Towards a predictive understanding of particle transport

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Why particle transport is important

- Conflicting constraints in a reactor:

  - peaked D-T profiles favour high fusion power (and high ratio n/n_G)

  - low level of ashes

  - weak impurity penetration for both low Z (radiating divertor) and high Z (PFC's)
- Traditional formulation $\Gamma = -D\nabla n + Vn \rightarrow$ $$\frac{\Delta n}{n} \approx \frac{Va}{D}$$
- Not extrapolable → predictive models.

Transport matrix

- General form of transport matrix

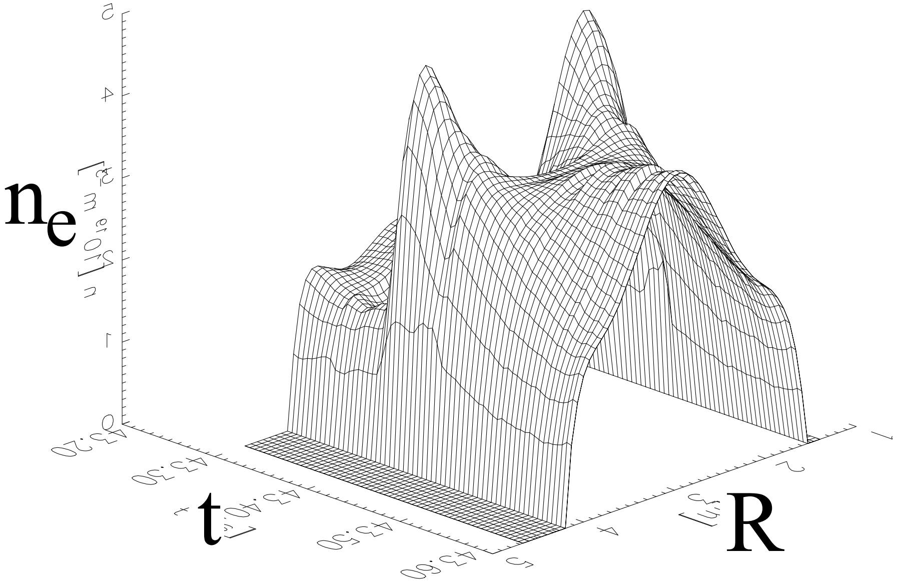
$$\begin{pmatrix} \Gamma/n \\ Q/nT \\ j/n \\ \ldots \end{pmatrix} = \begin{bmatrix} D & D_{\nabla T} & V_{wn} & \ldots \\ D_{\nabla n} & \chi_T & V_{wT} & \ldots \\ D_{bn} & D_{bT} & \sigma T/n & \ldots \\ \ldots & \ldots & \ldots & \ldots \end{bmatrix} \cdot \begin{pmatrix} -\partial_r n/n \\ -\partial_r T/T \\ E_{ind}/T \\ \ldots \end{pmatrix}$$

+ coupling to other species

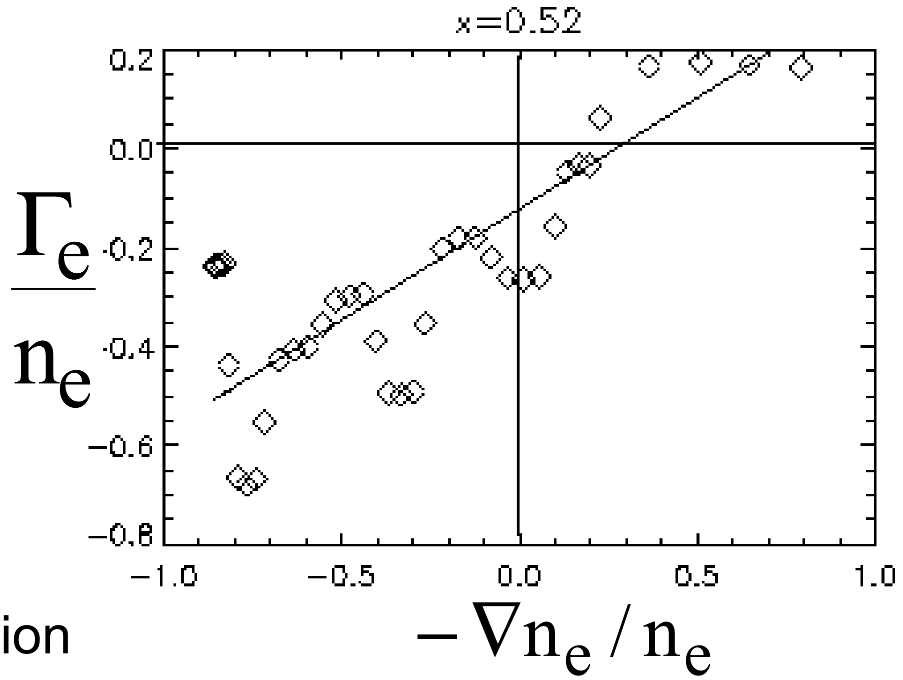
- Ambiguous form for turbulent fluxes as $D(\nabla n, \nabla T, \ldots)$, except for trace particles.

Transients are required to determine the transport matrix

- Steady state: only $D_{eff}=D-Vn/\nabla n$ is accessible.
- Example of transients : laser blow off, pellet injection, sawteeth, etc…
- Some impact of source uncertainties. Stober 01, Valovic 07



Courtesy L. Garzotti - JET pellet injection



Outline

- Collisional transport
  – transport matrix
  – limitations of neoclassical theory
- Turbulent transport
  – existing theories
  – numerical simulations
- Predictions versus experiments
  - particle transport
  - impurity transport
- Open issues

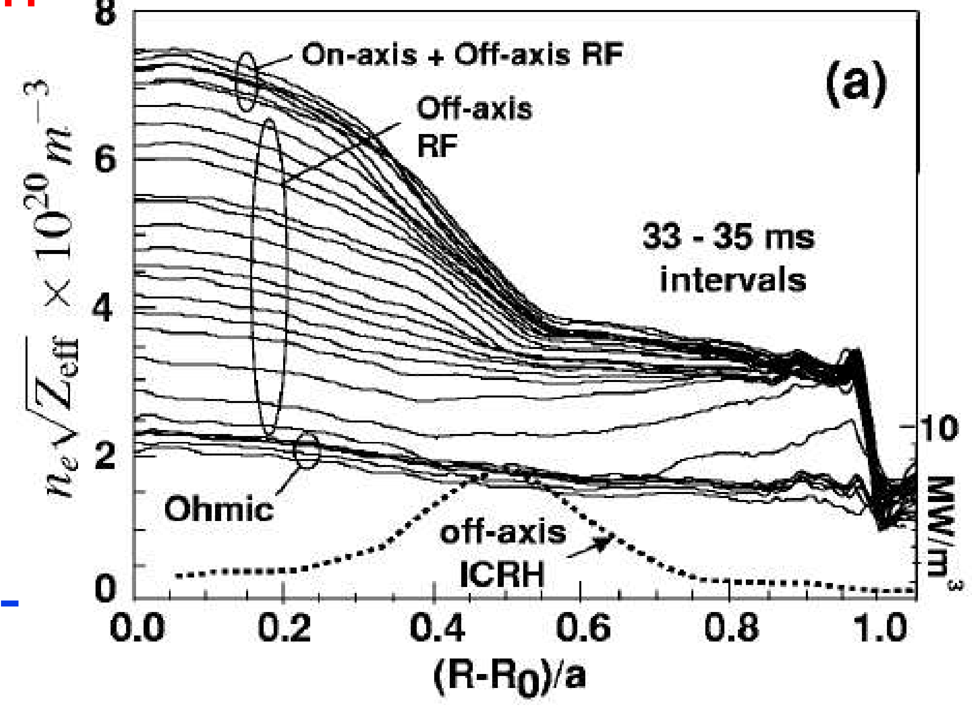
Neoclassical theory: Ware pinch

- For electrons, Ware pinch is the main off-diagonal term

$$V_{Ware} = 2.44\sqrt{r/R}\,\frac{E_{ind}}{B_p}$$

- Usually dominant in core plasmas Stroth and Wagner 93, Sirinelli 06.
- Responsible for density transport barrier in Alcator-C-Mod Ernst 04 .

