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Isotope dependence of energy, momentum and particle confinement in tokamaks

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Overview

Motivation
What are ‘isotope effects’?

Some experimental results (non-JET-ILW)

JET-ILW isotope experiments

global confinement in H-mode (energy, momentum, particles)
Impact on multi-machine scaling
Isotope effect on pedestal
L-modes
Isotope identity experiments
Mixed species experiments

Overview of species-dependent transport physics

Physics based modelling
Relevance of isotope effects in predictive modelling (JET DTE2)
Conclusion: Validation challenges

Motivation: Why study ‘isotope effects’ on transport?

- Current devices mostly in D → ITER, reactor in D-T mixtures
- Bewildering range of results, $\tau_E \propto A^0$-$A^{0.9}$ (A atomic mass number)
  ⇒ potentially significant impact on D-T fusion power
  - looks non GyroBohm or anti-GyroBohm
  - not robust, like I_p and size scaling
- Unseparable part of transport physics:
  - Isotope effects are not ‘in addition to’ known (or unknown) transport physics
  - Most transport processes / key parameters have Z and A dependencies, as do heat transfer processes
  - Changing A simultaneously affects all or most of them
  - Outcome of any experimental isotope scan is an ‘apparent mass scaling’, depends on on the balance of these processes, how they interact non-linearly, locally and globally.
- As a result of a multiplicity of transport processes depending on A, ‘isotope scaling’ is circumstantial, i.e. depends on the particular situation and experimental context.
- **⇒ Understanding transport in H, D, T and mixed plasmas is one of our most challenging tests for understanding plasma transport altogether**

What are ‘isotope effects’ ?

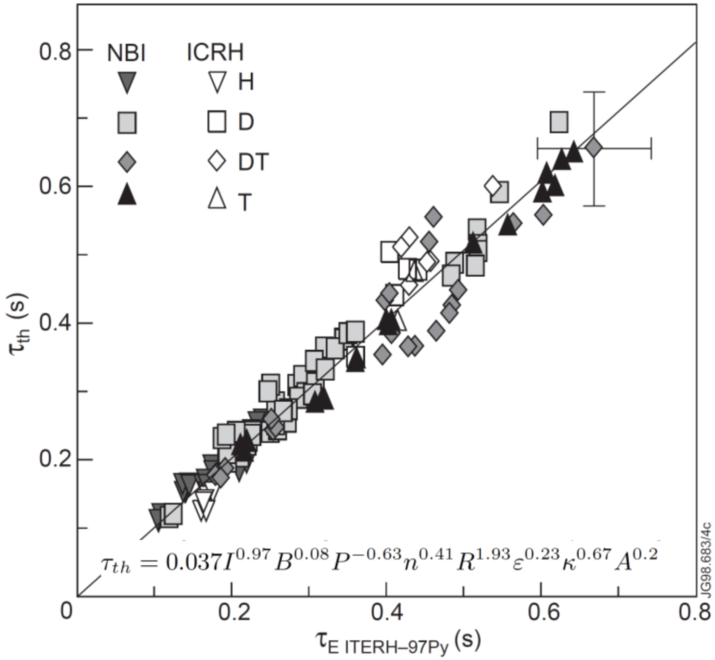
- Fundamental parameters depending on A change simultanously when changing plasma species:

  $v_{th} \propto A^{-1/2}$, $\rho_i \propto A^{1/2}$, $\nu_{ei} \propto A^{0}$, $\nu_{ii} \propto A^{-1/2}$, $v_{Alfven} \propto A^{-1/2}$

- Physics effects: kinetic electrons, collisions, electromagnetic effects, ExB shear effects… affect plasmas with different ion species differently

- Operational effects (not transport effects):
  - NBI & ICRH : Q_{is}/Q_{ie} depends on A_{fast}, E_{fast}, T_e
    Different ICRH scenarios in H, D, T
  - Power/torque/particle source ratios depends on A
  - Equipartional heat exchange depends on A
  - Cryopumping efficiency depends on A (affects edge/pedestal)
  - Edge neutral penetration higher at low A
  - Orbit losses lower at low A (for same E_f)
  - …?
- Caveat: Operational effects can obscure the ‘pure’ transport effects and make unambiguous identification of genuine transport effects difficult.

