# Turbulent impurity transport in the core of tokamaks, physical mechanisms, ongoing validation efforts, potential impact on plasma discharges

## Emiliano Fable

**Special acknowledgments for material and discussions**

**C. Angioni, C. Bourdelle, Y. Camenen, F. Casson, R. Dux, X. Garbet,**
**C. Giroud, R. Guirlet, T. Hein, H. Nordman, M. Valisa, D. Villegas, C. Veth**

**J. Candy and R.E. Waltz are warmly acknowledged for providing GYRO,**
**M. Kotschenreuther and W. Dorland for providing GS2,**
**F. Casson and A.G. Peeters for providing GKW**

# Turbulent transport of impurities

- Impurity transport can be produced by both neoclassical (collisional) and turbulent mechanisms

- Measured impurity transport levels can largely exceed neoclassical predictions, analysis and modelling of impurity transport requires the inclusion also of turbulent effects

- Microturbulence in the core of tokamaks is predicted to produce significant impurity transport, whose effects can be expected to be experimentally observable

- In this context, impurity transport has to be considered an important part in the framework of the validation of the paradigm of microturbulence as primary source of anomalous transport in the core of tokamaks

# Turbulence produces diffusive & convective mechanisms of impurities

- A general expression of the transport of impurities can be derived from first principles [see e.g. Camenen PoP 2009, Fable PPCF 2010, Casson PoP 2010]

$$\frac{R\Gamma_{nZ}}{n_Z} = D_{NZ}\frac{R}{L_{nZ}} + D_{ThZ}\frac{R}{L_{TZ}} + D_{UZ}u'_Z + RV_{pZ}$$

where $u'_{Zr} = (R^2/v_{thZ})d\Omega_Z/dr$

- The turbulent impurity flux is composed by diffusion, thermo-diffusion, roto-diffusion and pure convection [see also Frojdh NF 1992, Garbet PoP 2005, Angioni PRL 2006, Dubuit PoP 2007]

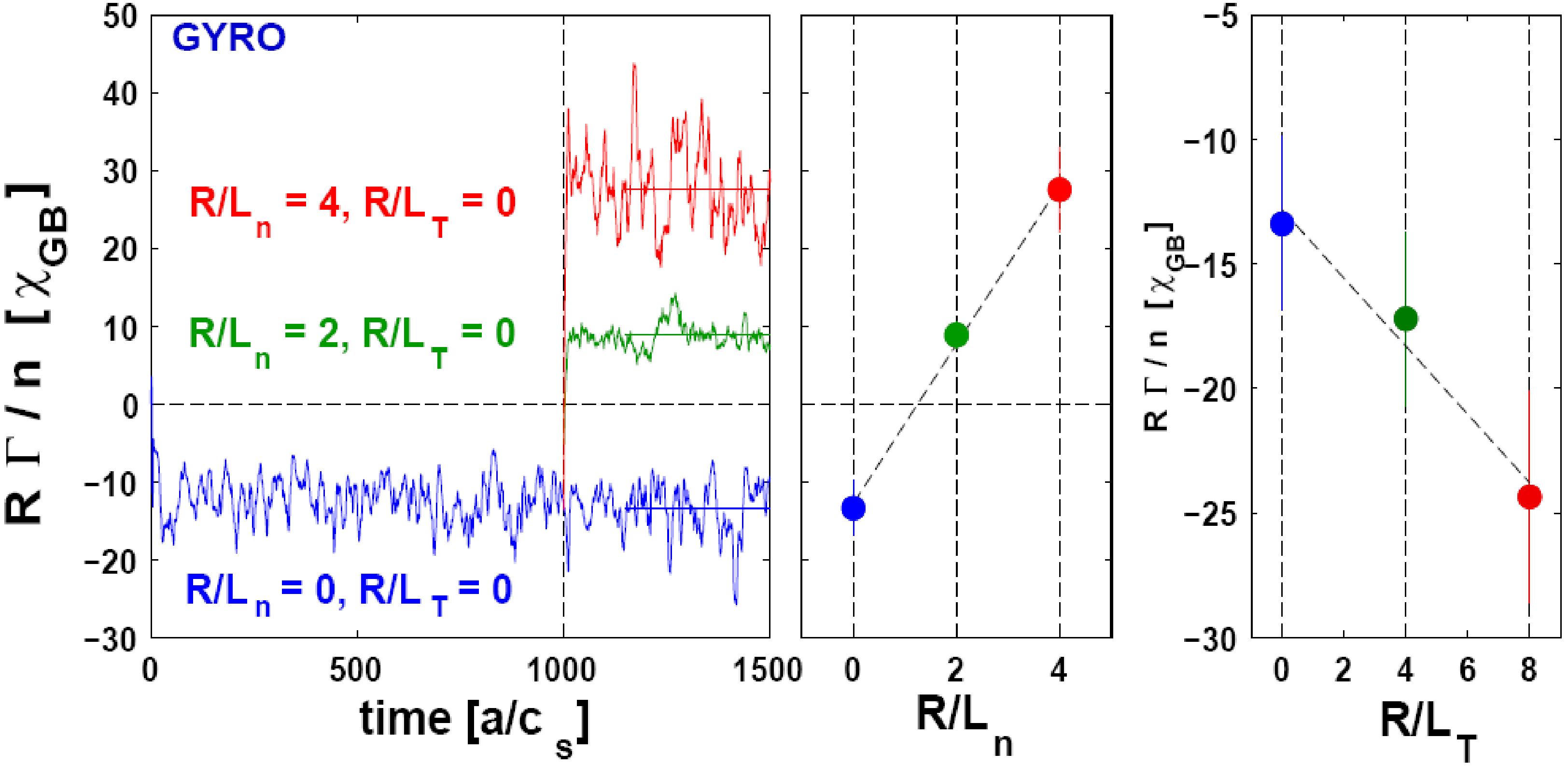
- This is an appropriate physical decomposition, but not a linear relationship
- It becomes linear in the limit of impurities in small charge concentration (trace particles)

# Linear for species in small charge concentration (also in nonlinear runs)

- **Linear relationship practical in impurity transport modelling, to separate diffusive and convective contributions**

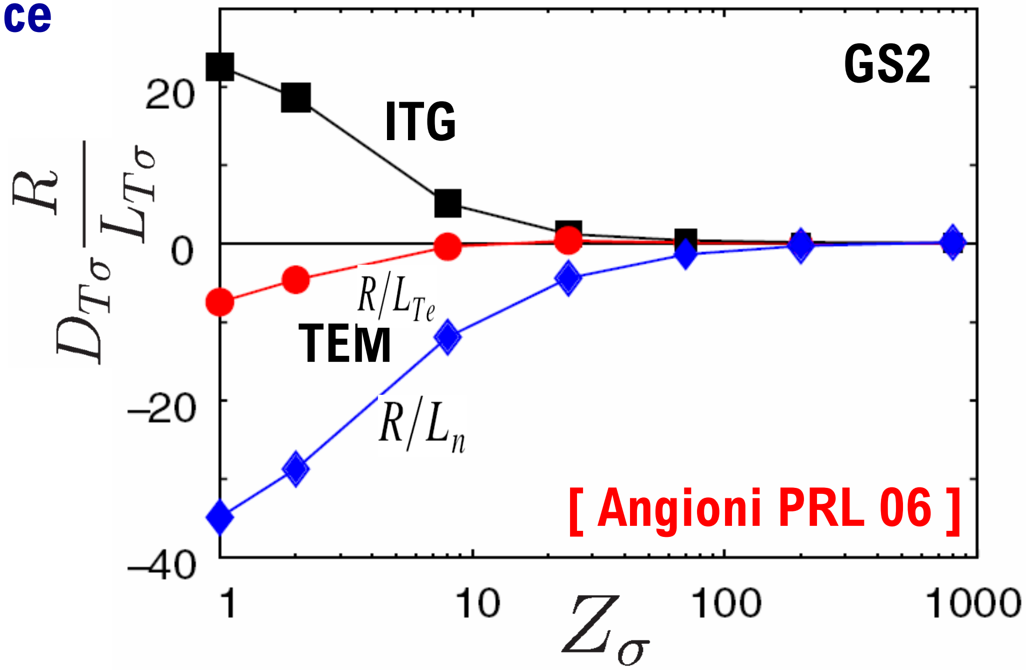
- Turbulent He particle flux is a linear function of the He density and temperature logarithmic gradients