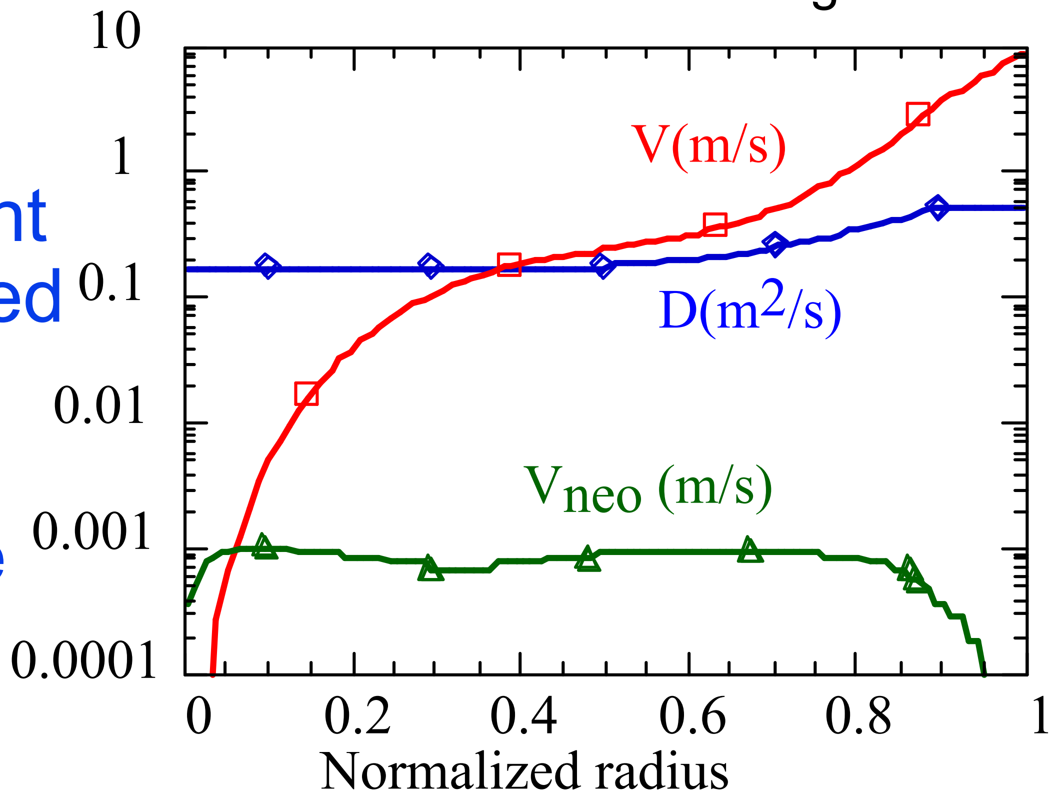
Ernst 04 Alcator C-Mod



The Ware pinch cannot explain all experiments

- Diffusion is usually anomalous in the gradient zone and the edge.
- Existence of a turbulent pinch has been debated for long.
- Unambiguous observation in L-mode with $E_{ind} \approx 0$ TS Hoang 04, TCV Zabolotsky 03.

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



Neoclassical theory: impurity peaking

- For impurities, main drive is the ion density gradient,
- Sign of thermodiffusion may change

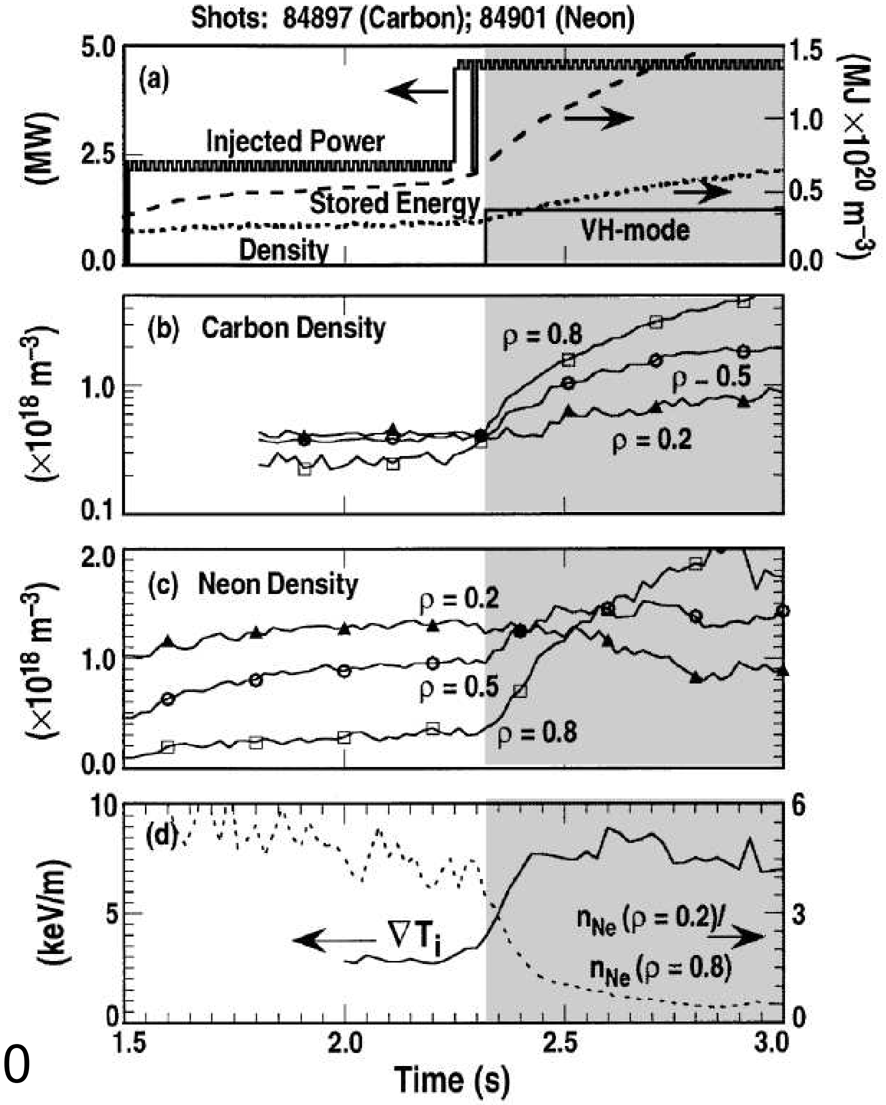
$$\frac{V}{D} = Z\left(\frac{\nabla n_i}{n_i} + H\frac{\nabla T_i}{T_i}\right)$$

Inward pinch

"Screening" if H<0

- Observed on JET Giannella 92, Asdex Fussman 91, DIII-D Wade00

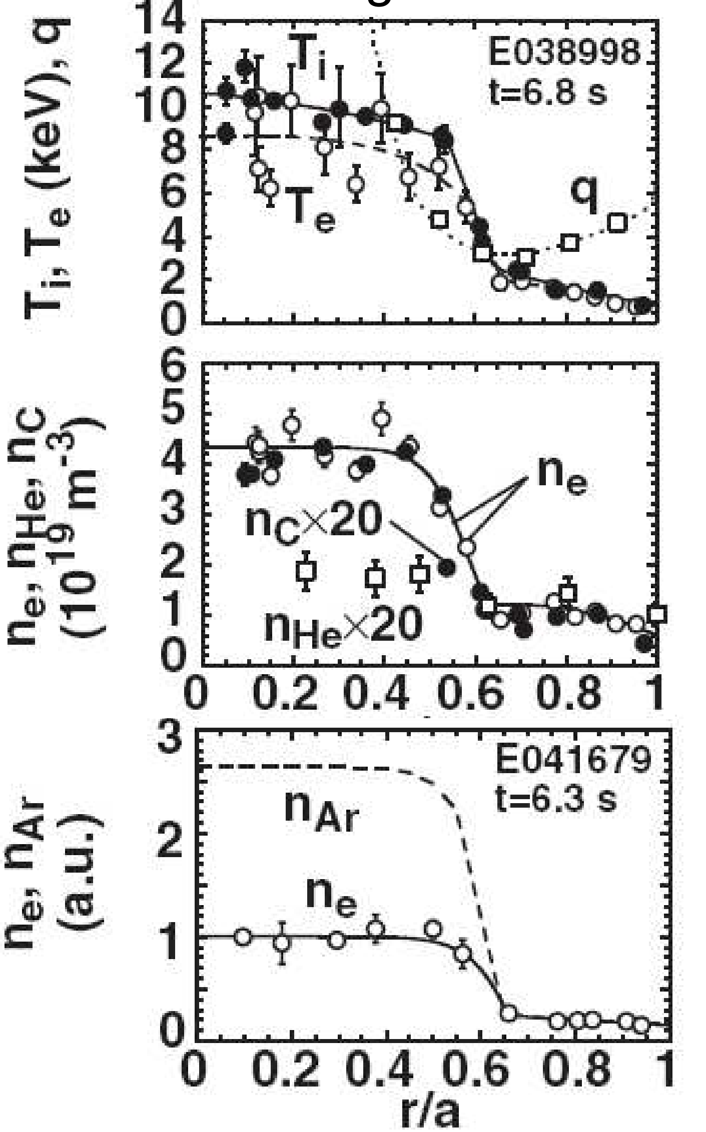
Wade 00 DIII-D VH mode



Impurity transport is close to neoclassical in transport barriers

- $D_{imp} \approx D_{neo}$ in plasma core
  Alcator Petrasso 86, Asdex Fussman 91, JET Giannella 92, AUG Dux 03
  or
- D_{imp} and V_{imp} close to neoclassical values within transport barriers JET Dux '04 and JT-60 Takenaga 03.

