], V. Grandgirard, R. Guirlet, O. Gürcan[4], P. Hennequin[4], S. Heuraux[5], G.T. Hoang, C. Honoré[4], R. Sabot, Y. Sarazin, A. Sirinelli[3], E. Trier[4], L. Vermare[4], D. Villegas.

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Outline

- Comparison between fluctuation measurements and simulations – towards a reduced transport model.

- Large scale flows : interplay between turbulence generation and collisional damping

- Impurities as tracers of turbulent transport

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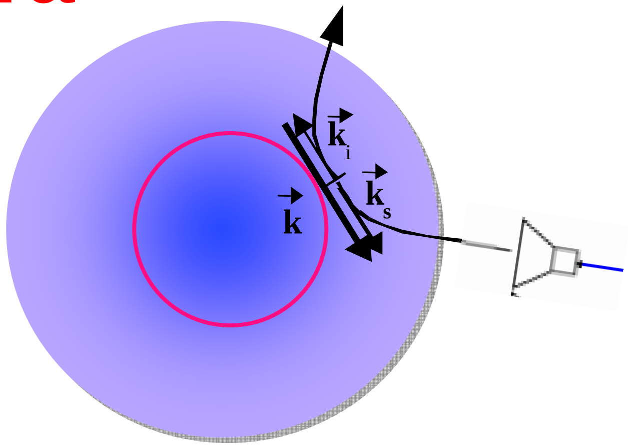
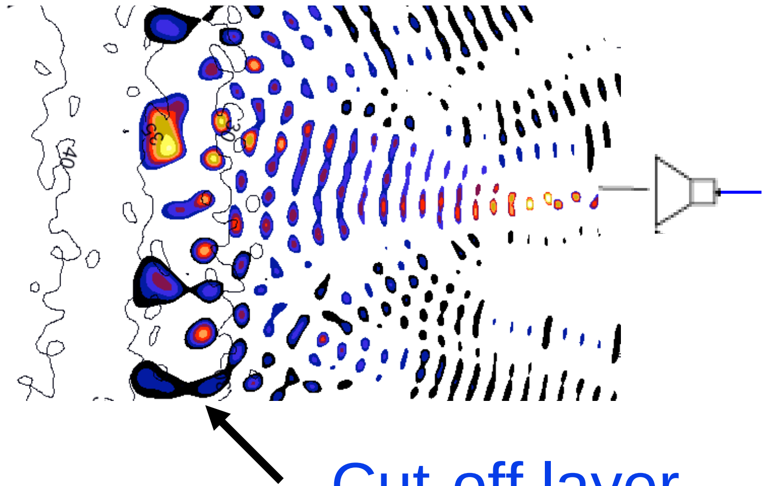
Diagnostics and codes on Tore Supra

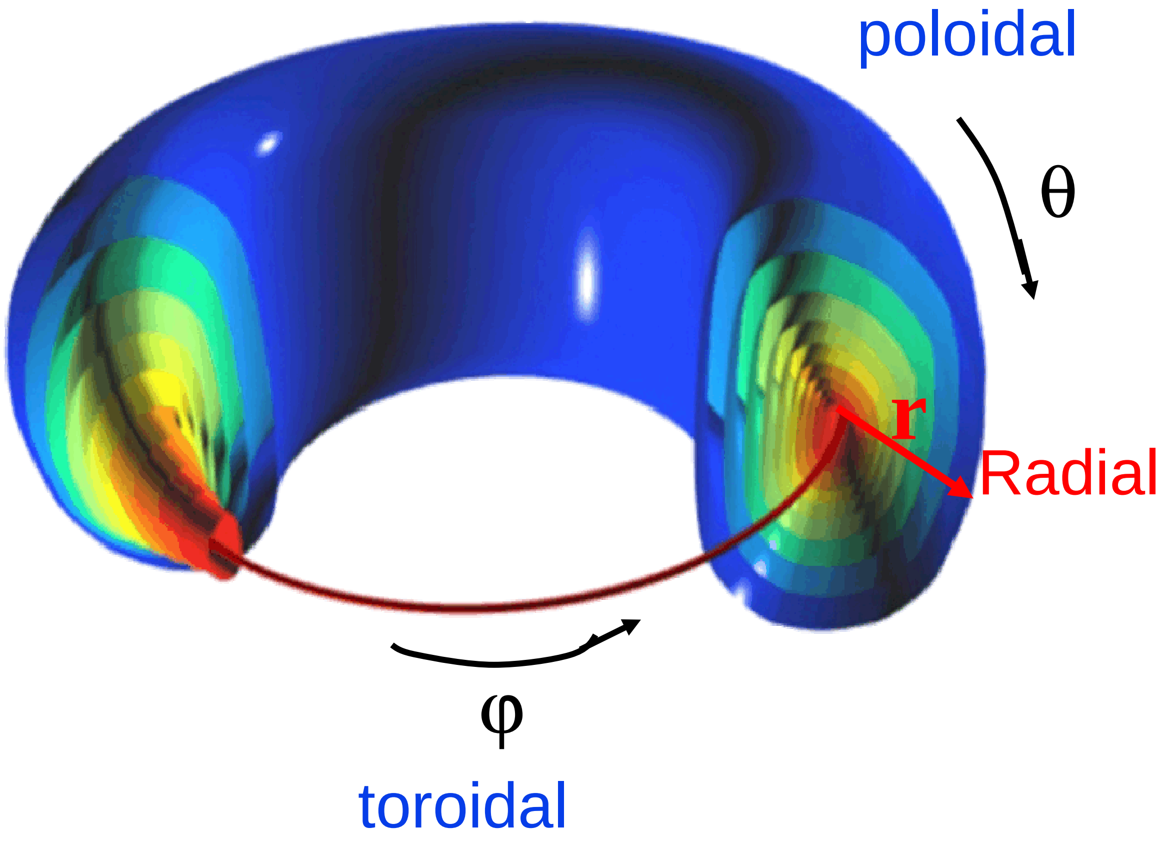
- 2 Doppler and 2 fast sweeping reflectometers: profile of turbulence intensity, frequency and wavenumber spectra
- Numerical tools: global (GYSELA) local (GYRO, GENE) gyrokinetic codes, integrated modelling (CRONOS)





Cut-off layer

Geometry



Is it possible to build a reliable reduced transport model?

- Most models are based on quasi-linear theory Vedenov 61, Drummond 63

$$D = \sum_k \left|v_{Ek}\right|^2 \tau_{ck}$$

and a mixing-length rule Prandtl 25 , e.g.

$$\frac{e\delta\phi_k}{T} \approx \frac{\delta p_k}{p} \approx \frac{1}{kL_p}$$

- Some open questions : validity of QL theory, better description of fluctuation spectra.

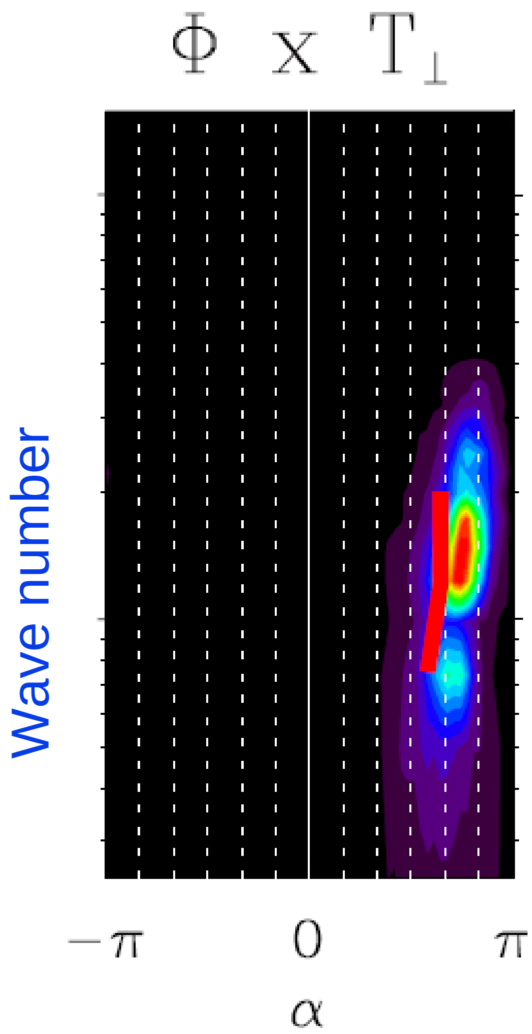
Test of Quasi-Linear Theory

- QLT assumes linear cross-phase

$$\Phi_T = \frac{3}{2}\langle p v_E \rangle$$

- Looks like a reasonable hypothesis at low k. Seems to work even close to threshold.
- Factor 1.4 between simulations and QLT Waltz 08