[ Angioni, NF 09 ]



# Off-diagonal contributions can reverse sign depending on type of turbulence and main resonance

- A typical example is provided by thermodiffusion, for usual instabilities provided by the curvature resonance



- Impurity thermodiffusion is directed inward for TEM and outward for ITG

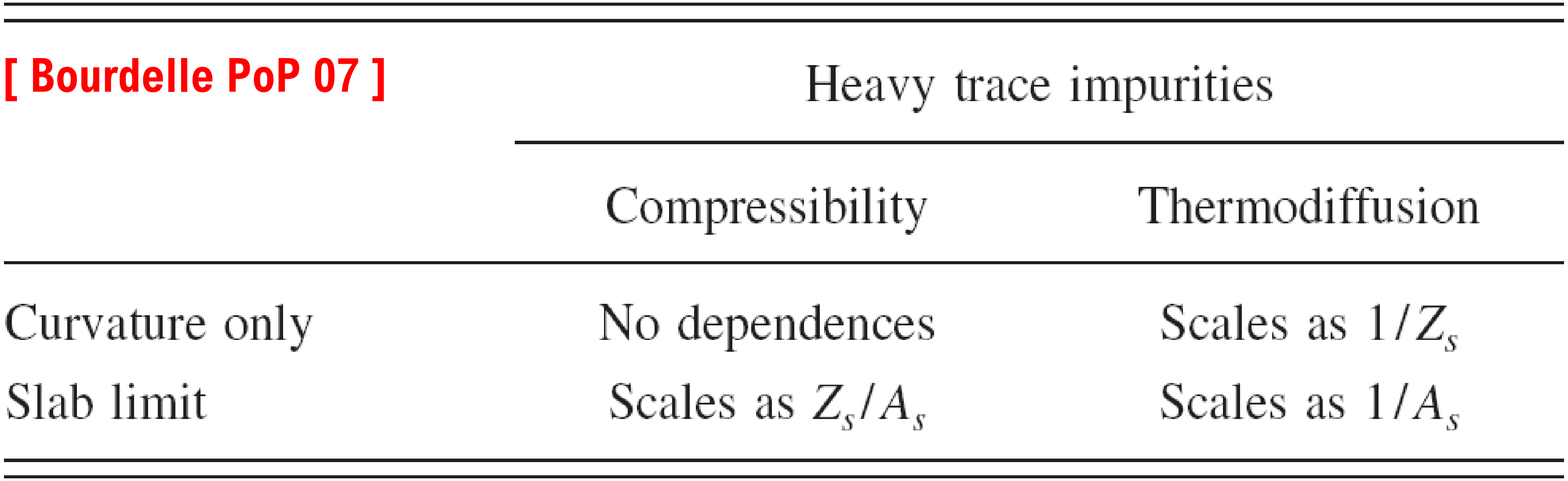
- In addition we observe that thermodiffusion depends on the impurity charge

- This might be surprising, since ExB transport could be expected to be charge independent, like the ExB drift

- In reality, one should consider that ExB transport is produced by the phase relation between fluctuating transported field and the fluctuating (transporting) potential, and this phase relation does depend on charge (and mass)

# Dependence on charge and mass directly reflect the charge and mass dependences of the relevant resonant motions

[ Bourdelle PoP 07 ]



|  | Heavy trace impurities |  |
|---|---|---|
|  | Compressibility | Thermodiffusion |
| Curvature only | No dependences | Scales as $1/Z_s$ |
| Slab limit | Scales as $Z_s/A_s$ | Scales as $1/A_s$ |

- **Although electrostatic turbulent transport is produced by fluctuating ExB drift, dependences on Z and A arise from the resonances, provided by the perpendicular and parallel gyro-centre motions**
  - **Perpendicular motion, curvature and grad B drift prop. to 1/Z, ExB compression independent of Z and A**
  - **Parallel motion, electric force term proportional to Z/A, pressure term proportional to 1/A**

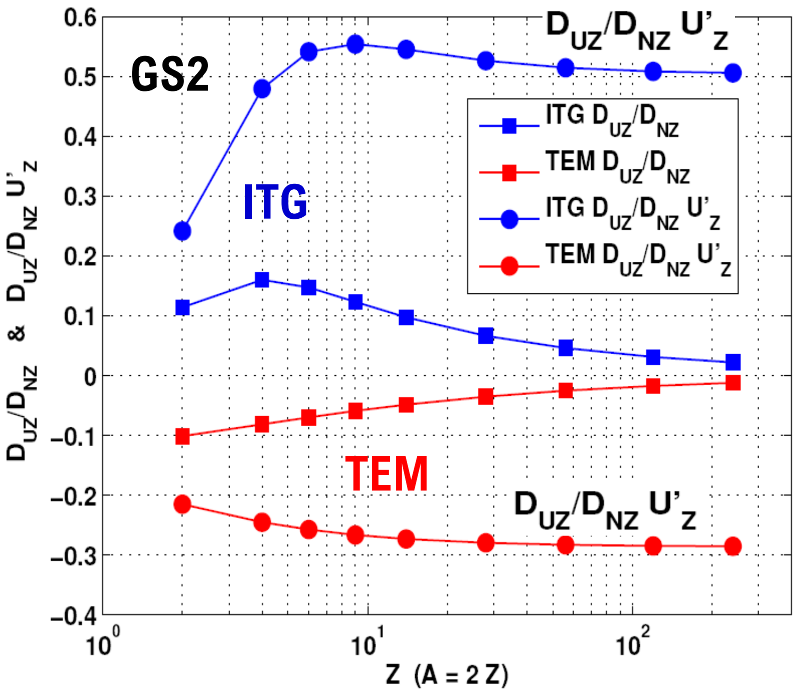
# Impurity inertia makes rotational effects non-negligible in impurity transport

$$\frac{R\Gamma_{nZ}}{n_Z} = D_{NZ}\frac{R}{L_{nZ}} + D_{ThZ}\frac{R}{L_{TZ}} + \boxed{D_{UZ}u'_Z} + RV_{pZ}$$

**where** $u'_{Zr} = (R^2/v_{thZ})d\Omega_Z/dr$

**[ Camenen PoP 09, Casson PoP 10 ]**

- **Without toroidal rotation velocity and rotation velocity gradient, symmetry properties imply that roto-diffusion is zero**
- **But, tokamak plasmas have finite toroidal rotation velocity and velocity gradient, and impurity roto-diffusion can be non-negligible**
- **Like thermodiffusion, roto-diffusion is directed outward in ITG, and inward in TEM**
- **In contrast to thermodiffusion, it is prop. to A/Z, remains finite at large Z**



# In summary …

$$\frac{R\Gamma_{nZ}}{n_Z} = D_{NZ}\frac{R}{L_{nZ}} + D_{ThZ}\frac{R}{L_{TZ}} + D_{UZ}u'_Z + RV_{pZ}$$