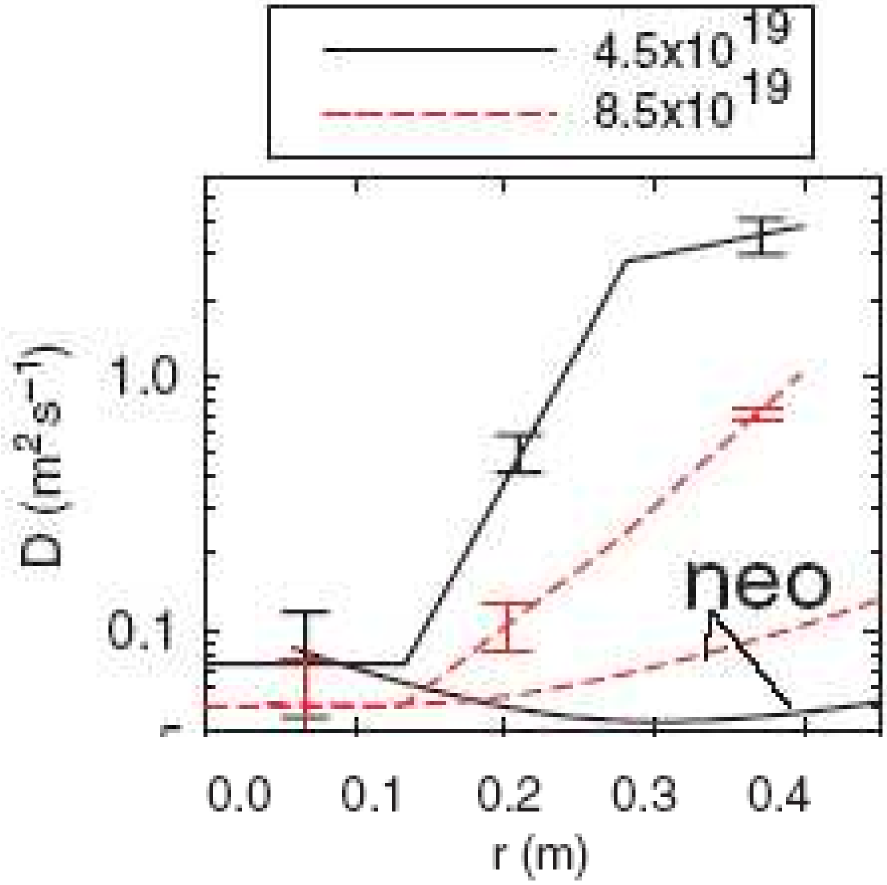
Takenaga 03 JT-60 ITB



Impurity transport is turbulent in the gradient region and in the edge

- $D_{imp} >> D_{neo}$ in most cases: C-mod Rice 97, TFTR Efthimion 98, DIII-D West 02, FTU Carraro 04, JET Dux 04, TS Guirlet 06.
- In the gradient zone, the pinch velocity is usually turbulent and often directed inward.
- V_{imp} may change sign.

R. Dux AUG 03

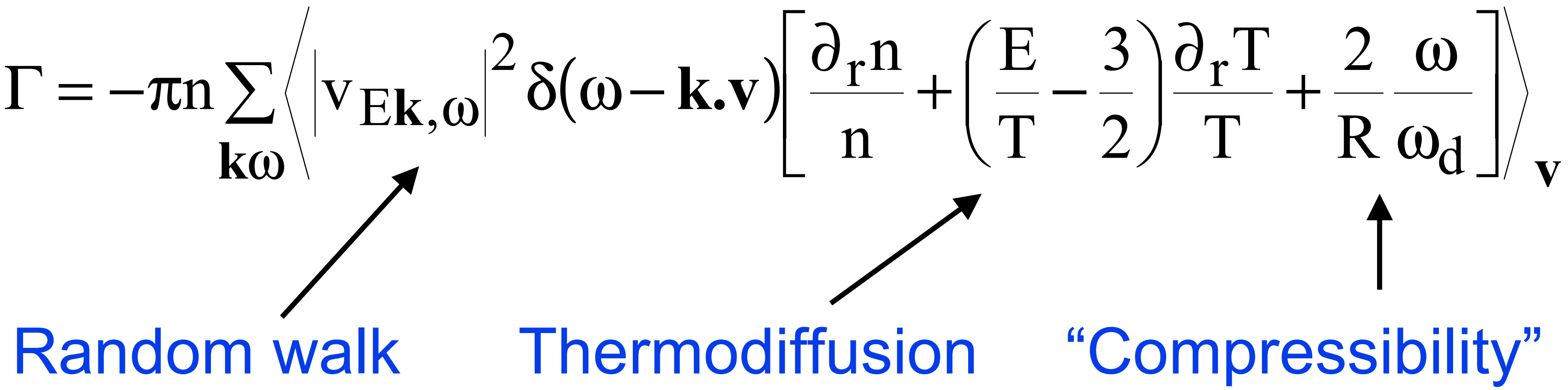


Part II: turbulent transport - theory

- Turbulent flux $\Gamma = \langle \tilde{n}\tilde{V} \rangle$
- Explicit formulation of D and V not obvious.
- Existing theories:
  - Quasi-linear theory
  - Turbulence EquiPartition theory
  - Non QL theories
- Parametric dependences: $R\nabla n/n$, $R\nabla T_e/T_e$, $R\nabla T_i/T_i$, mass and charge numbers, collisions.

Quasi-linear theory has been the reference for long

- General expression for particle flux Horton 83



$$\Gamma = -\pi n \sum_{\mathbf{k}\omega} \left\langle \left|v_{E\mathbf{k},\omega}\right|^2 \delta(\omega - \mathbf{k.v}) \left[\frac{\partial_r n}{n} + \left(\frac{E}{T} - \frac{3}{2}\right)\frac{\partial_r T}{T} + \frac{2}{R}\frac{\omega}{\omega_d} \right] \right\rangle_{\mathbf{v}}$$

Random walk

Thermodiffusion

“Compressibility”

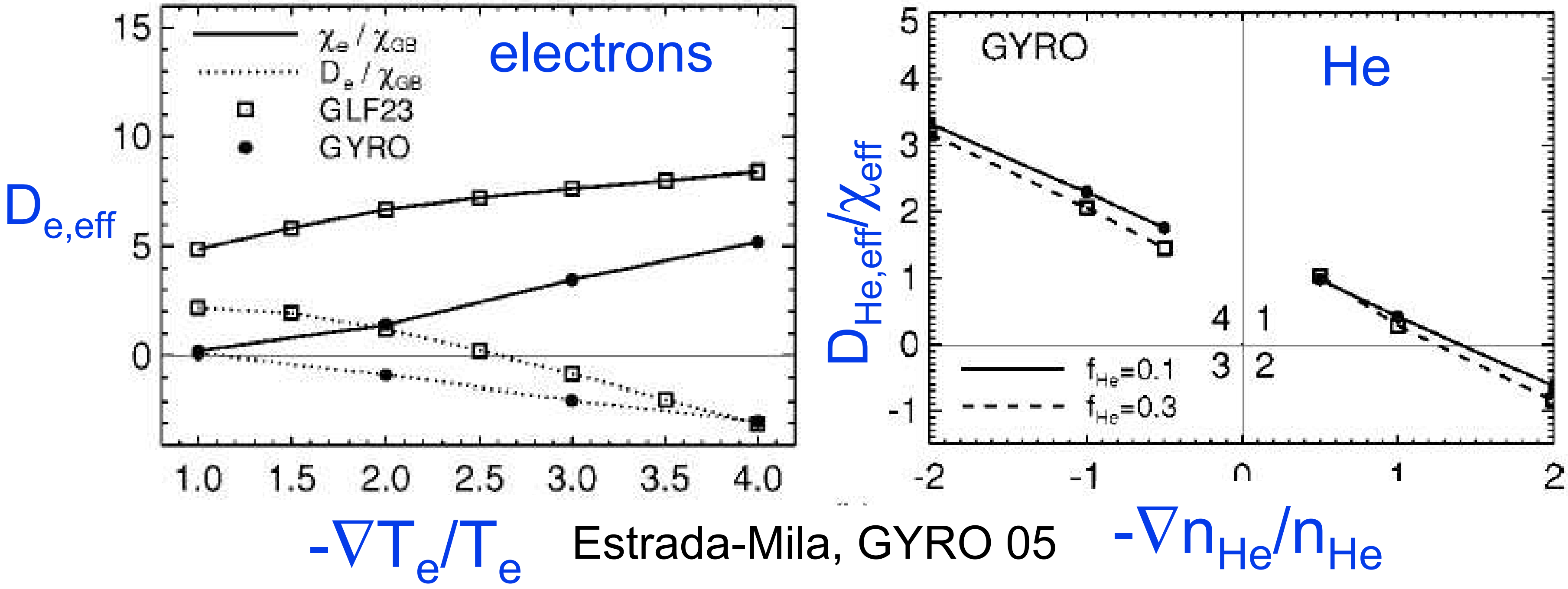
$$D \approx \left\langle \left|v_E\right|^2 \right\rangle \tau_c$$

$$\omega_d = -k_\theta \frac{2T}{eBR}$$

- Thermodiffusion and “compressibility” terms may change sign.