Dannert 05



Test of Quasi-Linear Theory - 2

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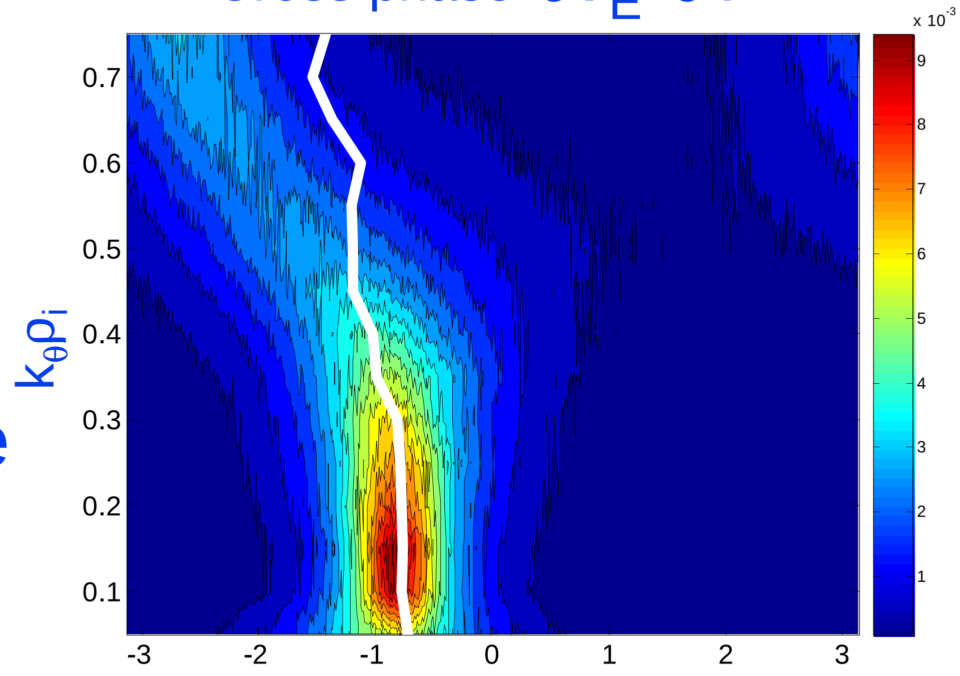
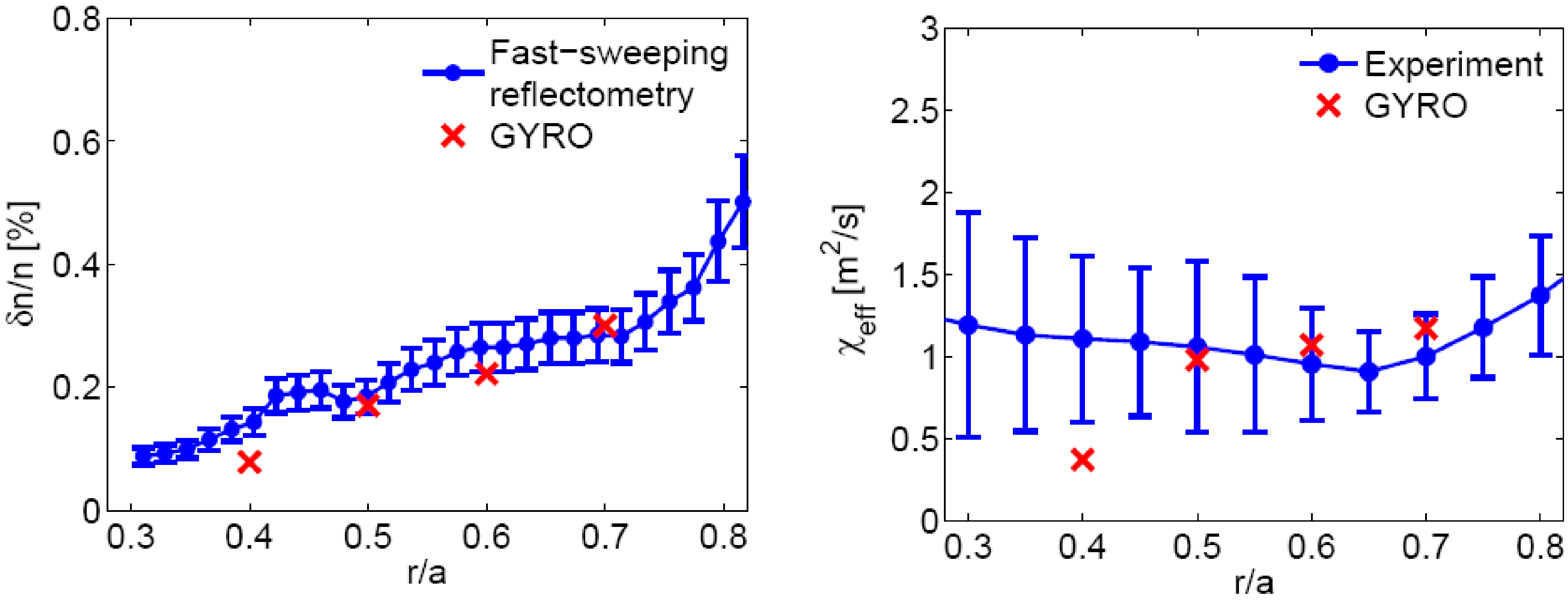
Casati 08 - GYRO

Cross phase δv_E-δT



Agreement is found between density fluctuation measurements and simulations.

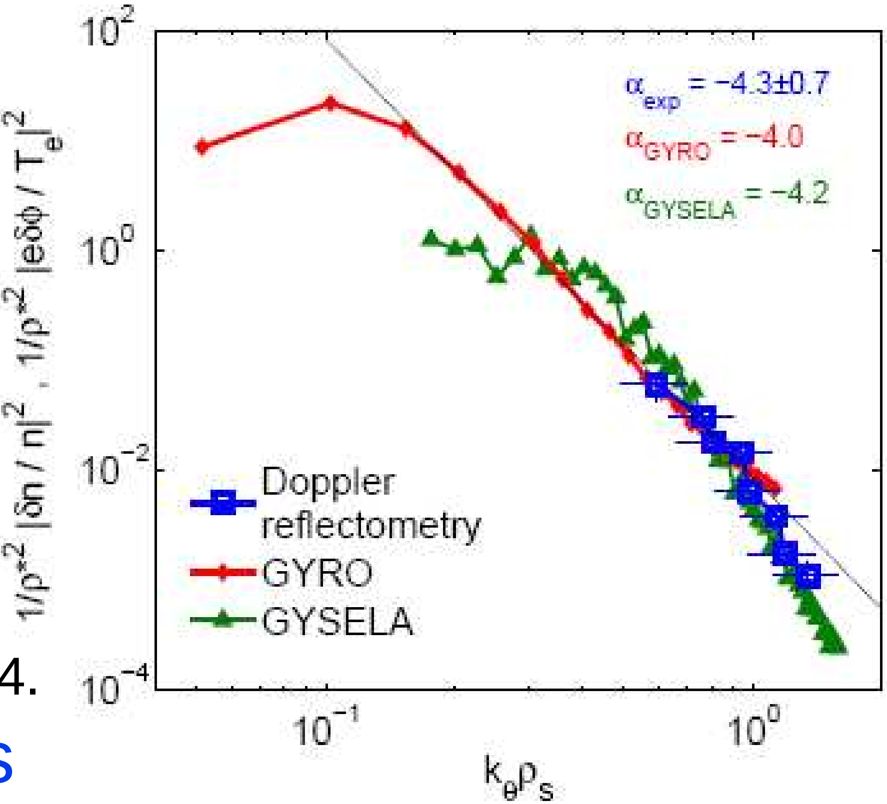
Casati 09



Wave number spectra are also well reproduced

- Slope always the same $\rightarrow$ NL effects dominant.
- Discrepancies between simulations : inward propagating GAMs in GYSELA. Zonca 08
- Change of slope is usually observed at $k_\perp \rho_i \approx 1$ Hennequin 04. Possible effect of zonal flows Gurcan 09.

Casati 09



Wave number spectra are also well reproduced - II

• Slope always the same → NL effects dominant.