Some experimental findings: JET-C, DTE1, 1997

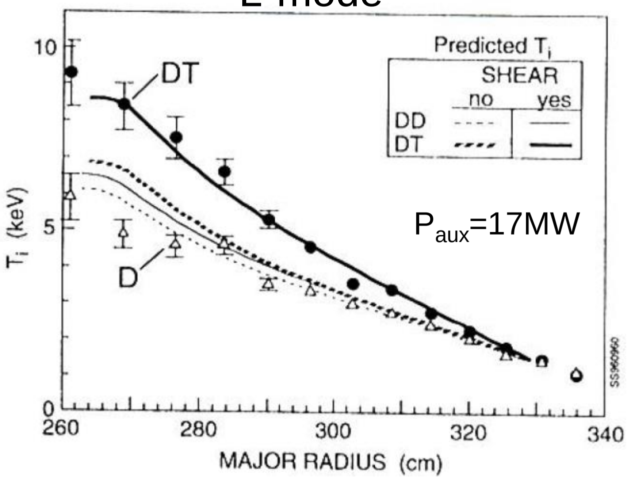


- ELMy multi-machine isotope scalings from 1992[1]. $\tau_E \propto A^{0.4}$ with data from 6 devices[1]
- IPB97(y,2) [ref2,3] for ELMy H-mode $\tau_E \propto A^{0.2}$, $\rightarrow$incorporated into IPB98(y,2) [ref4] with $\tau_E \propto A^{0.19}$
- IPB L-mode scaling $\tau_E \propto A^{0.19}$ similar to IPB98(y,2)
- IPB98 ELM-free scaling $\tau_E \propto A^{0.43}$ hints at importance of pedestal[2]
- Subset with matched pairs of similar pulses shows no isotope scaling [ref5]: $\tau_E \propto A^{0.03}$
- Two-term analysis [ref5] (pedestal+core) suggest strong pedestal $\tau_E \propto A^{0.96}$ and negative core scaling, implying R/L_T depends on species
- **Note: given the large range of exponents, we should not consider expressions like $\tau_E \propto A^x$ as scaling 'laws', but just as indicators for the strength of the isotope effect observed in a particular experiment or analysis**

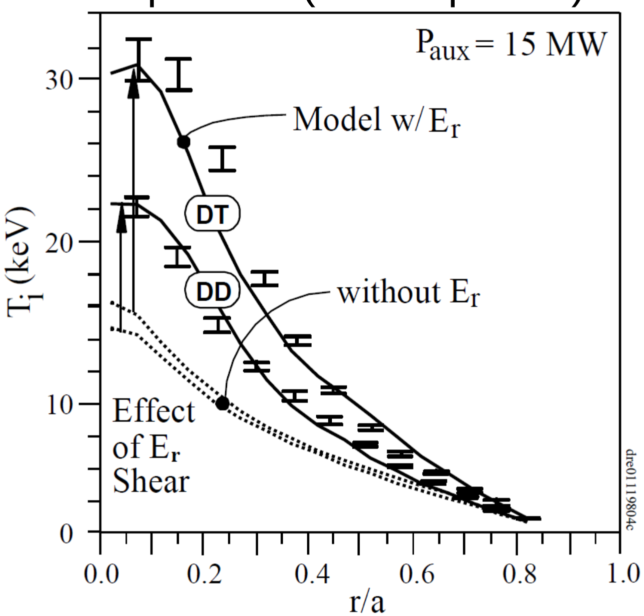
[1] H-mode database WG, Plasma Physics & Controlled Nuclear Fusion Research, 14th IAEA Würzburg 1992
[2] JET Team,1999 Nucl. Fusion 39 1227
[3] G. Saibene 1999 Nucl. Fusion 39 1133
[4] ITER Physics basis, NF 1999, chapter 2
[5] J.G. Cordey *et al* 1999 *Nucl. Fusion* 39 301

Some experimental findings: TFTR, mid-nineties

L-mode[1]



Supershot (with Li pellets)[3]