Comparison to numerical simulations is now possible

- Turbulent pinch observed in non linear fluid (TRB) and gyrokinetic (GYRO, GS2, GENE) simulations.
- Agree qualitatively with QL theory.



Estrada-Mila, GYRO 05

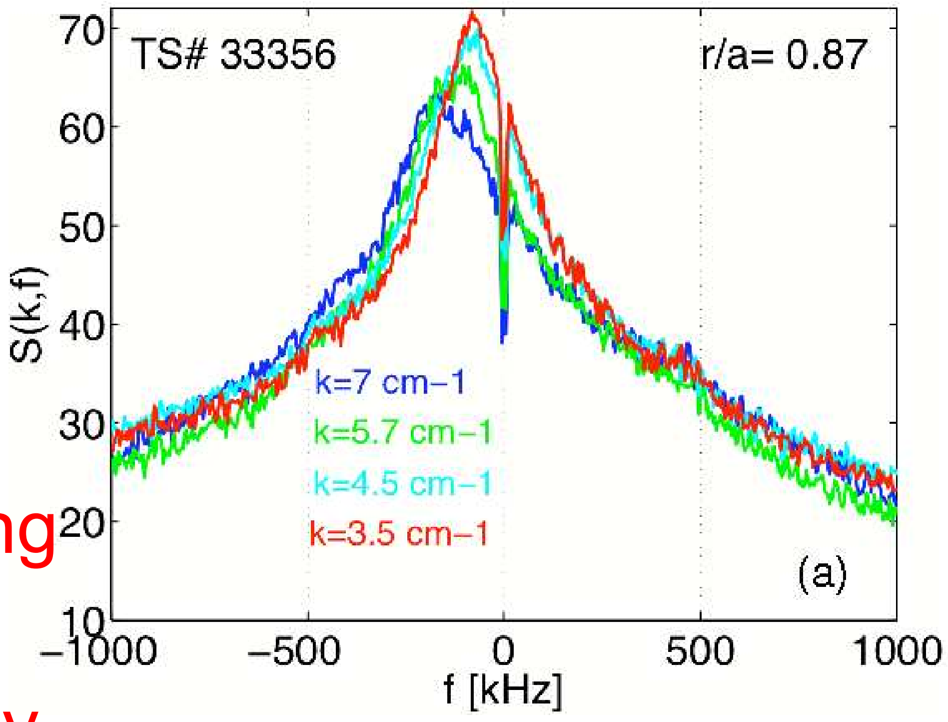
Phase velocity matters

- Fluctuation spectrum

$$|v_{E\mathbf{k},\omega}|^2 = \frac{|v_{E\mathbf{k}}|^2 \gamma_{\mathbf{k}}}{(\omega-\omega_{\mathbf{k}})^2+\gamma_{\mathbf{k}}^2}$$

Shifted resonance Broadening

- Shift $\omega_{\mathbf{k}}$ depends on the underlying instabilities: may change sign Conway 06 AUG.



Hennequin 06 Doppler reflectometry Tore Supra

Thermodiffusion

Coppi &Spight 78, Tang 86, Waltz & Dominguez 89,
Terry 89, Nordman et al. 90

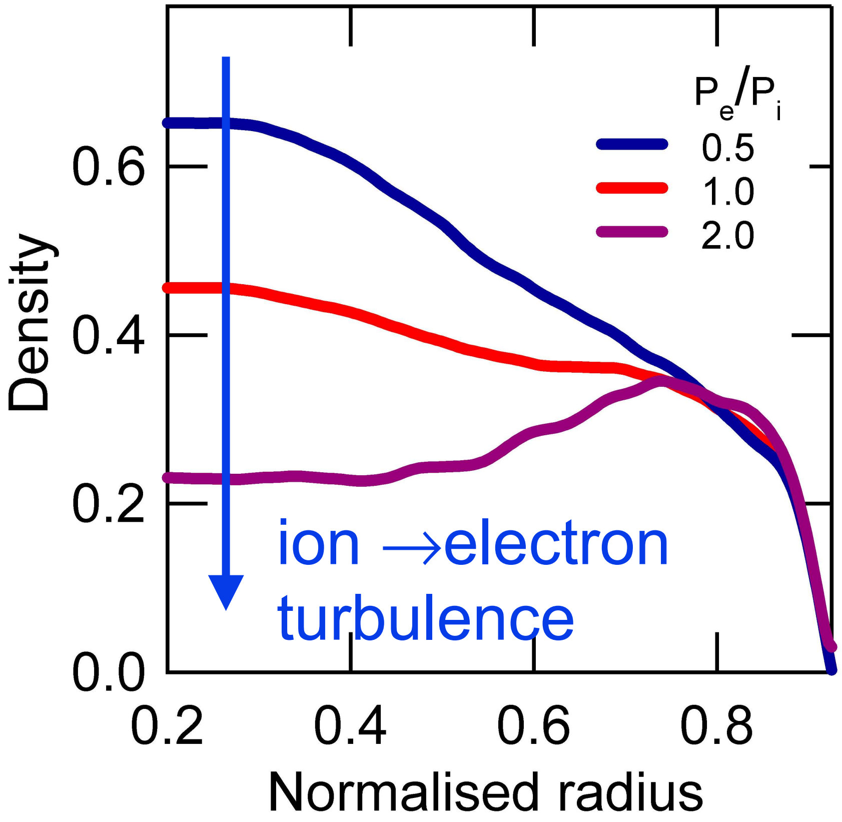
- Trapped particles

$$\frac{VR}{D} \approx \frac{\omega_{\mathbf{k}}\omega_{dt}}{\gamma_{\mathbf{k}}^2}\left(\frac{-R\partial_r T}{T}\right)$$

directed outward if turbulence driven by species with same charge, scales as 1/Z.

- Contribution from passing particles (Jenko 00, Hallatschek & Dorland 06)- still debated.

Garbet TRB 03



“Compressibility” term

- Trapped particles Isichenko, Gruzinov & Diamond 96 , Baker & Rosenbluth 98, Garbet 03

Inward curvature pinch

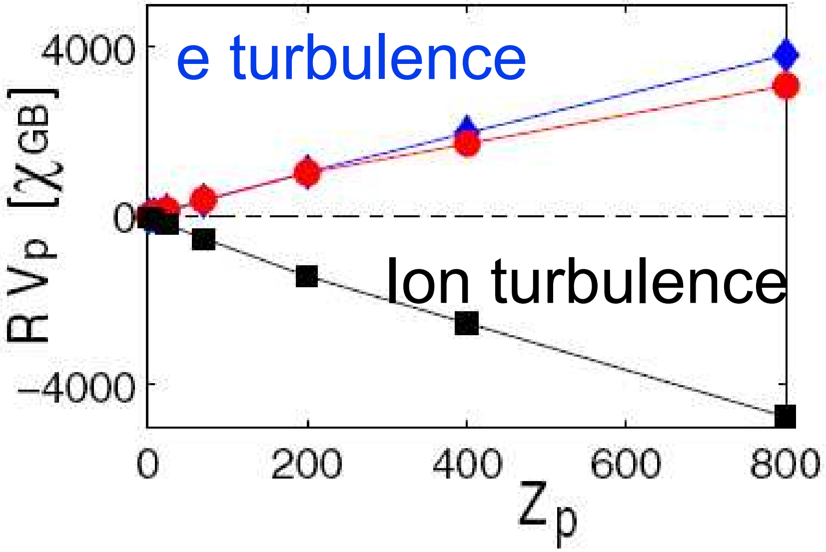
$$\frac{VR}{D} = -\left(\frac{1}{2}+\frac{4s}{3}\right) \quad ; \quad s = \frac{rdq}{qdr}$$

- Passing ions

$$\frac{VR}{D} \approx -C_{\perp}(s) - C_{//}\frac{\omega_{\mathbf{k}}}{\omega_d}\left(\frac{k_{//}v_T}{\gamma_{\mathbf{k}}}\right)^2$$

Inward for ion turbulence, scales as Z/A

Angioni & Peeters 06



- What is the physical nature of the curvature pinch ? →TEP theory.