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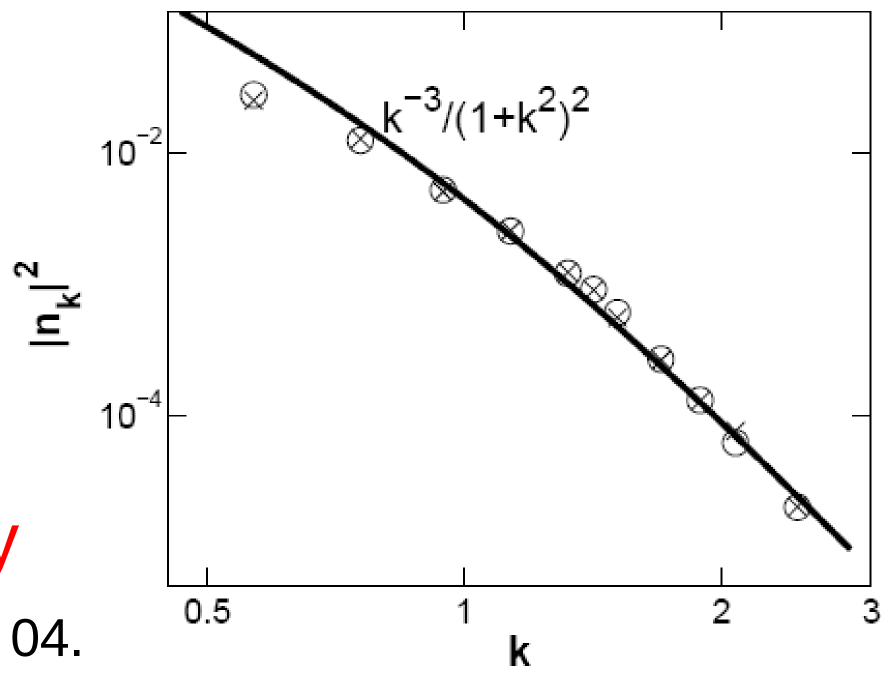
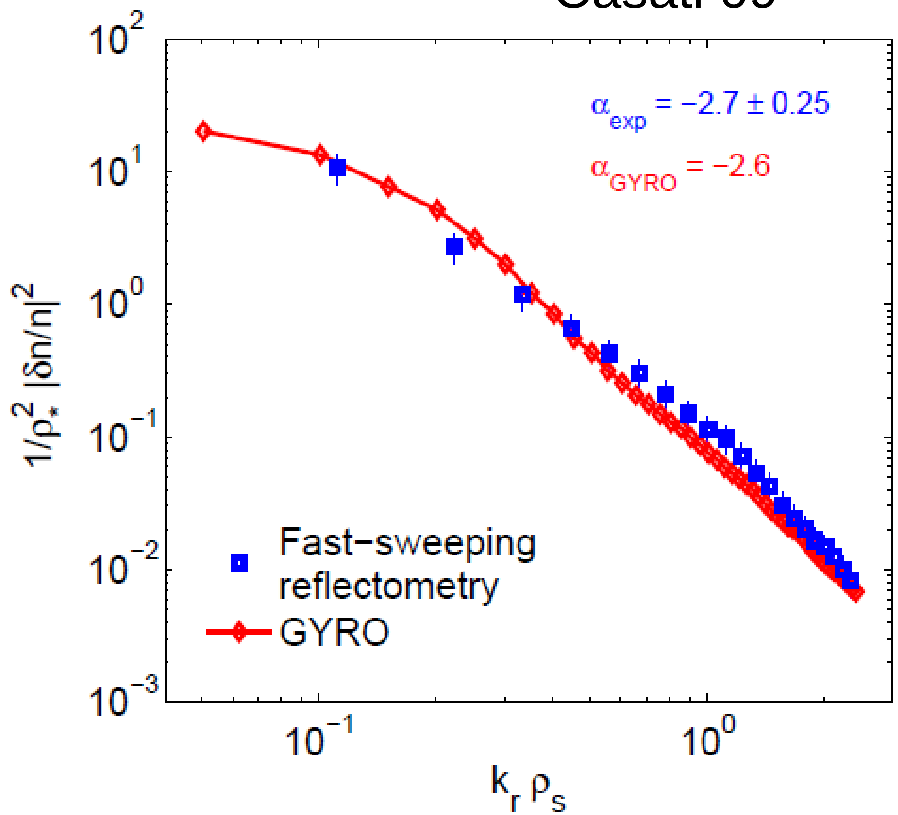
Gurcan 09



Fast sweeping reflectometry provides information on k_r spectra

- Access to distribution of density perturbations→ k_r spectra Vermare 04
- Spectrum index is different : instrumental effect
- Spectra are isotropic at high k

Casati 09



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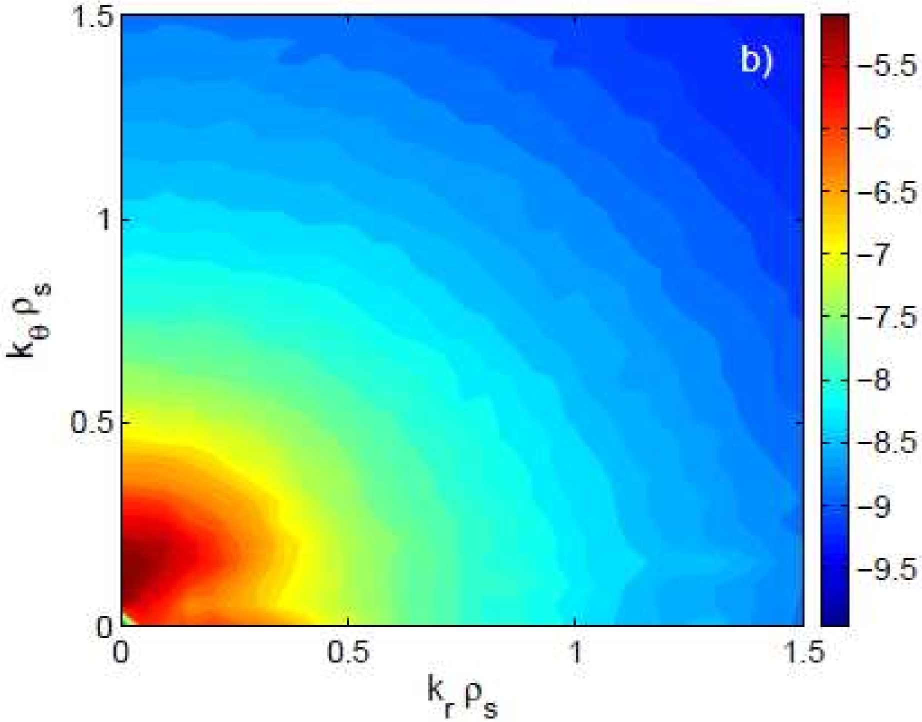


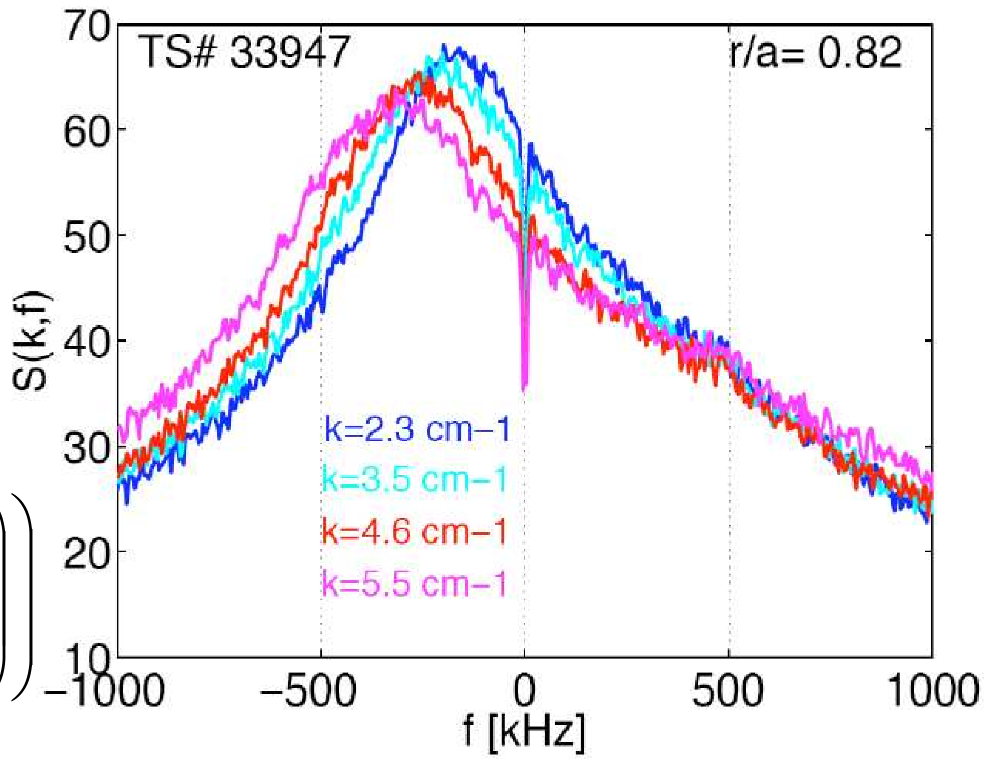
GYRO simulations of k spectra

Frequency spectra

- Measured with Doppler reflectometry Hennequin 06
- $\Delta\omega_k \neq \gamma_k$ - $\Delta\omega_k \equiv k^\alpha$, agrees with convective /diffusive model
  Hennequin 99

$$C(k,\tau) = \exp\left(-\frac{1}{2}k^2u^2\tau_L^2\left(\frac{\tau}{\tau_L} - 1 + e^{-\frac{\tau}{\tau_L}}\right)\right)$$