**Curvature resonance only (usually the most relevant)**

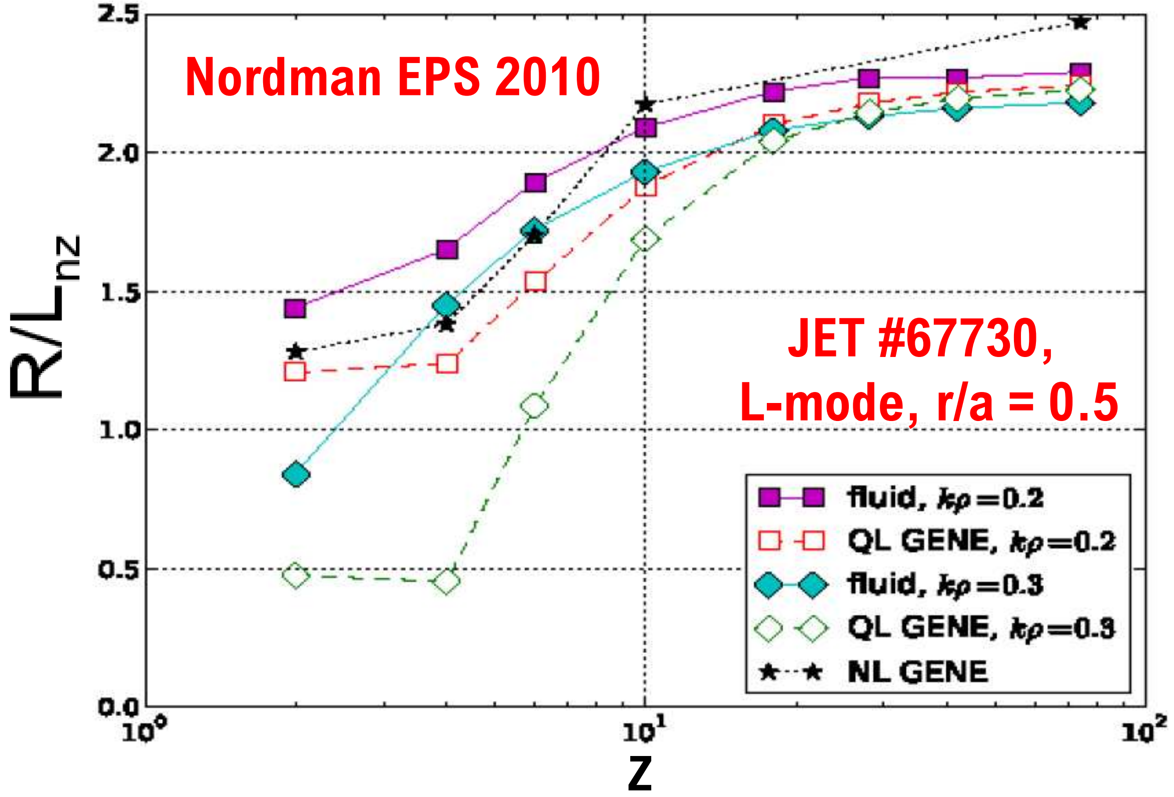
- Thermodiffusion and roto-diffusion outward in ITG, inward in TEM [Camenen PoP 2009]
- Pure convection inward, can be outward with negative shear [Dubuit PoP 2007, Futatani PRL 2010]

**Slab resonance only**

- Thermodiffusion inward
- Pure convection inward in ITG, outward in TEM [Angioni PRL 2006]

- Final result depends on relative role of various transport mechanisms
- Complexity increased by the inclusion of centrifugal effects (poloidal asymmetry, additional dependences on mass) [Casson PoP 2010], and electromagnetic effects [A. Eriksson PoP 2005, Hein PoP 2010]

# Verification efforts, benchmark among different models and codes



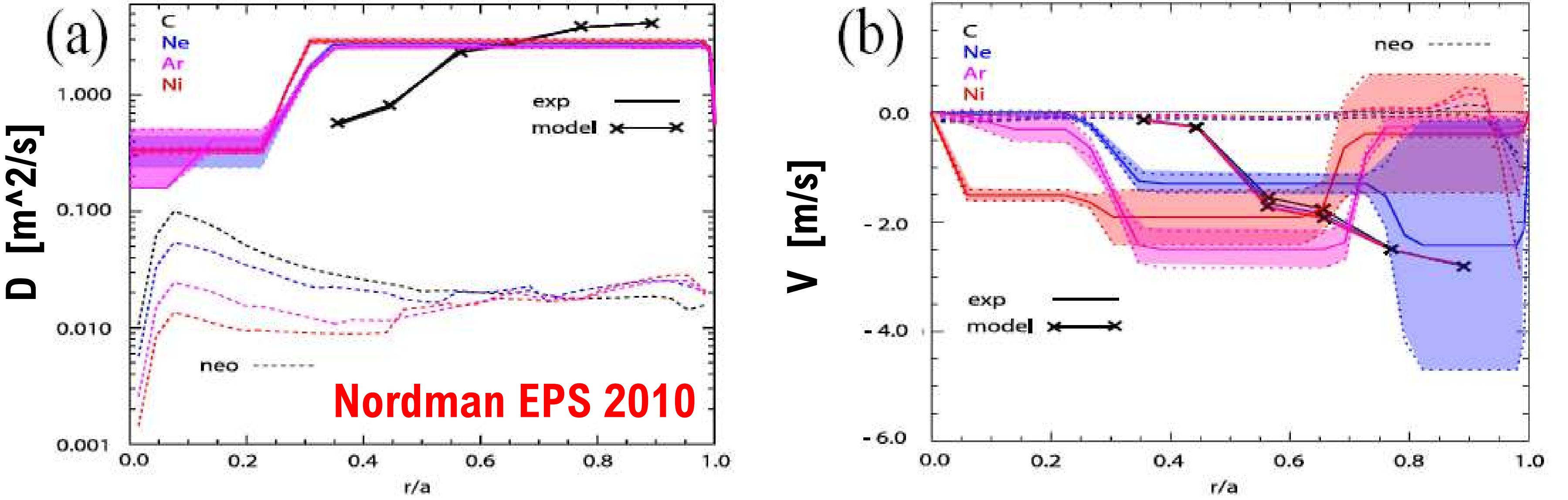
Nordman EPS 2010

JET #67730,
L-mode, r/a = 0.5

- Typical example of Z dependence (without roto-diffusion and centrifugal effects) for an ITG case around mid-radius
- Z dependence mainly provided by thermodiffusion, directed outward, whose reduction with increasing Z leads to increased predicted peaking
- Good agreement among fluid (Weiland, QL) and GK (GENE QL and NL) models