Turbulence EquiPartition Theory

- ExB convection in an inhomogeneous magnetic field

Yankov 94, Nycander & Yankov 95, Isichenko & Yankov 97, Naulin 98.

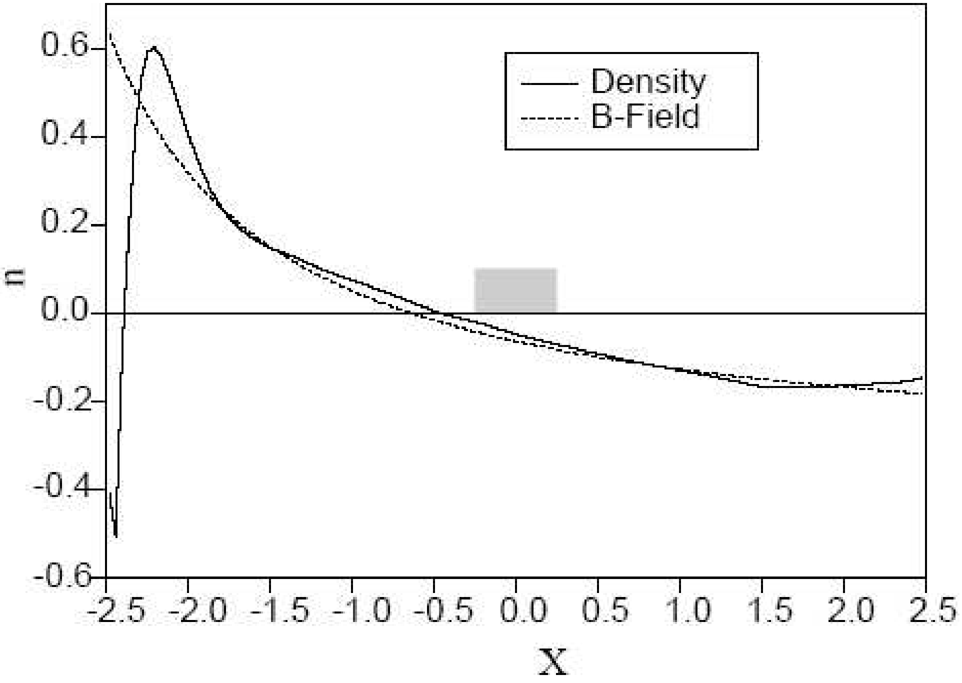
$$\partial_t n + \nabla\cdot(n\mathbf{v_E}) = 0 \quad ; \quad \mathbf{v_E} = \frac{\mathbf{B}}{B^2}\times\nabla\phi \quad ; \quad \nabla.\mathbf{v_E} \neq 0$$

- Equivalent to an advection of n/B

$$(\partial_t + \mathbf{v_E}\cdot\nabla)\left(\frac{n}{B}\right) = 0$$

- Turbulence mixing → relaxation towards the canonical profile $n_{can}=B(x)$

Naulin '98

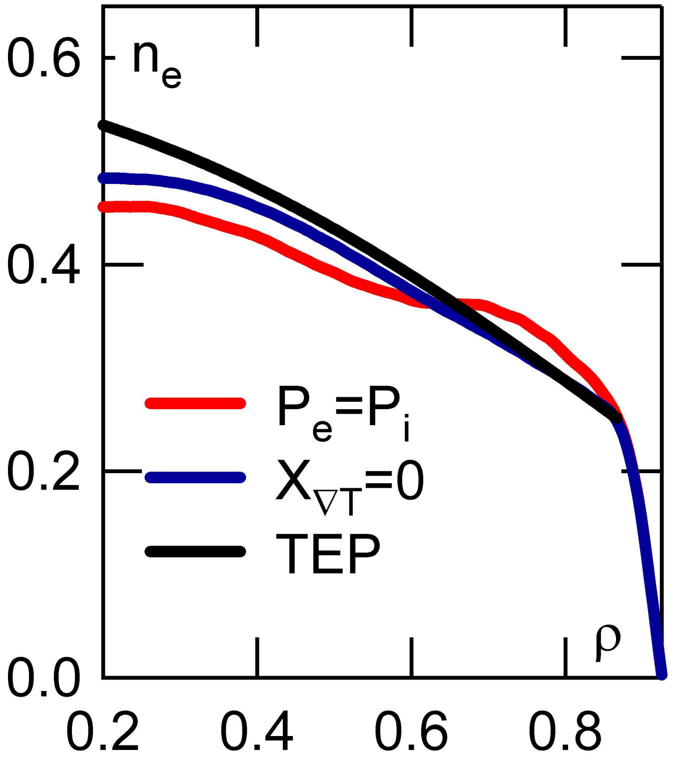


Kinetic TEP applied to tokamak plasmas

- Diffusion in space of motion invariants: flow is compressible.
- Application to trapped electrons Isichenko, Gruzinov & Diamond 96 - Baker & Rosenbluth 98 : pinch velocity same as curvature pinch!
- Canonical profile depends on magnetic shear.
- Extension to toroidal momentum Hahm, this conference

$$\left(\partial_t + \mathbf{v_E} \cdot \nabla\right)\left(nV_{//} / B^3\right) = 0$$

Garbet 03 TRB



A unified formulation for test particles

- Particle and heat fluxes versus gradients Garbet 05

$$\begin{pmatrix} \Gamma / \bar{n} \\ Q / \bar{n}\bar{T} \end{pmatrix} = -\begin{bmatrix} D & D_{\nabla T} \\ D_{\nabla T} & \chi \end{bmatrix} \cdot \begin{pmatrix} \partial_r \bar{n} / \bar{n} \\ \partial_r \bar{T} / \bar{T} \end{pmatrix}$$

- Thermodynamical forces are gradients of density and temperature normalised to canonical values

$$\bar{n} = \frac{n}{n_{can}} \qquad \bar{T} = \frac{T}{T_{can}}$$

- Entropy production rate >0, matrix is symmetric: Onsager symmetry.

Collisions reduce the peaking factor

- Collisions stabilise TEM

Kadomtsev 70, …, Dannert & Jenko 05

$$\nu_{\mathrm{eff}} = \frac{R}{r}\,\frac{\nu_{\mathrm{ei}}}{\omega_{\mathrm{dte}}} > 1$$

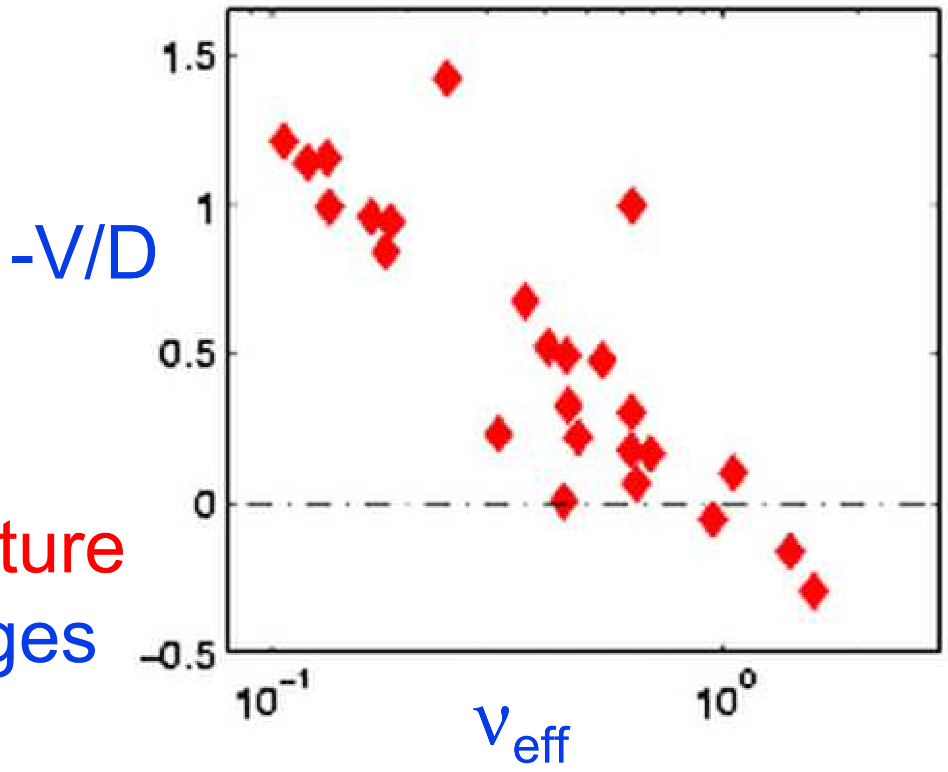
- Resonance broadening

$$\rightarrow \qquad \frac{VR}{D} \approx \frac{1}{\nu_{\mathrm{eff}}}$$

- Very sensitive to temperature gradient : threshold changes

Estrada-Mila 05

Angioni 03 GLF23



A short summary

- Magnetic shear controls curvature pinch.
- P_e/P_i controls TEM vs ITG → sign of $\langle \omega_{\mathbf{k}} / \omega_d \rangle$
- Collisionality controls $\langle \omega_{\mathbf{k}} / \omega_d \rangle$, decreases ratio V/D.