- Ongoing modelling with EDQNM



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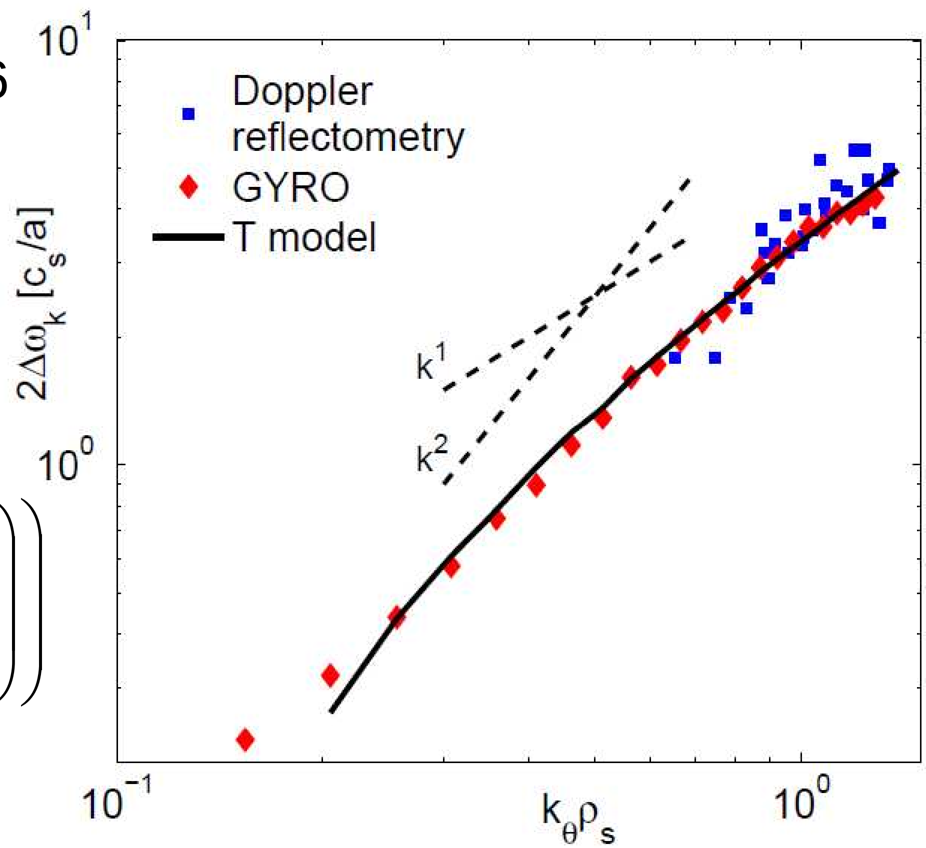
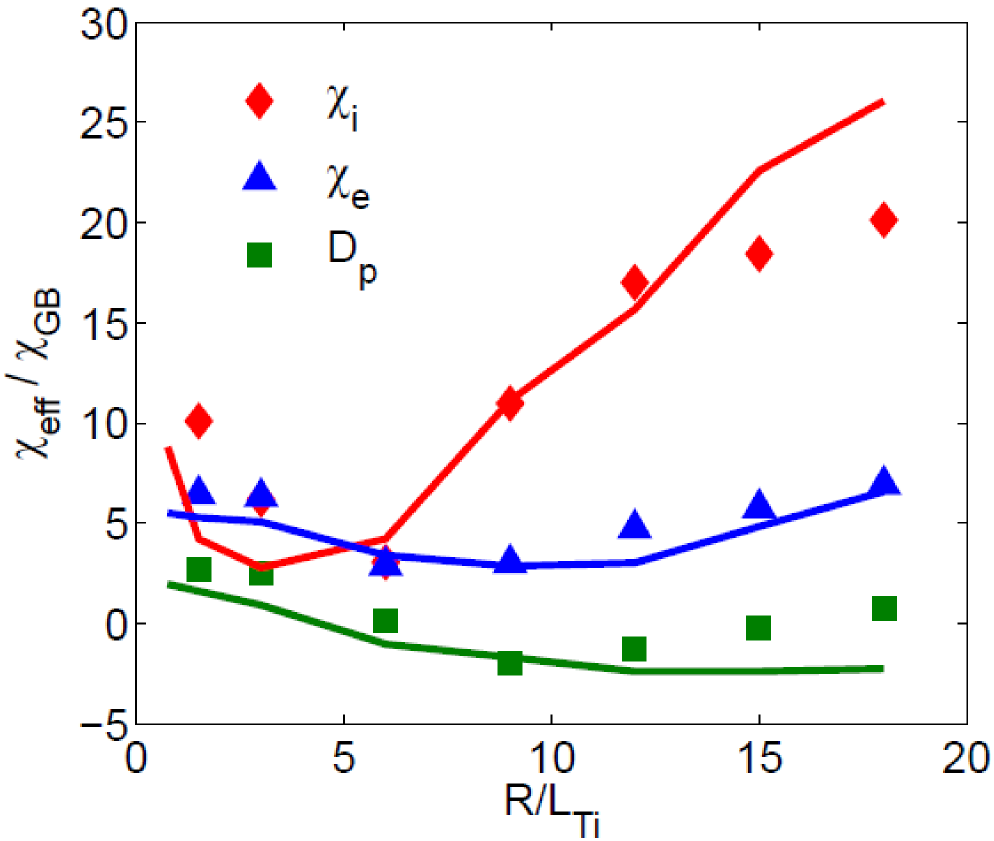


Present status of transport modelling

- Qualikiz : QLT, k^{-3} spectrum (cut-off Dannert 05), lorentzian frequency spectrum. Bourdelle 08

- Encouraging results, except at low magnetic shear.



Casati 09 – GYRO (pts) vs Qualikiz

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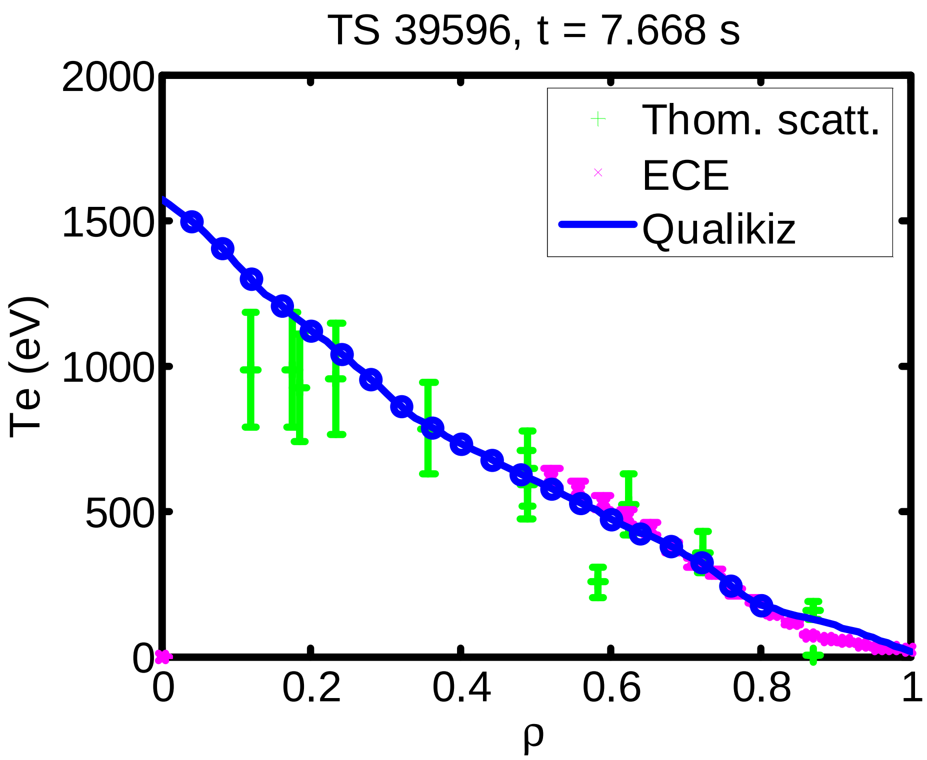


Predicted temperature

Large scale flows : interplay between turbulence generation and collisional damping

- On Tore Supra, magnetic field corrugation (ripple) is large (7%)
- Leads to magnetic braking in toroidal direction
- Competes with turbulence Reynolds stress

Flow dynamics

- Force balance equation

$$E_r + V_\theta B_\varphi - V_\varphi B_\theta - \frac{\nabla_r p}{ne} = 0$$

- Reynolds stress + collisional viscous damping

Smolyakov 09

$$\partial_t \langle \mathbf{V} \rangle = -\nabla \cdot \langle \tilde{\mathbf{V}}\tilde{\mathbf{V}} \rangle - \nu_{neo}\left(\langle \mathbf{V} \rangle - k\mathbf{V}_{neo}\right)$$