# Validation efforts dedicated to both charge and radial dependence

**JET #67730, #67732, L-mode [ C. Giroud TTG 2008 ]**



**Nordman EPS 2010**

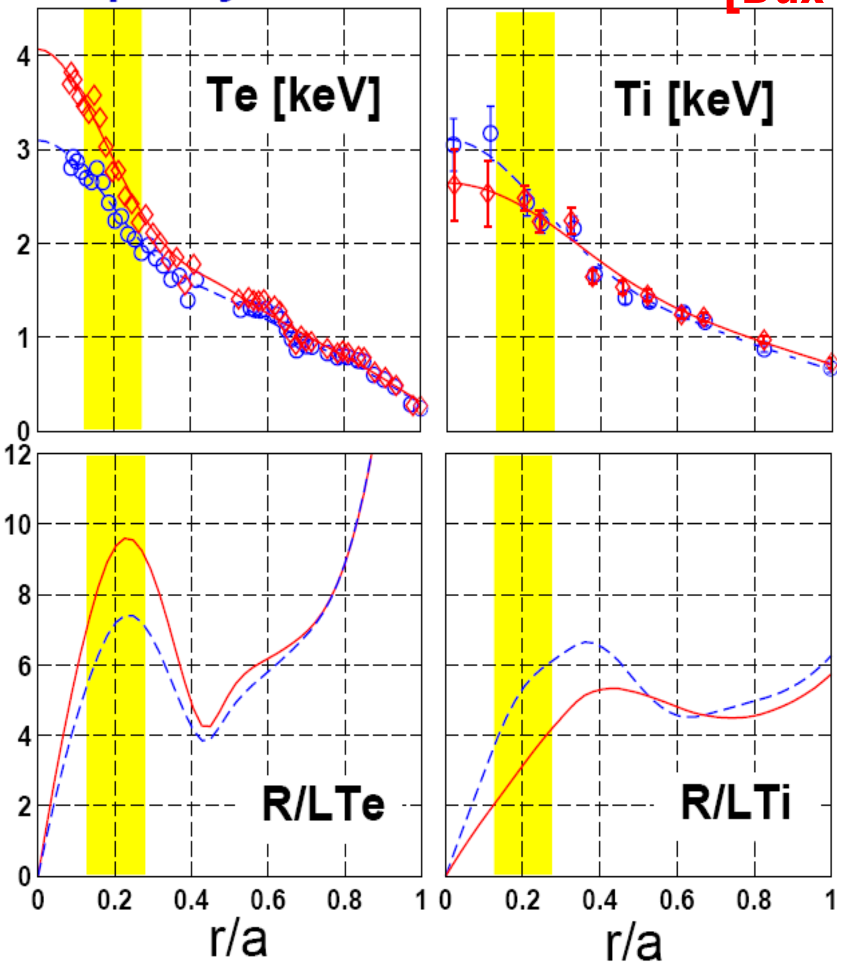
- **Measured diffusion comparable to neoclassical levels only in the centre, otherwise 2 orders of magnitude larger**

- **Turbulent predictions (Weiland Model) in reasonable agreement, particularly around mid-radius (simulations do not include any rotation effect)**
- **Clear sign of disagreement only on carbon, predicted peaked ( R/Ln ≈ 1.8 ) and measured rather flat ( R/Ln ≈ 0 )**

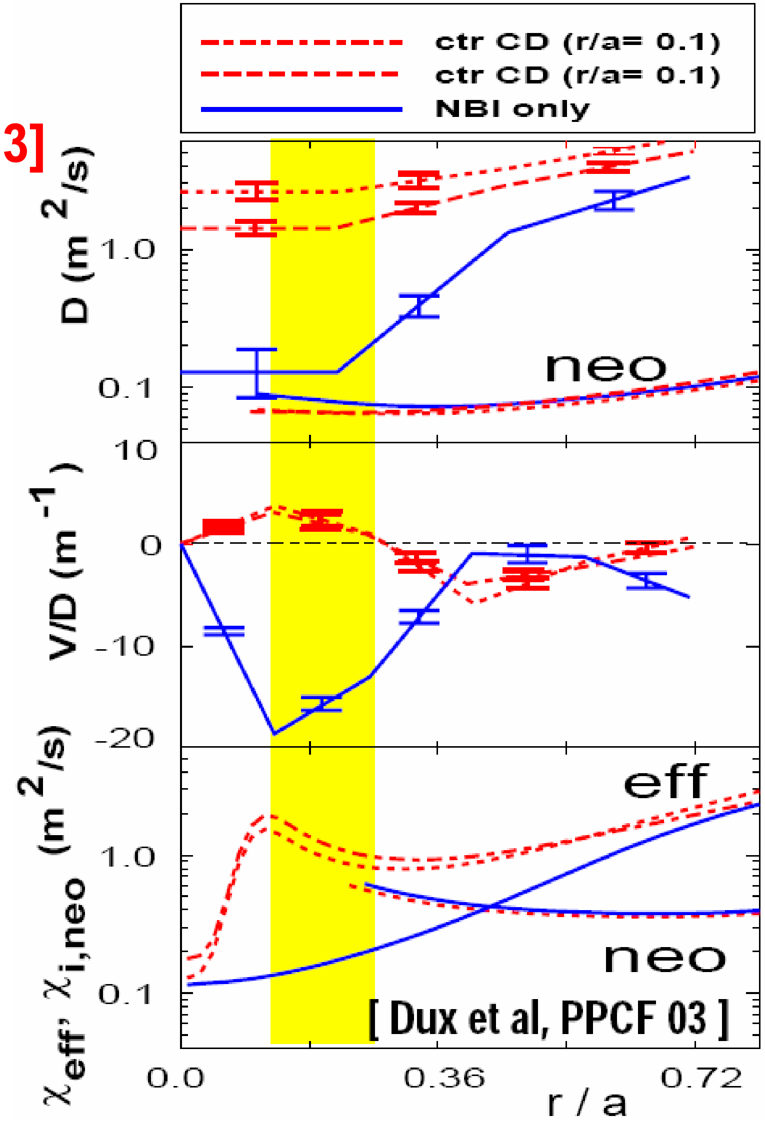
# Validation efforts also dedicated to impurity transport response to auxiliary heating

- **Laser ablation in AUG H-mode plasmas show Si outward convection with central ECH**

[Dux PPCF 2003]



**Si**



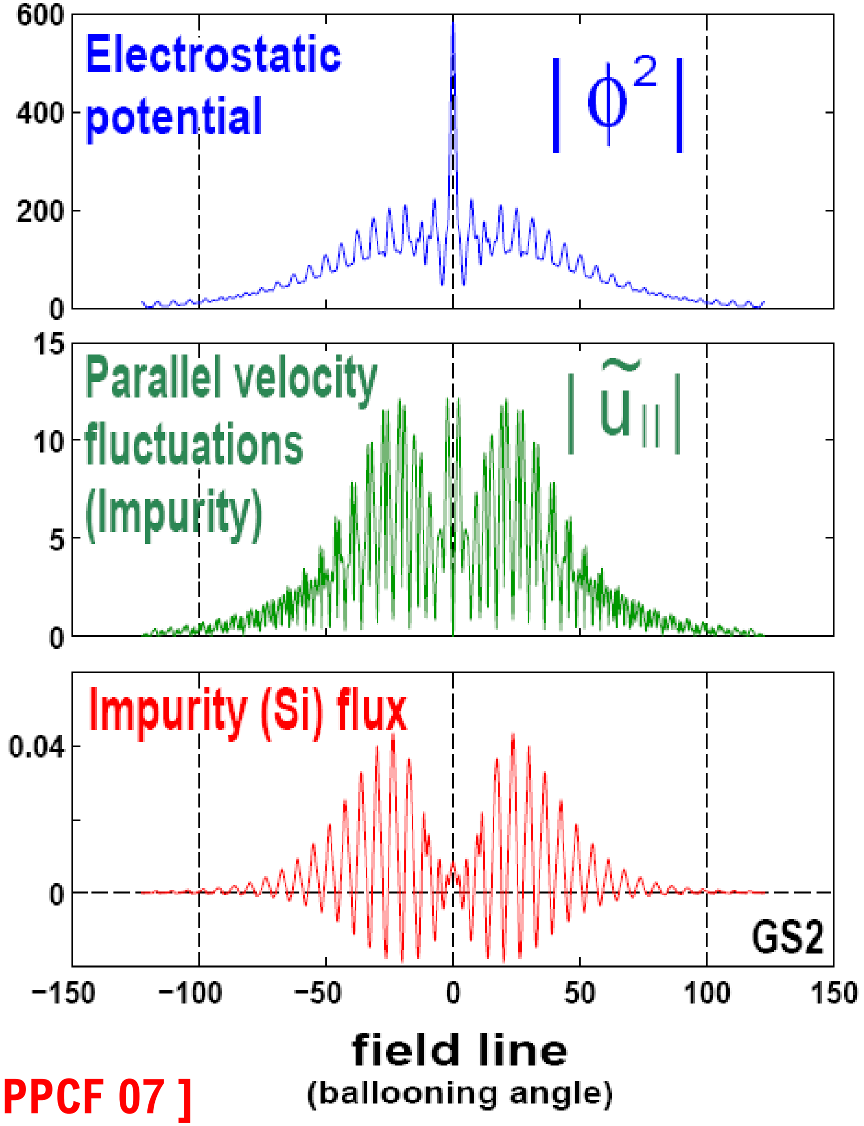
# Destabilization of modes propagating in the electron drift direction can explain the reversal