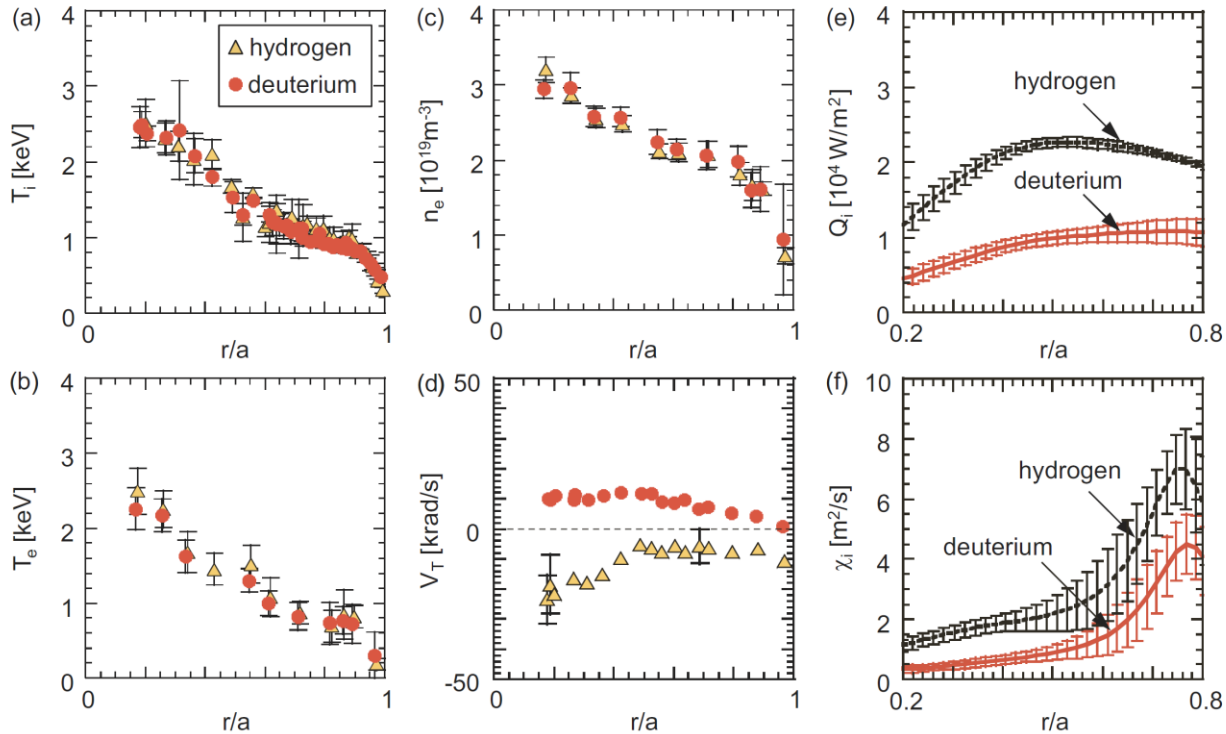
$I_p \leq 3MA$, $B_T \leq 6T$, $R_0 \cong 2.4m$, $a \cong 0.8m$, $P_{NBI} \leq 40MW$

- Ohmic plasmas[1]:
  no discernible isotope scaling between D and DT mixture $\tau_E \propto A^0$, but D plasmas had slightly ($\leq$10%) higher τ_{EOhmic} than H plasmas
- L-mode [ref1,2] scaling $\tau_E \propto A^{0.5\text{-}0.6}$, reduces to $\tau_E \propto A^{0.4}$ when alpha heating included in power balance[1,2]
- Supershots were obtained following Li pellet injection, which provided transient wall pumping and access to low edge densities, very peaked profiles and sheared rotation.
  Supershot scaling [ref2,3]: $\tau_E \propto A^{0.85}$
- Shear flow stabilisation essential for understanding stronger isotope effect at higher power/rotation[1,3]

[1] Scott IAEA-CN-64/A6-6, 573 [2] Scott PoP **2**, (1995) 2299
[3] Ernst PRL 81 (1998) 2454

Some experimental findings: JT60-U, 2013

- Identical T_i, T_e, n_e achieved in H and D, **provided P_{NB} in H 2x P_{NB} in D**