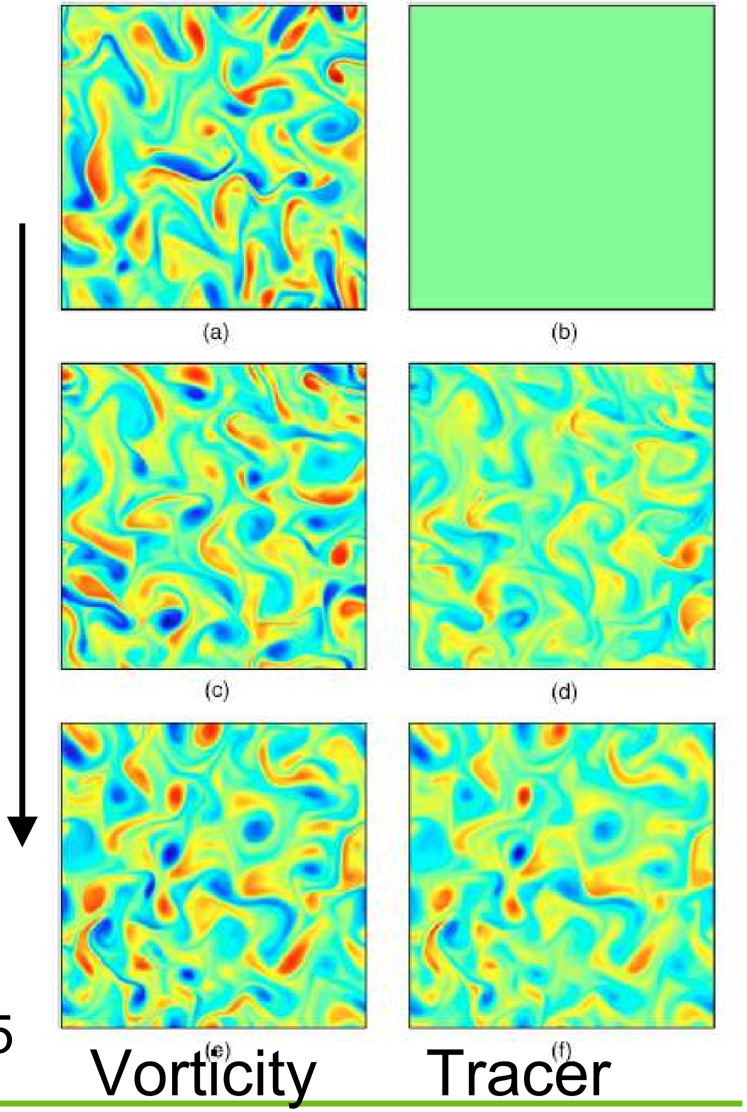
$$\frac{VR}{D} = -C_{\mathrm{comp}}\left(s,\frac{\omega_{\mathbf{k}}}{\omega_d}\right) + C_{\nabla T}\left\langle \frac{\omega_{\mathbf{k}}\omega_d}{\gamma_{\mathbf{k}}^2}\right\rangle \left(\frac{-R\partial_r T}{T}\right)$$

Compressibility: ⊥ component is inward - // component is inward when $\omega_{\mathbf{k}}\omega_d>0$, ≈Z/A.

Thermodiffusion outward when $\omega_{\mathbf{k}}\omega_d>0$, ≈1/Z

Beyond the quasi-linear theory

- Fractional kinetics Castillo del Negrete 05 or CTRW Van Milligen 04.
- Mode coupling effect for TEM turbulence Terry 06
- “Ratchet” effect Vlad 06 : same as curvature pinch?
- Turbulent mixing: relation between passive scalar and vorticity transport Priego 05 , Benkadda 06.



Priego 05

Part III: comparison theory/experiment

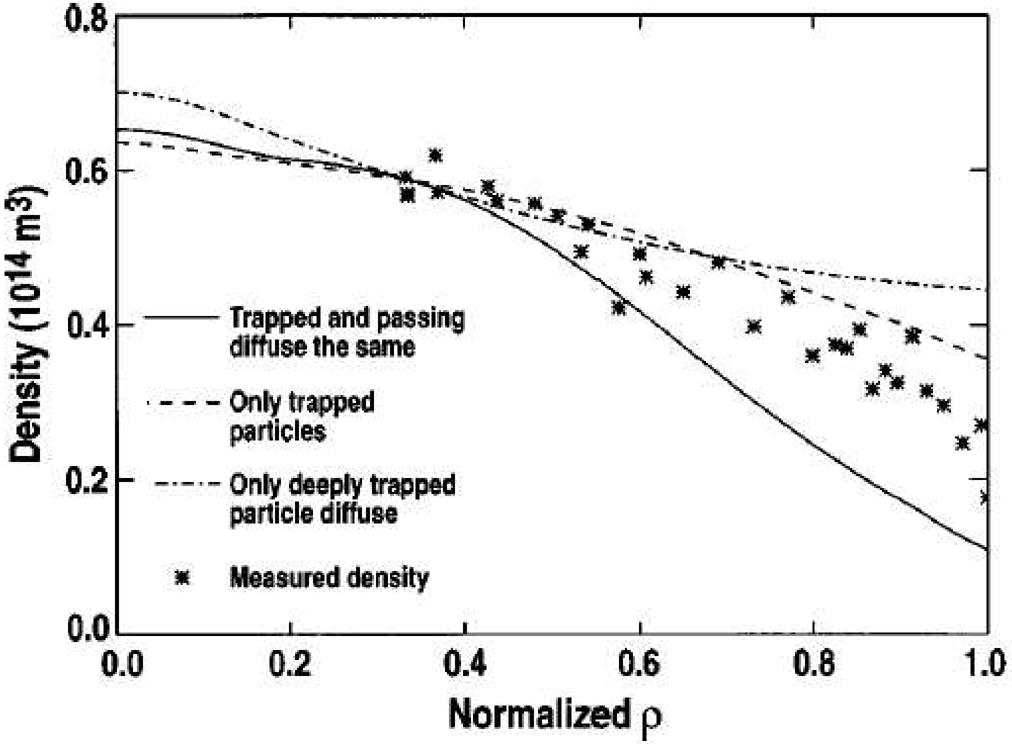
- Particle transport
  - - dependence on magnetic shear
  - - effect of collisions
  - - reversal of pinch velocity
- Impurity transport
  - - scaling with Z
  - - effect of heating
  - - reversal of pinch velocity

Density and safety factor profiles are correlated in L-mode

→ density and q profiles are correlated in L-mode DIII-D Baker 98, TCV Zabolotsky 03, JET Weisen 04, Tore Supra Hoang 04…

→ Traces back to “profile consistency” Coppi 80

→ correlation not found in JET H-mode plasmas!