- Unstable mode shows elongated eigenfunction which generates Si parallel velocity fluctuations

- Parallel compression of those fluctuations generates radial Si flux on average directed outward

- In the absence of ECH, a dominant ITG mode is found, leading to inward convection of Si

- This study can be proposed as evidence for the validation of a mechanism of convection reversal, this time critically involving parallel dynamics ( slab resonance )

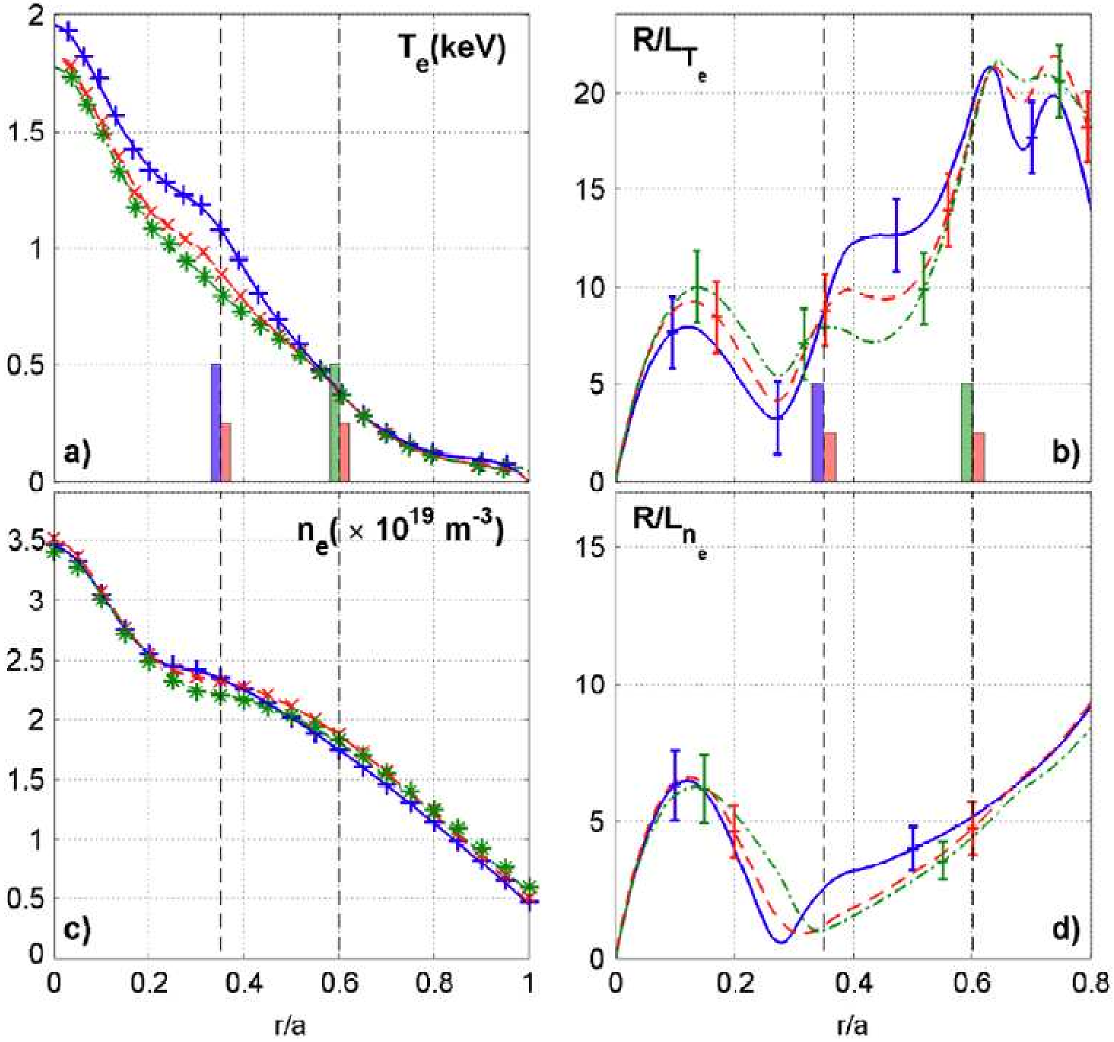


[ Angioni PPCF 07 ]

# Effect of localilized electron heating on Ni transport studied in TORE SUPRA

[ Villegas PRL 2010 ]

Deposition r/a (2 gy)
0.6
mixed (0.35 + 0.6)
0.35



**Total ECH power constant, two radial deposition locations, different fractions of heating power [the F. Ryter's experiment, Ryter NF 2003]**

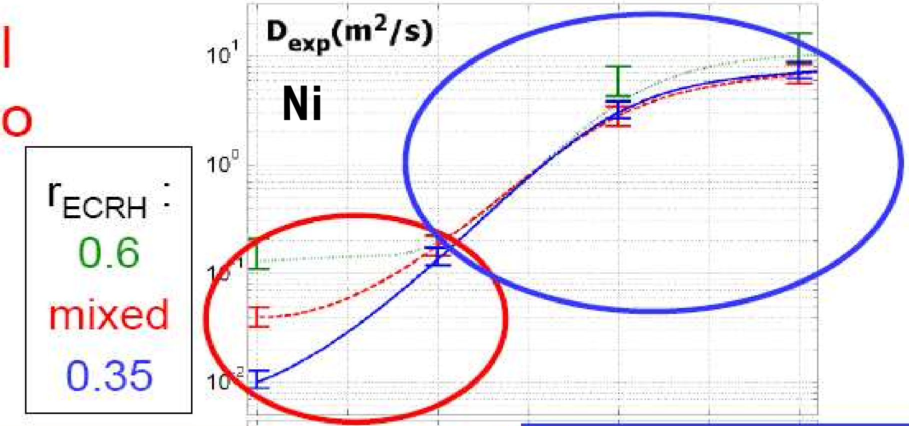
# Increase of diffusivity with increasing R/LTe observed in the central region, where dominant TEM turbulence is predicted

Radial transport analysis: ITC iterative resolution of coupled continuity equations