Reynolds stress Π

Viscous damping

$\rightarrow$ determine V_θ , V_φ , et E_r

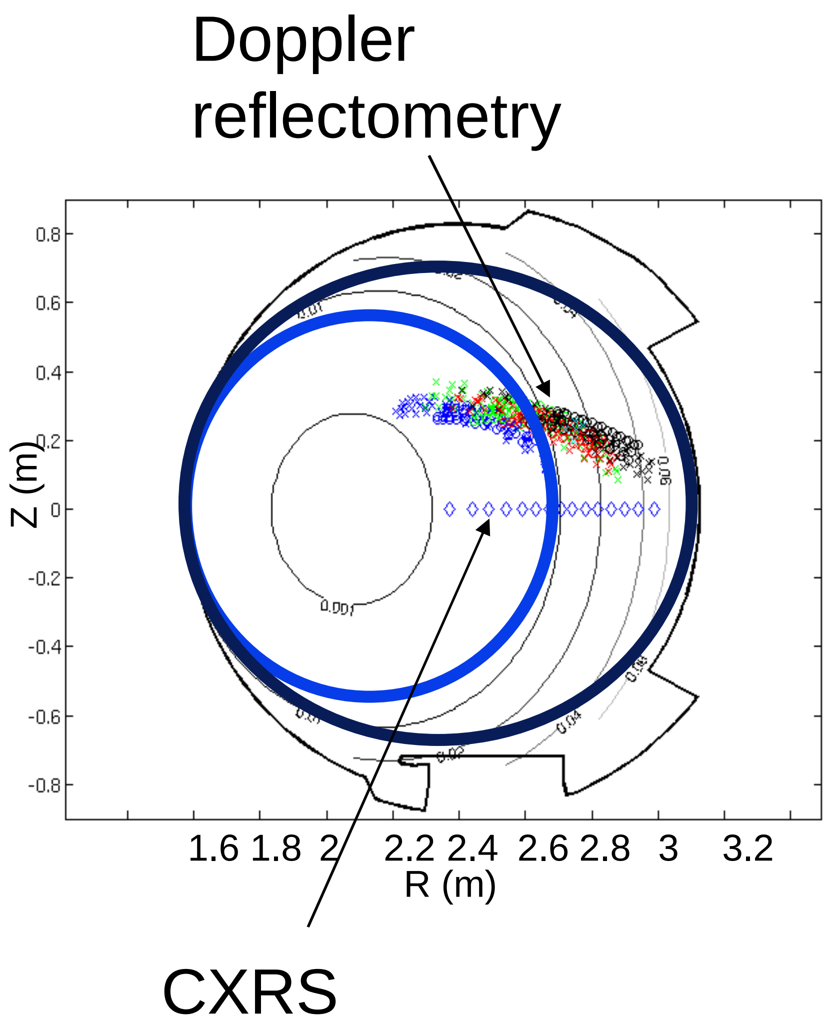
Rotation measurements

- Doppler reflectometry

$$V_{lab} = -\frac{E_r}{B} + V_{ph}$$

Assumption : $V_{ph} \ll -E_r/B$ -
supported by simulations $\longrightarrow$
direct measurement of E_r

- CXRS: measurements of V_{φ}



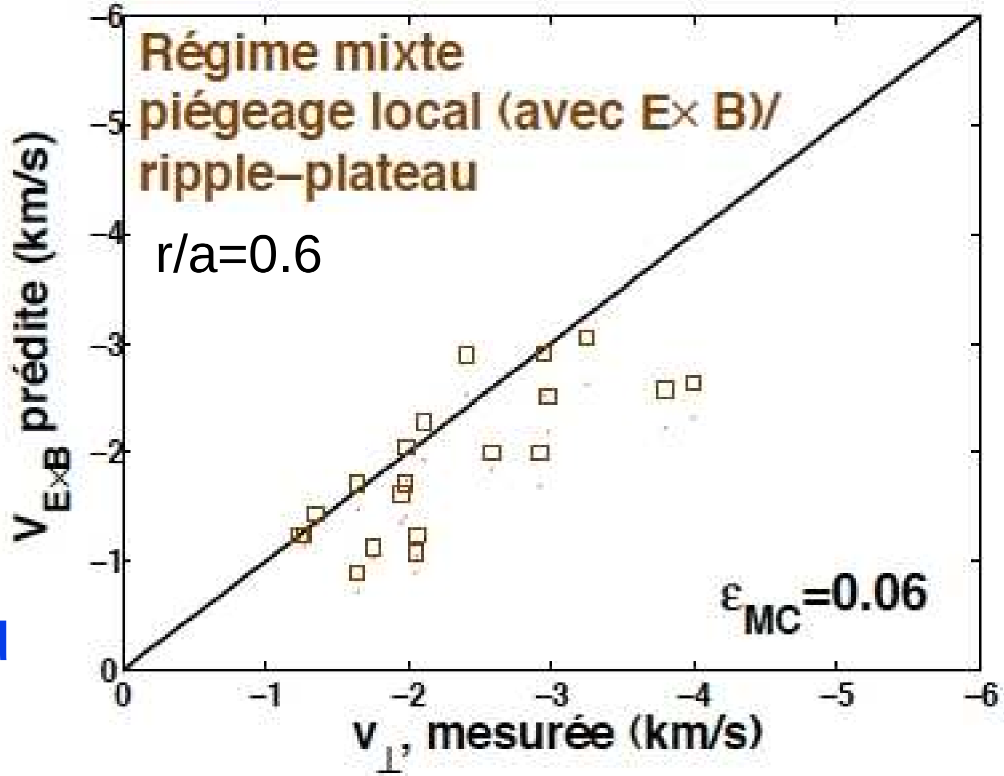
Radial electric field

- Radial electric field is negative : controlled by thermal ripple losses

$$E_r = \frac{T_i}{e}\left(\frac{dn_i}{n_i dr} + k_{rip}\frac{dT_i}{T_i dr}\right)$$

- Local trapping k_{rip}=3.37 Connor 73 . Ripple-plateau k_{rip}=1.5 Boozer 80

Trier 08

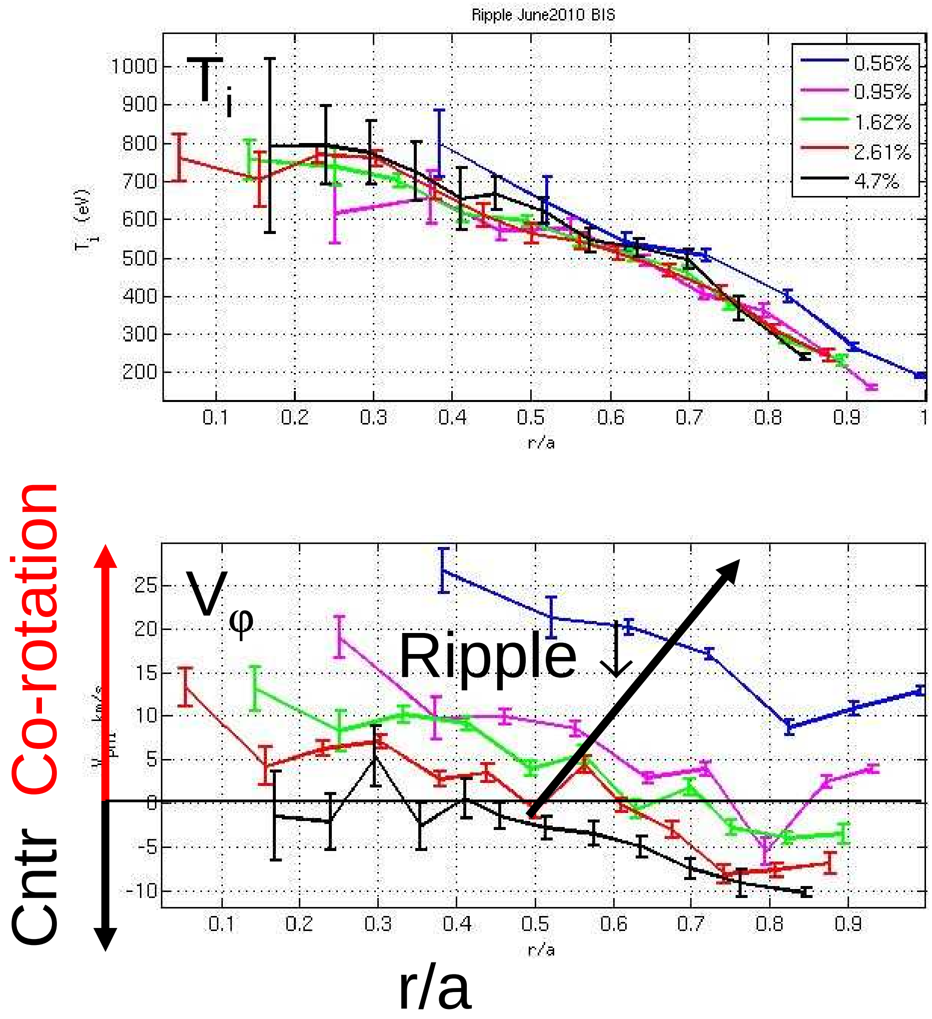


Intrinsic toroidal rotation

Fenzi 09

- Counter-rotation in Ohmic plasmas. Co-rotation with smaller ripple.