Baker 98 DIII-D

Density profiles are peaked at low collisionality in H-mode

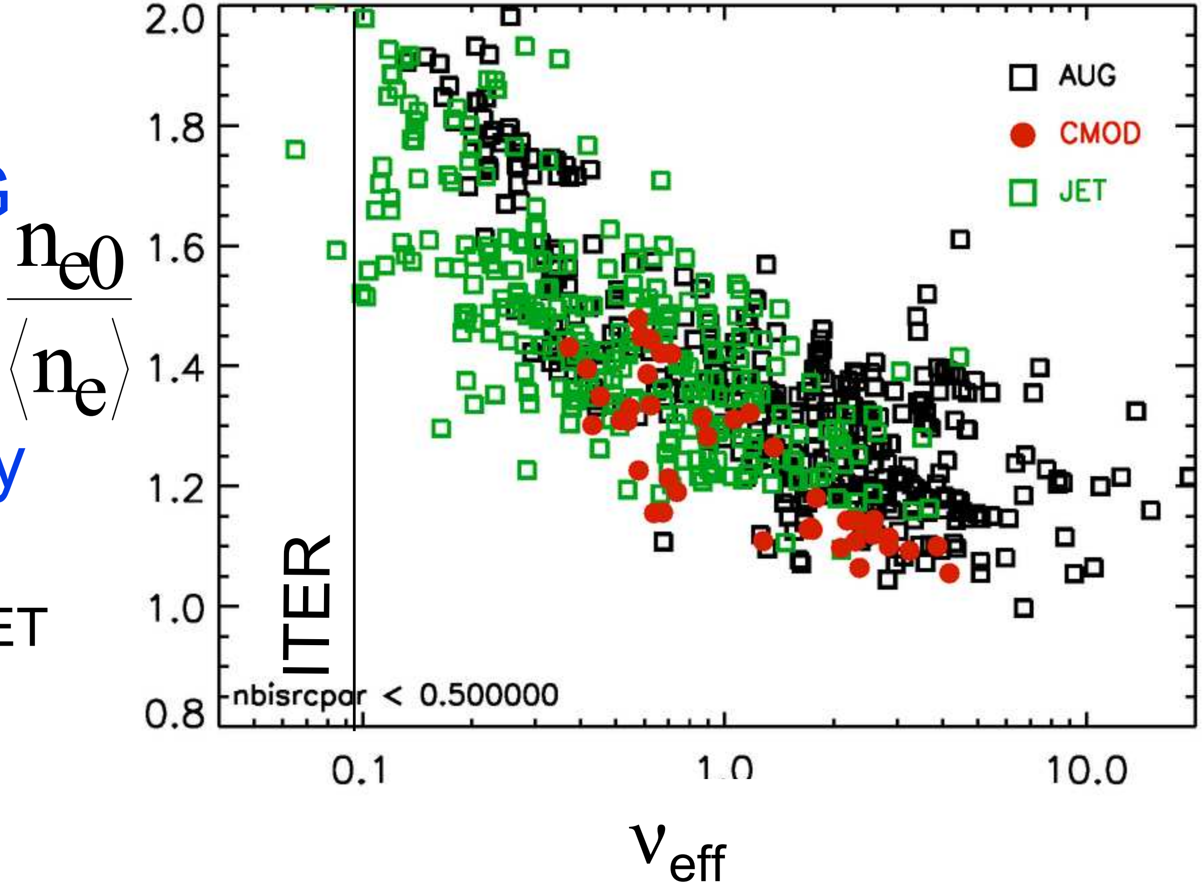
- V/D decreases with collisionality.
- Consistent with observations on AUG JET, and Alcator C-Mod (RF only).
- At large collisionality $V_{turb} \approx V_{ware}$

Stober 01 AUG, Valovic 00 JET

- Prediction for ITER

$$\frac{n_{e0}}{\langle n_e \rangle} \approx 1.5$$

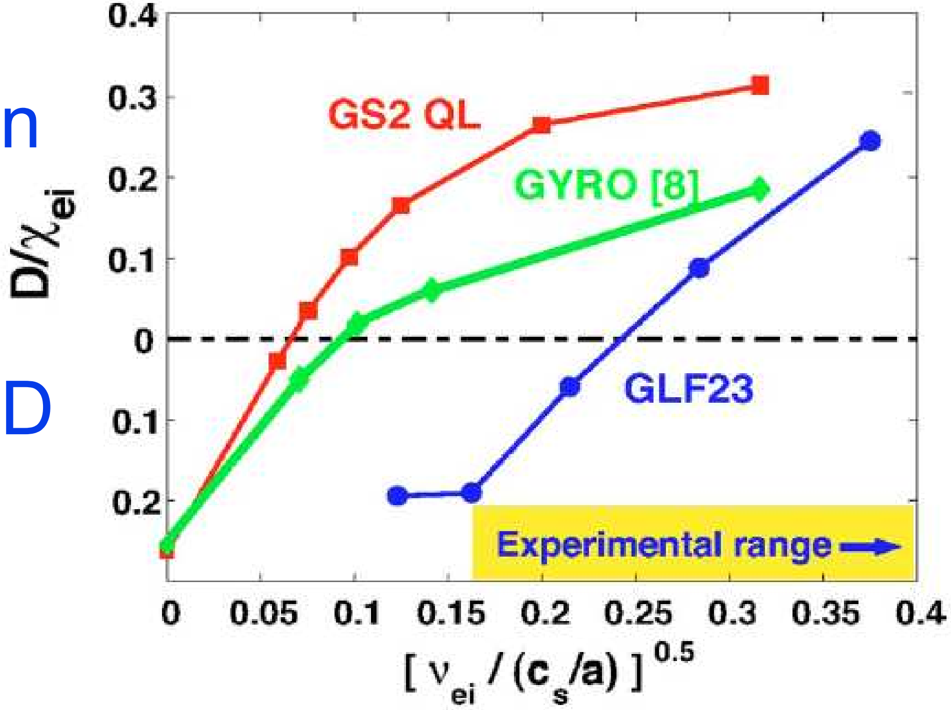
Angioni & Weisen 06, Greenwald 07



Effect of collisions: a hot debate…

- Experiment agrees with GLF23 prediction.
- Strong reduction of V/D in gyrokinetic simulations due to ν_{eff} .
- Agreement found in DIII-D using GYRO Estrada-Mila 06
  → realistic parameters.

Angioni 05



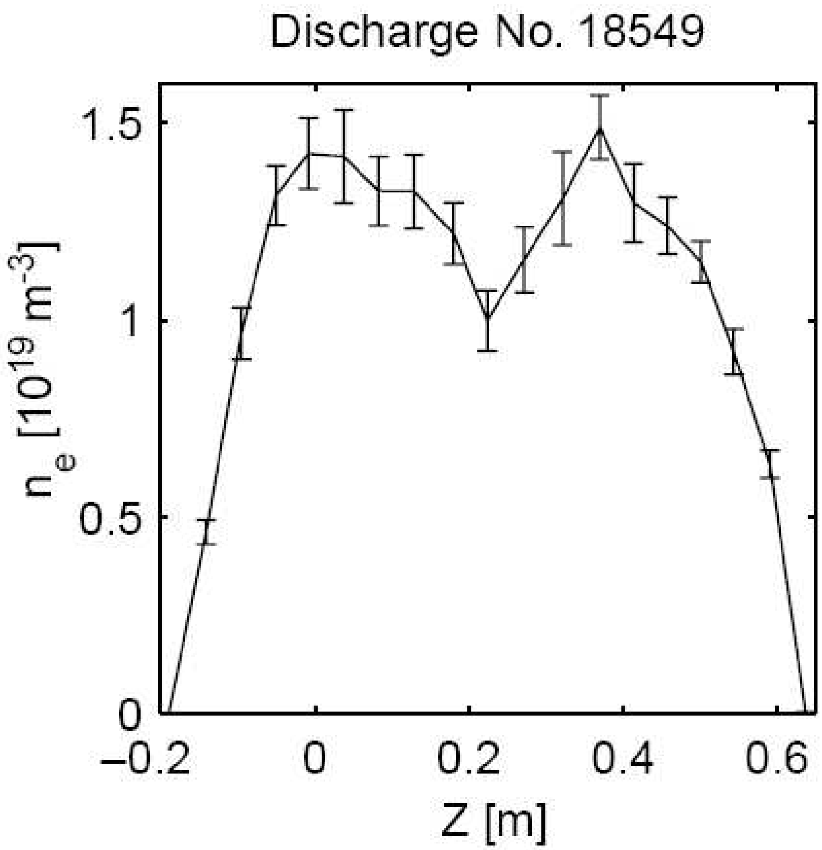
- Important issue for extrapolation to ITER.

Reversal of pinch velocity

- Thermo-diffusion changes sign when increasing $\nabla T_e/\nabla T_i$.
- May explain particle « pump-out » with ECRH at low density (RTP, TCV, AUG): TEM dominant

Angioni 05.

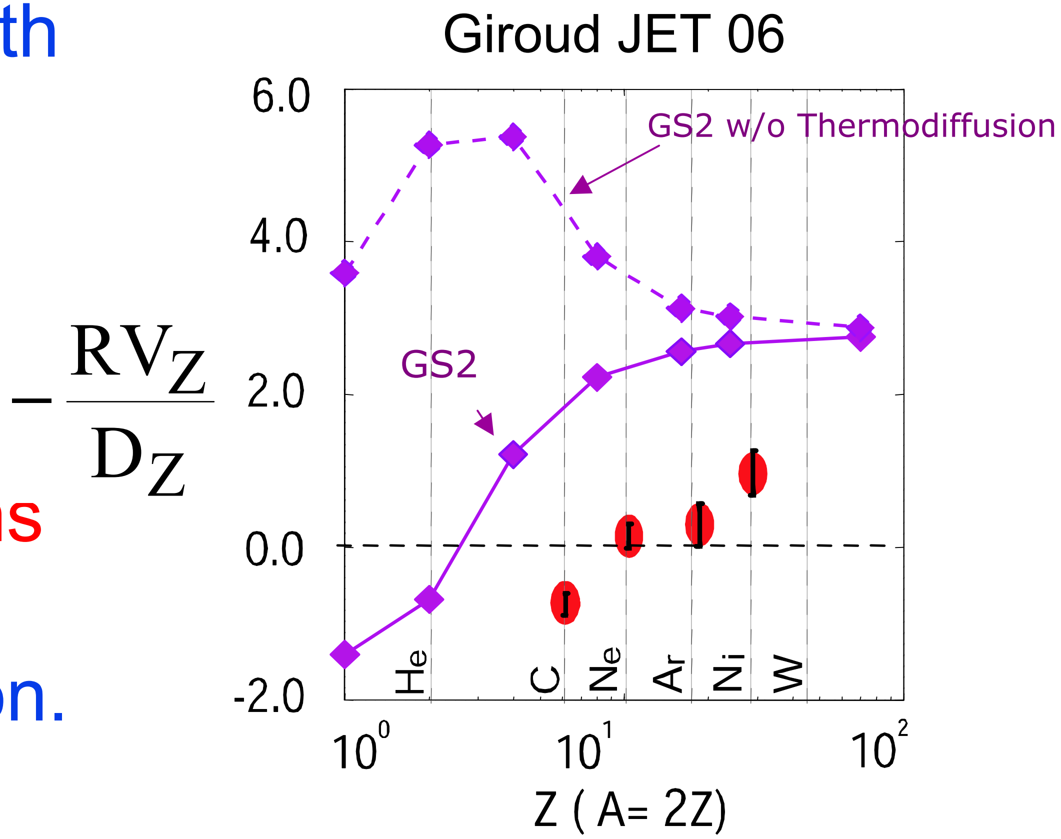
- At higher densities, rather due to a V/D decrease.