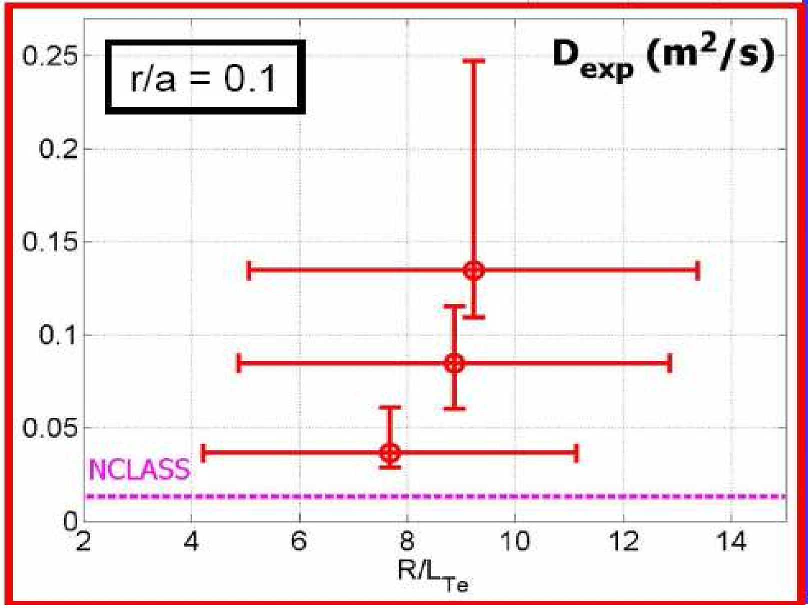
**[ Villegas PRL 2010 ]**

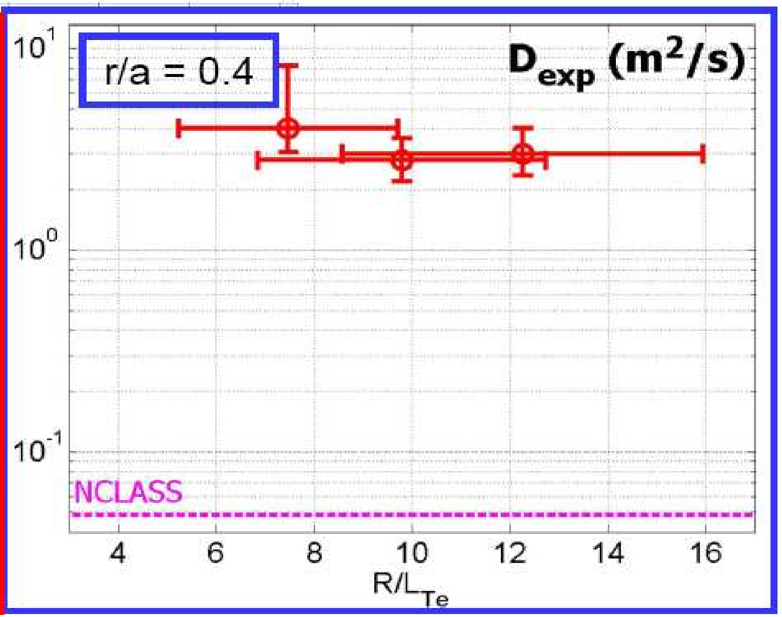
Only central D sensitive to $r_{ECRH}$

**Ni**

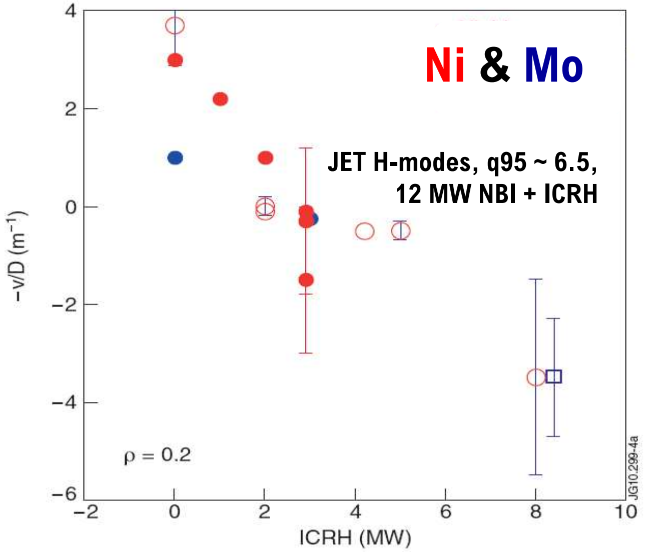


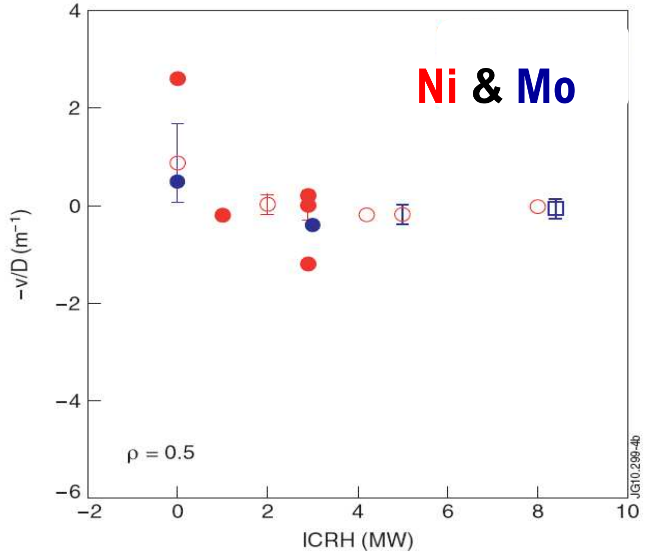
Outer D insensitive to $r_{ECRH}$





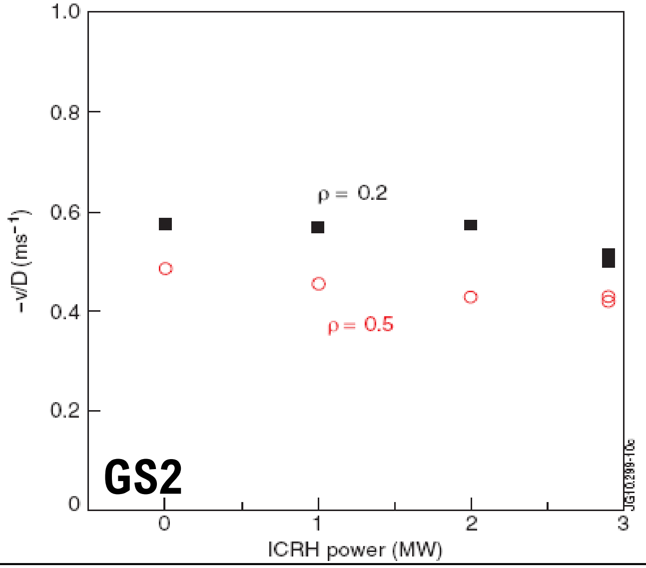
# JET shows strong flattening and eventually centrally hollow metal impurity profiles with increasing central ICRH power



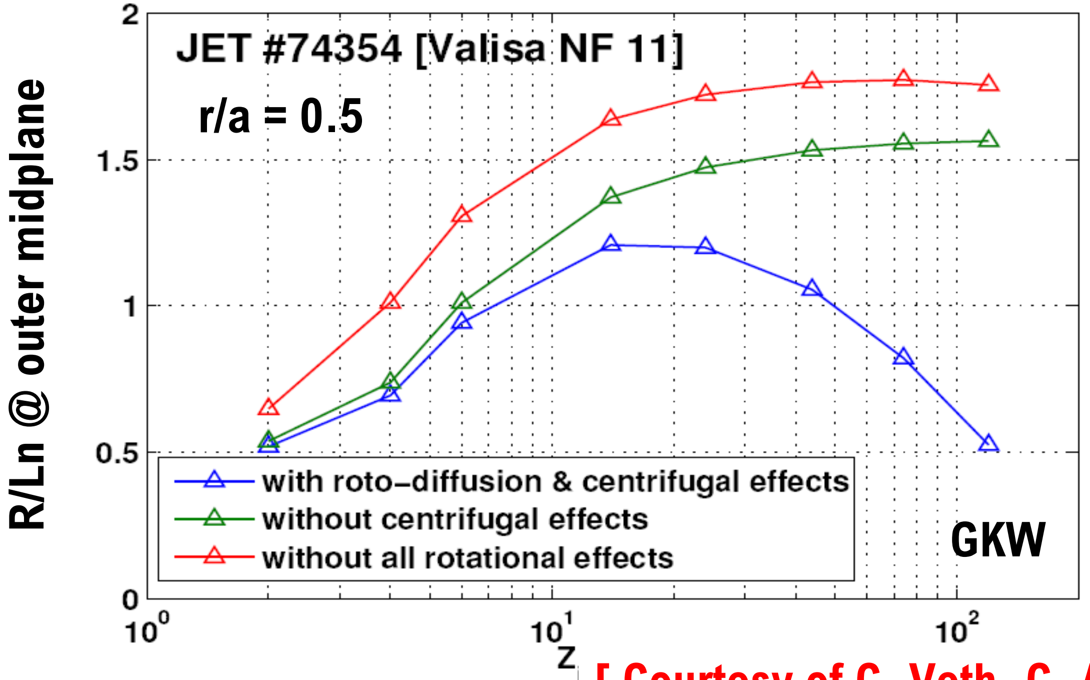


- Central ICRH (H minority) produces impurity pump-out in the centre, pump-out strength increases almost linearly with increasing ICRH power
- Neoclassical transport too low to explain observations
- Turbulent transport (w/o any rotation effect) cannot explain the observations either
- Modelling including rotation effects presently ongoing