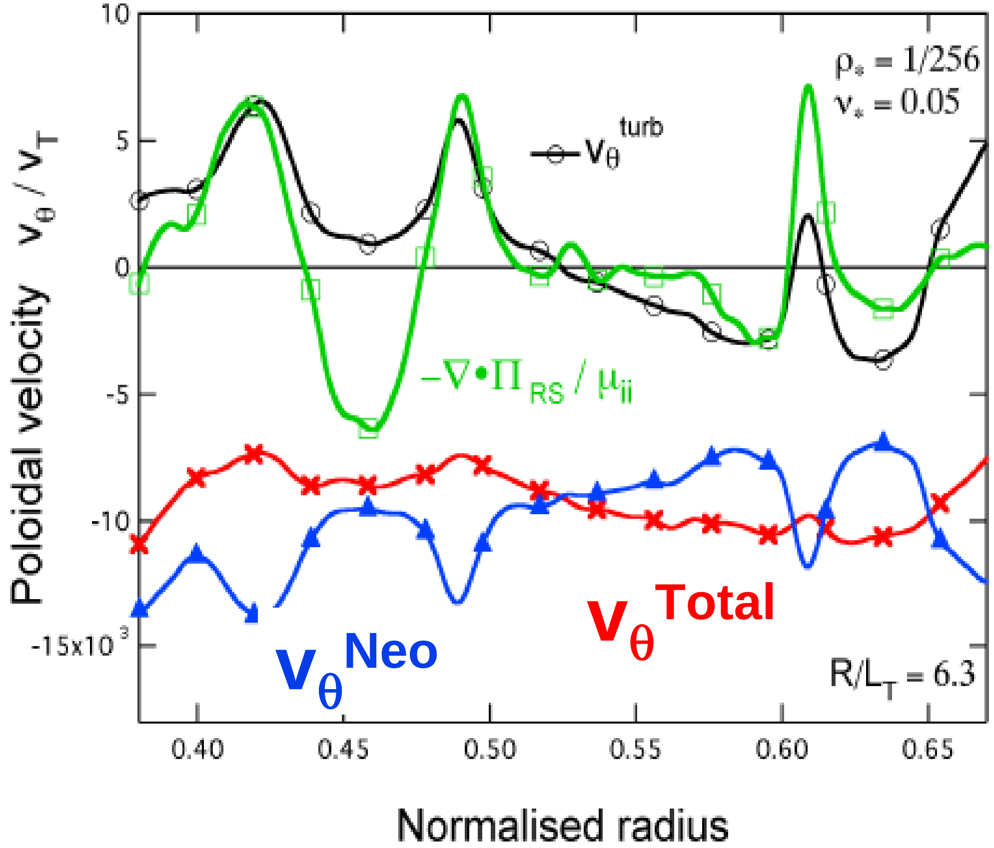
- Consistent with competition between ripple friction and turbulent Reynolds stress.



Poloidal rotation agrees with neoclassical theory in global simulations

Dif-Pradalier 09

- Consistent with poloidal viscous damping
- However: large corrugations due to turbulent Reynolds stress.



Disagreement on poloidal rotation?

- Doppler reflectometry $\rightarrow$ E_r agrees with Γ_{ripple}=0 in the core

- CXRS $\rightarrow$ V_φ changes from cntr to co-rotation when ripple becomes weaker

$\rightarrow V_\theta \neq V_{neo}$? e.g. JET Crombé 06, DIII-D Kim 94

- Turbulence simulations find $V_\theta \approx V_{neo}$ + turbulence corrugations

Particle and impurity transport

- Ion heat transport well known, particle and electron heat transport make progress, impurity transport not well documented
- Related to turbulent transport of passive tracers for low impurity concentrations
- Reference is collisional transport in axisymmetric systems: neoclassical theory

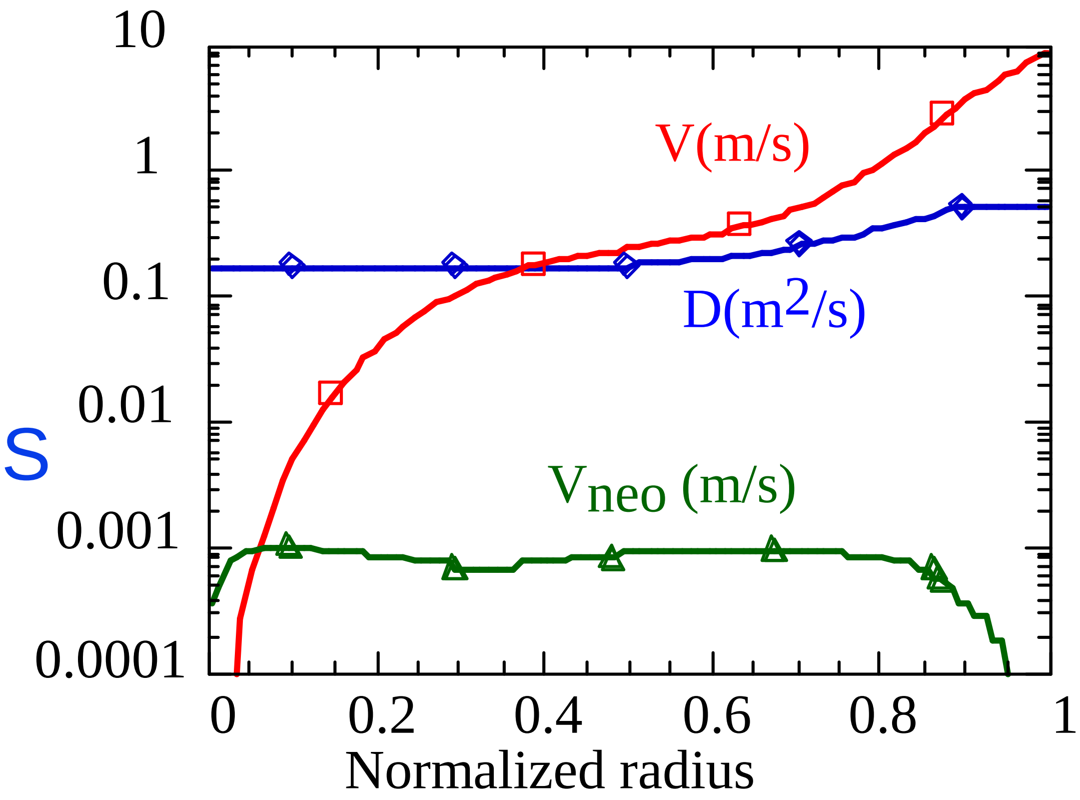
Particle pinch is turbulent

- Particle flux of the form

  Γ=-D∇n+Vn

- Unambiguous observation of an anomalous pinch in TS long pulses Hoang 04, (Ware pinch=0)

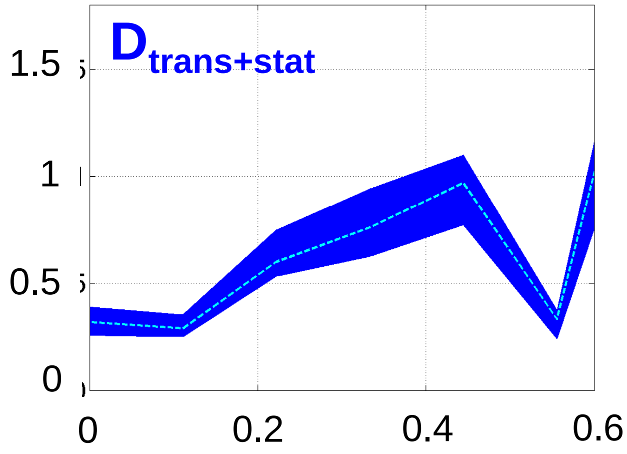
Diffusion and pinch velocity vs radius - TORE SUPRA - G.T. Hoang 04

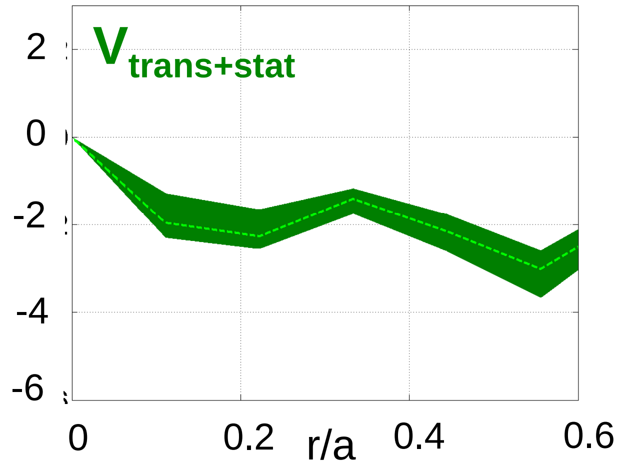


What about impurities?