Weisen 01 TCV ECCD

Scaling with charge number

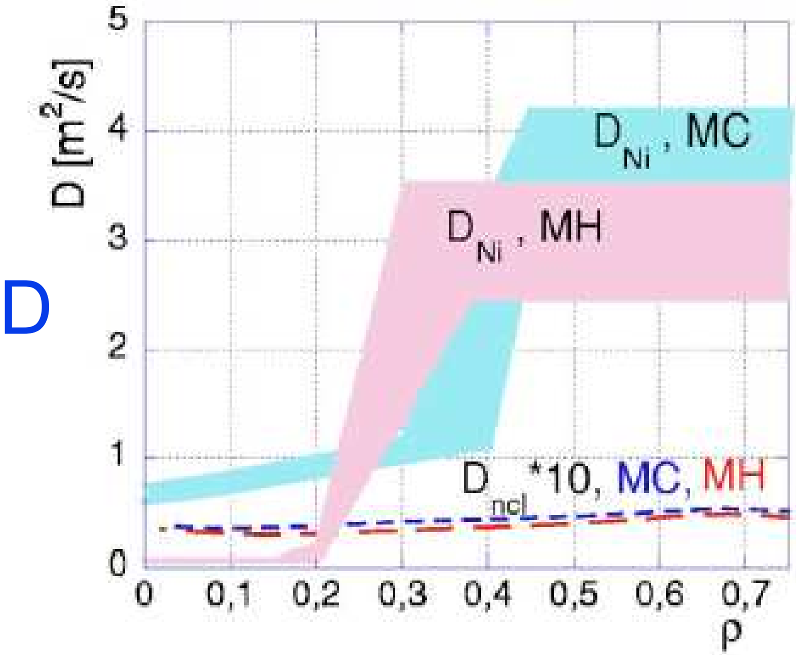
- VR/D changes sign with Z in JET plasmas.
- Qualitative agreement with gyrokinetic QL calculations.
- Thermodiffusion seems too small to provide a satisfactory explanation.



Effect of heating on impurity transport

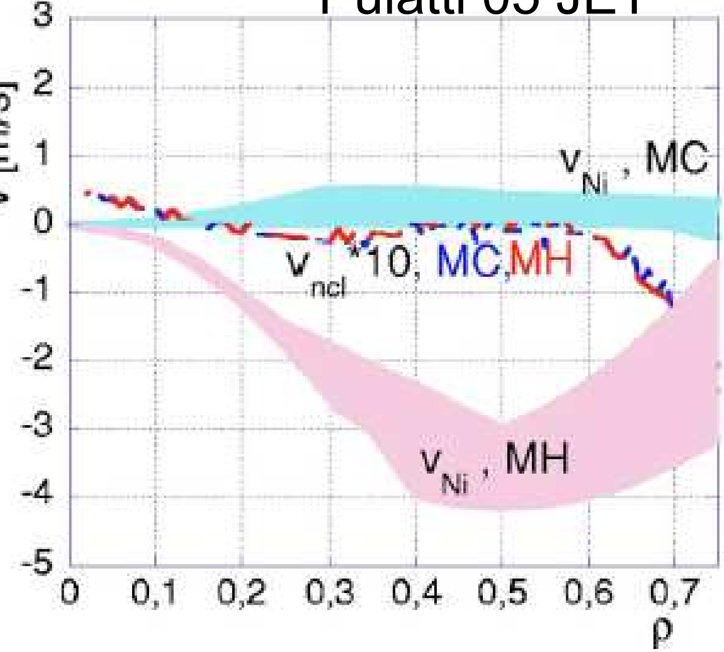
- Central heating enhances D_{imp} : reduces impurity content . Textor Van Oost 95, AUG Dux 03, DIII-D Doyle 02.
- Effect of electron heating : reversal of pinch velocity - interpreted as an effect of parallel compressibility.

D



V

Puiatti 05 JET

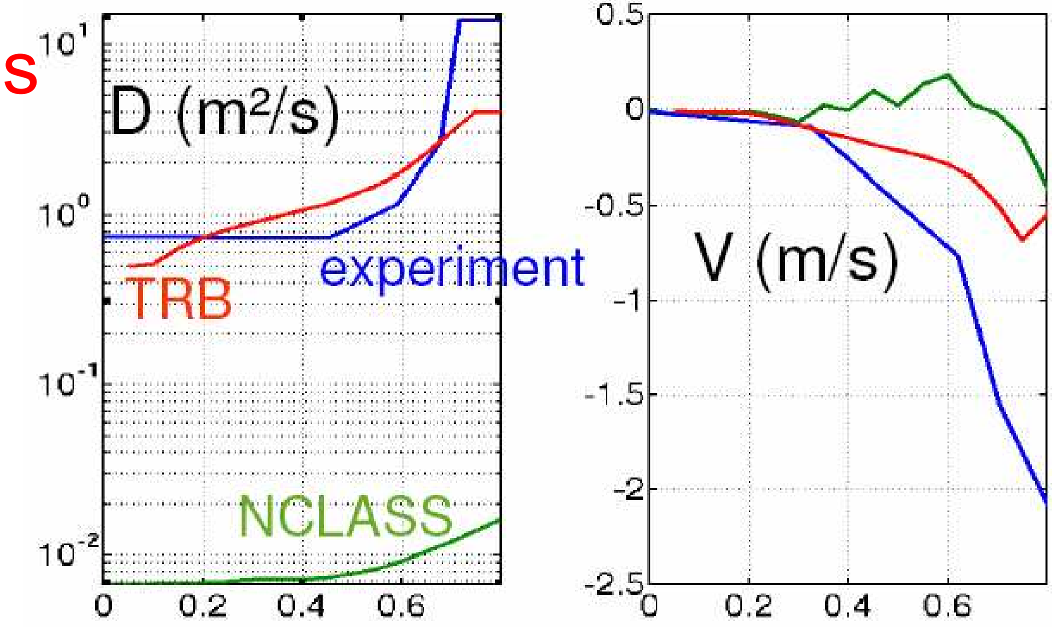


Direct comparison between turbulence simulations and measurements is in its infancy.

Budny 04 GS2, Budny 06 GYRO, Estrada-Mila 06 GYRO

- Usually profiles of D,V agree, but values are different .
- Reasons: error bars, sensitivity to gradients (stiffness), missing physics?

Parisot & Dubuit 06 Tore Supra



Conclusions

- Simulations are globally consistent with the quasi-linear theory. Does not fully exclude other effects.
- QL theory: pinch velocity is a combination of compressibility effects and thermodiffusion.
- QL theory is consistent with TEP theory - 2nd principle is safe!
- Pinch velocity may change sign. Related to the sign of the phase velocity.
- Experimental results are qualitatively in agreement with theory. However many discrepancies remain.

Open issues - Theory

- Why quasi-linear theory seems to work that well? Evidence of non QL effects?
- TEP theory: tested in fluid turbulence. Does it work in kinetic turbulence?
- Effect of collisions: seems stronger than expected. Difference between transport models (e.g. GLF23, Weiland) and gyrokinetic simulations? Discrepancy with expt? Very important for ITER.
- Need direct comparison between fixed flux gyrokinetic simulations and experiments.

Open issues - Experiments

- Error bars tend to be large. Usually no direct measurements of the ionization sources are available.
- Effect of magnetic shear: observed in L-mode, but not in H-mode. Why?
- Effect of β : was observed at JET (trace T expts): explanation?
- Impurity transport: scaling of D and V with Z still unclear. Effect of e-heating is controversial.
- Prediction for ITER based on present knowledge

$$\frac{n_{e0}}{\langle n_e \rangle} \approx 1.5$$

Angioni & Weisen '06 Degree of confidence?