[ Valisa NF 2011 ]



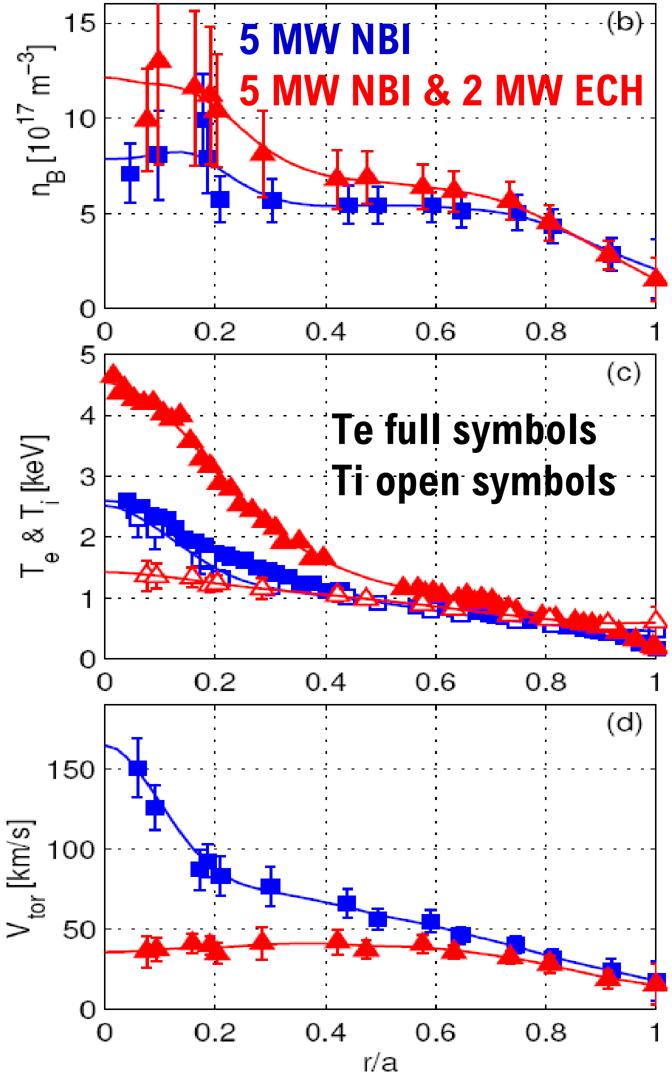
# Inclusion of roto-diffusion and centrifugal effects modify the Z dependence



[ Courtesy of C. Veth, C. Angioni & F. Casson ]

- Differences in predicted Z dependence might be too small, and remain within experimental error bars
- Predicted values remain close to those of the electron density
- In contrast to neoclassical transport, turbulent transport is predicted not to lead to strong accumulation
- This provides handle for impurity control, by localized central heating, which prevents neoclassical transport to remain dominant

# Role of roto-diffusion possibly identified in AUG H-modes, boron locally flat with NBI only, moderately peaked adding ECH

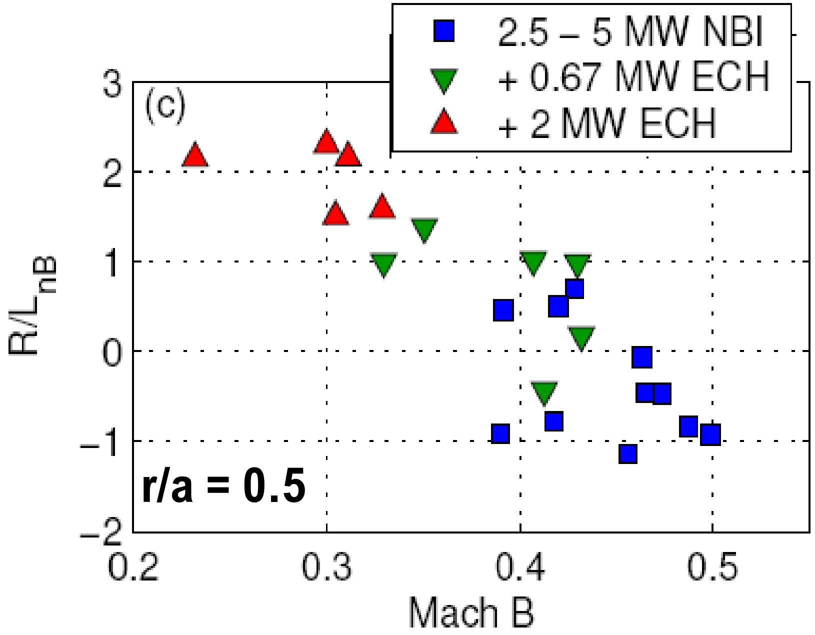


- **In low current 600 kA AUG NBI H-modes, central ECH strongly breaks plasma toroidal rotation**