Guirlet 08

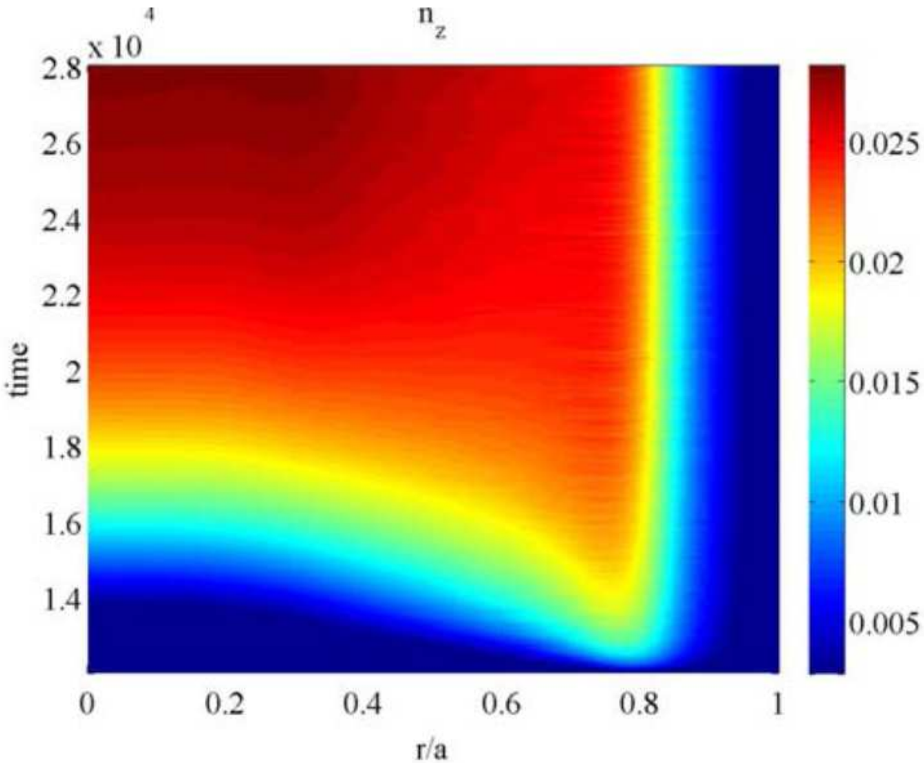
- Supersonic impurity gas injection.
- Both transient and steady profiles are used to assess fluxes $\Gamma = -D\nabla n + Vn$
- Allows to reduce error bars on D and V by a large factor.

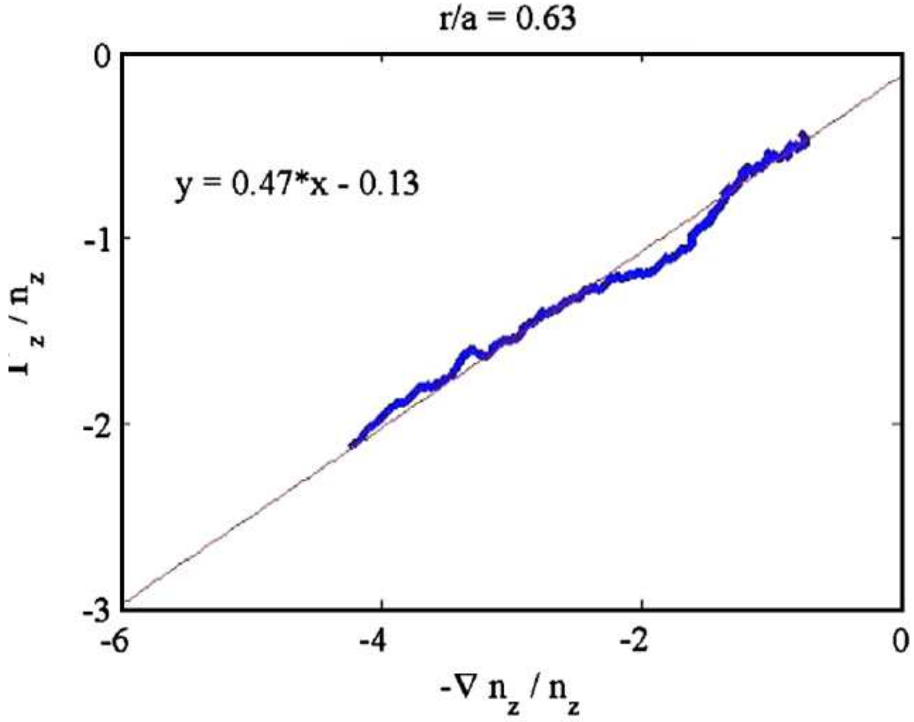




Modelling of transient confirm the diffusion/convection model

Futatani 10

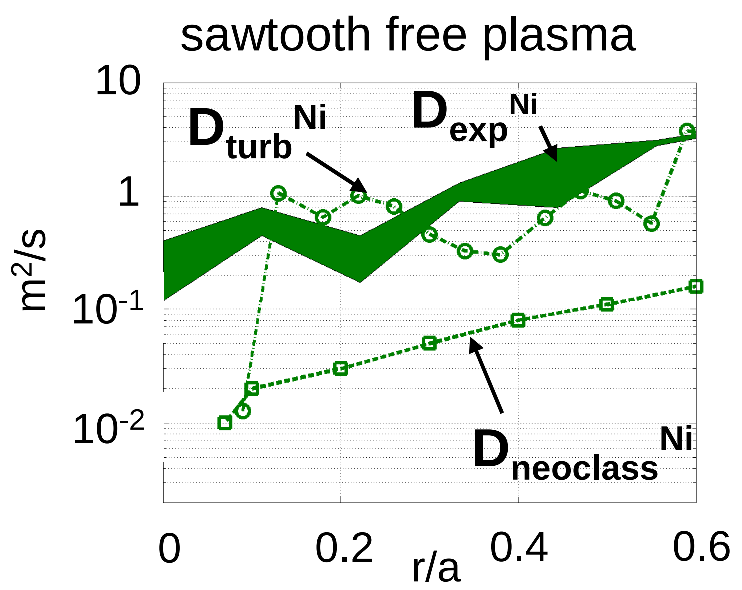




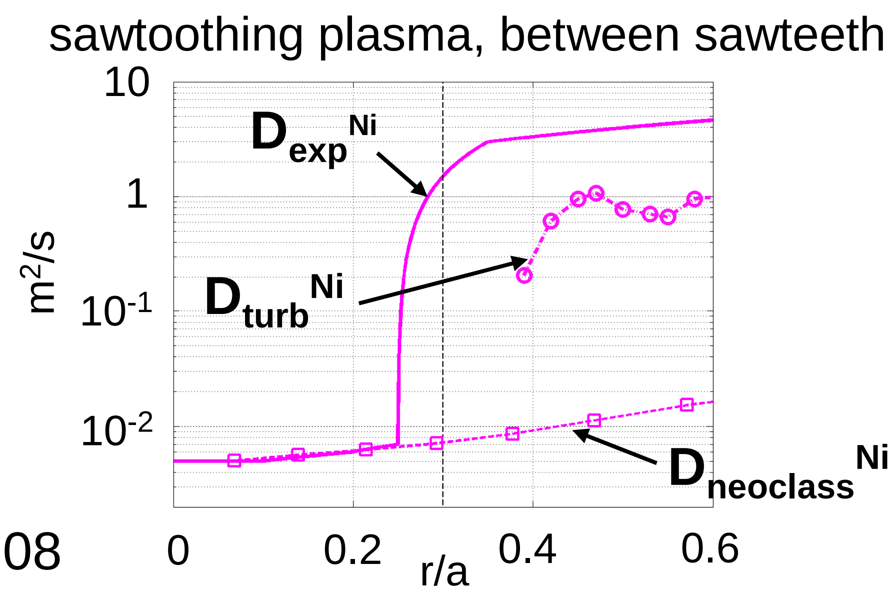
Impurity transport is turbulent

- Diffusion is always turbulent in the gradient zone

- Qualitatively agree with quasilinear theory (Qualikiz).