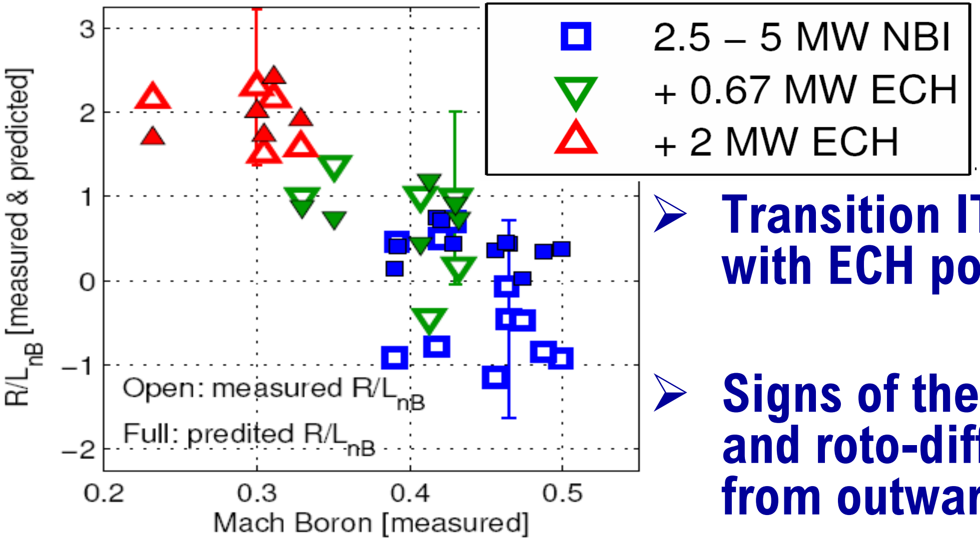
**[ McDermott PPCF 11 ]**

- **GK modelling of behaviour of boron log density gradient at r/a = 0.5**

**[ Angioni NF 11 ]**

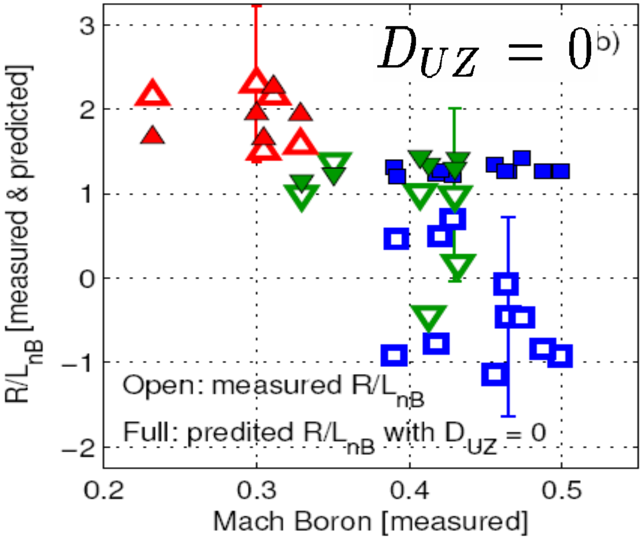


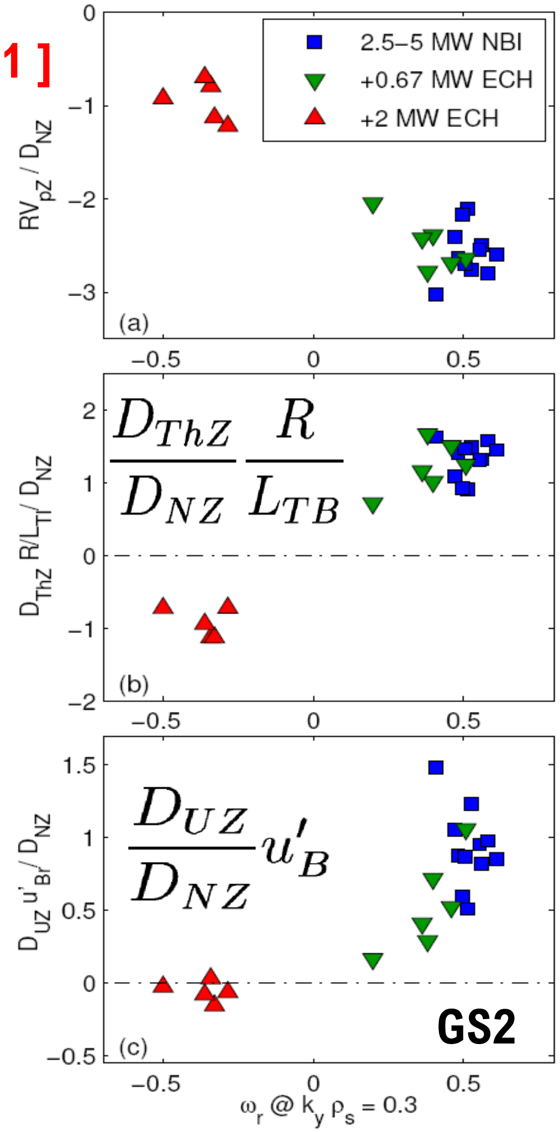
# Roto-diffusion found non-negligible, its role important to reproduce experimental behaviour



[ Angioni NF 11 ]

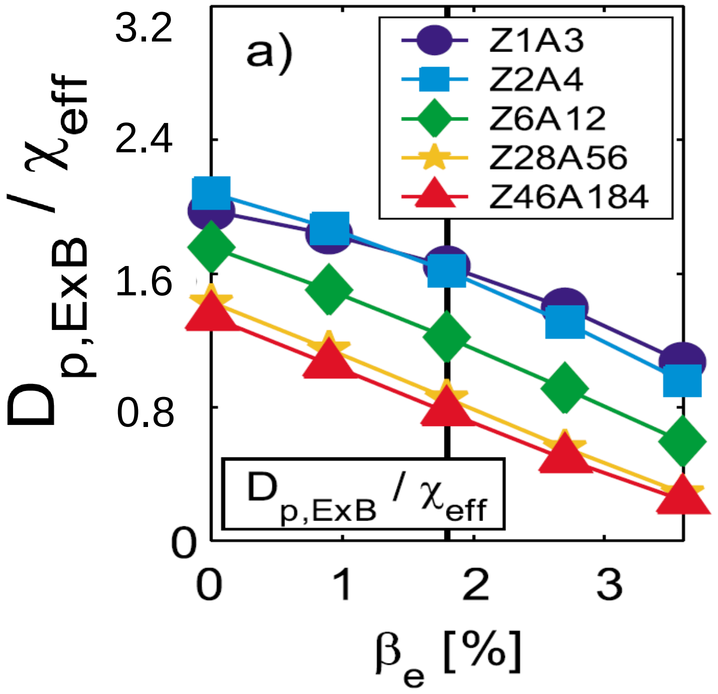
- **Transition ITG to TEM with ECH power**
- **Signs of thermo-diffusion and roto-diffusion change from outward to inward**
- **With high ECH power, roto-diffusion becomes very small (flat rotation profile and slow rotation)**
- **NBI only, roto-diffusion not large enough to provide local hollowness (still produces non-negligible flattening)**

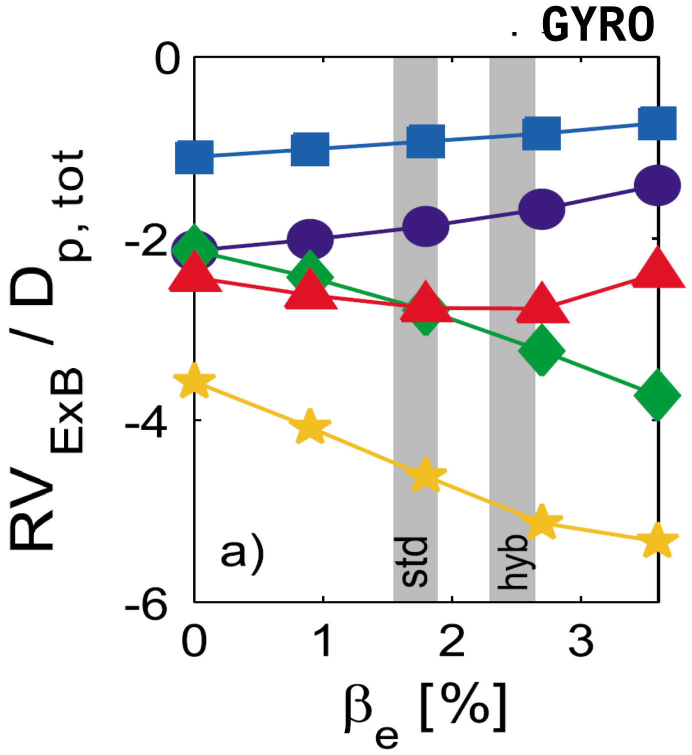




# Electromagnetic effects can become important in high beta plasmas

- **Electromagnetic effects have to be included in the modelling when treating high beta plasmas, since they can be non-negligible [ Hein PoP 10 ]**
- **Impurity diffusion to heat conductivity ratio decreases with increasing beta**
- **For typical H-mode parameters, different behaviour of the total convection for low and high Z impurities, magnetic flutter small**





# Conclusions

- Impurity transport experiments are challenging, but important, for both the development of stable scenarios and the progress in physics understanding of turbulent transport

- Microturbulence in the core of tokamaks is predicted to produce significant impurity transport, and a validation effort is ongoing in order to identify it in the observations
- Several off-diagonal transport mechanisms are at play, and theory becomes increasingly complex, and complete, in taking all of them into account
- Codes are available in the community to compute impurity transport including most of these effects (in particular GKW includes also centrifugal effects)
- Poloidal asymmetries of heavy impurity densities have to be included in the analyses

- No mechanism of strong impurity accumulation increasing with increasing impurity charge is predicted to take place caused by turbulence transport