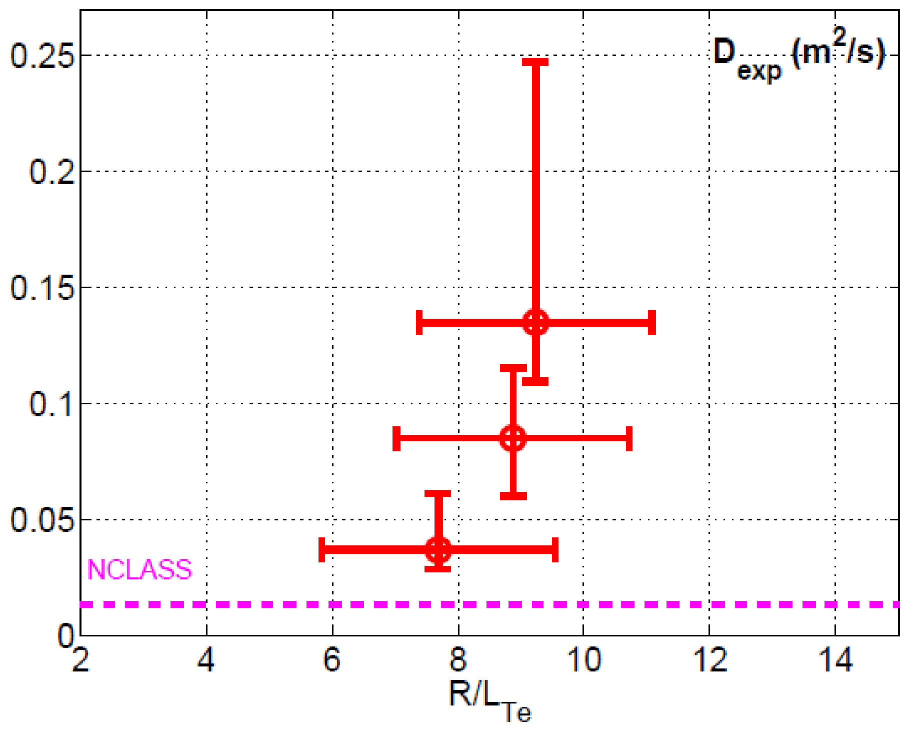
Guirlet 08



Evidence of a critical gradient

- Evidence of an instability threshold
- Agrees with expectation from drift wave (ITG/TEM) model

Villegas 10



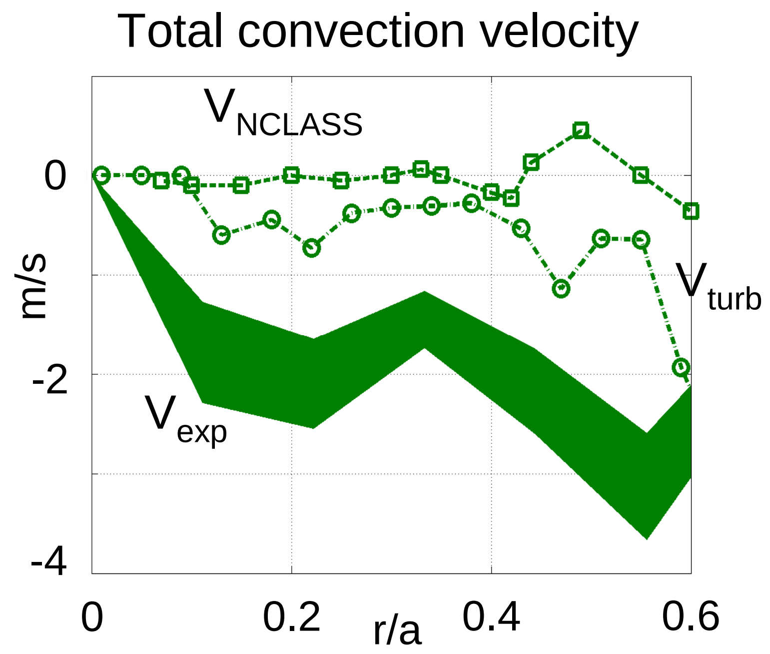
D_{Ni} vs temperature log. gradient

Impurity transport depends weakly on charge number

- D and V depend weakly on the charge number (7<Z<32) – also agrees with QualiKiz. Different from JET?

- Pinch velocity directed inward.

Bourdelle/Guirlet 08



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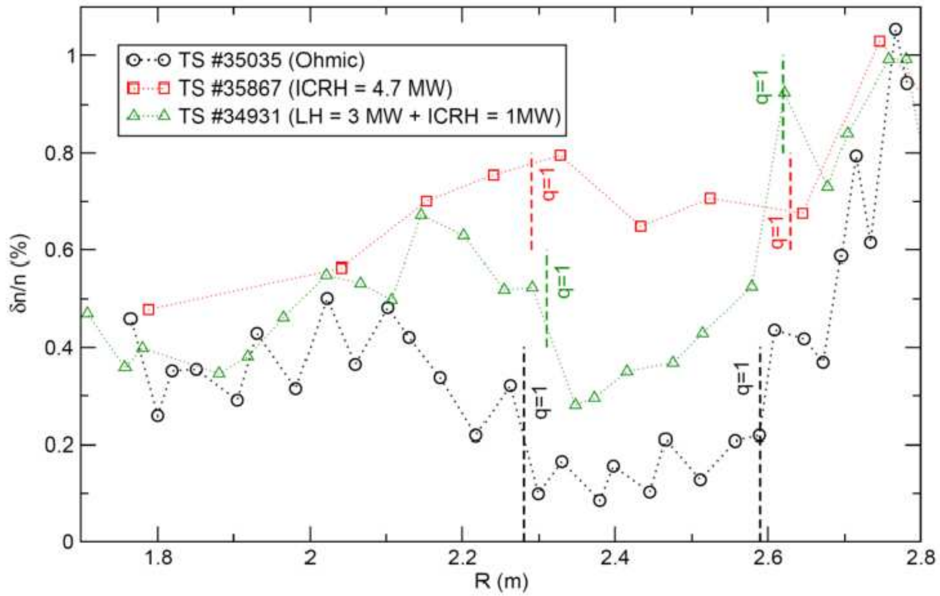
Impurities are neoclassical in the core, electrons are not

- Low level of fluctuations in the core
- electron pinch velocity is above neoclassical, V_{nickel} is neoclassical
- Effect of an internal kink mode?

Sabot 10



Level of fluctuations

Impurities are neoclassical in the core, electrons are not

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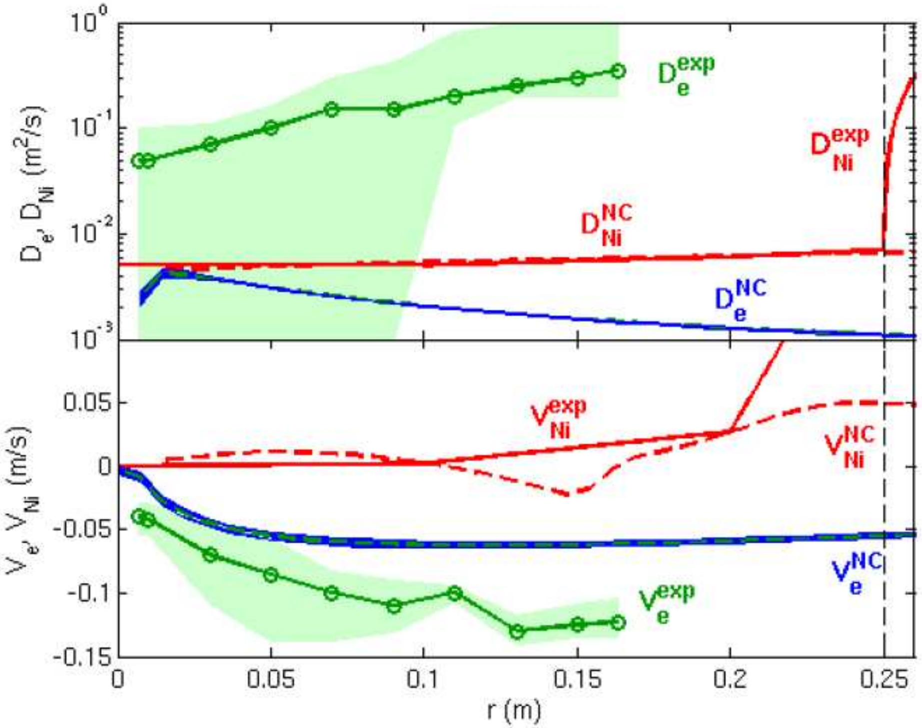

D and V for electrons and Nickel vs neoclassical

Conclusions

- Agreement between measured and calculated density fluctuations, for both intensity and spectra$\rightarrow$ quasilinear transport model under test.

- E_r and V_φ agree with neoclassical theory in ohmic plasmas, with strong ripple. Situation for V_θ to be clarified.

- Impurity transport is turbulent in the gradient zone, neoclassical in the core of Ohmic plasmas. Dependence on charge and mass numbers unclear.