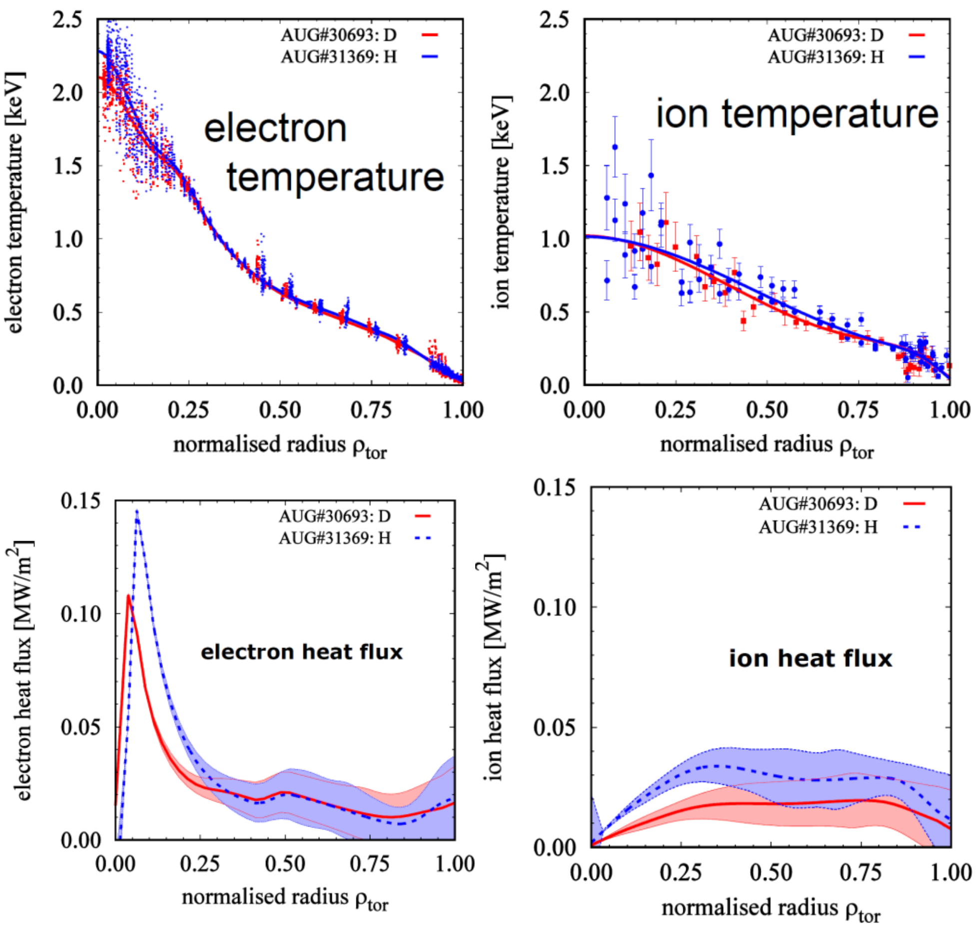


- Transport analysis shows discharges are ITG-dominated
- R/L_{Ti} about 20% less in hydrogen than in deuterium at same χ_i
- Differences: β_{fast} larger in Deuterium, more ripple losses in hydrogen (leading to counter-rotation)

H. Urano, Nucl. Fusion **53** (2013) 083003

Some experimental findings: ASDEX & AUG, 198?-2017

- ‘Old’ ASDEX: comprehensive study[1] already showed $\tau_E \propto A^{0.65}$ in H-mode
- AUG example[2], Electron heated L-mode (ECRH,T_e>T_i, but in ITG)
- T_e, T_i, n_e, ω_ϕ profiles match well in H and D, with P_H=1.4MW >P_D =1.06MW
- TRANSP analysis shows that net electron heat flux Q_e is same in H & D. The extra power in H is collisionally transferred to ions: Q_i ~2x larger in



$$p_{ie} = \sum_i c_{eq} \Lambda_{ie} \frac{Z_i^2}{A_i} \frac{n_i \cdot n_e}{T_e^{3/2}} (T_i - T_e)$$

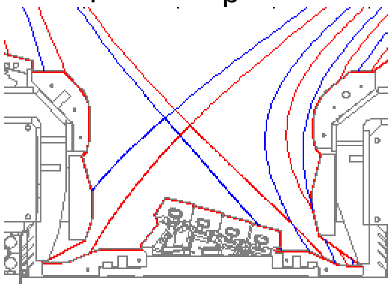
- ASTRA simulation using a critical gradient model[3]: The extra ion heat flux makes no difference to T_e and little difference to T_i
- ‘Isotope effect’ in this case[2] is down both to isotope dependence of equipartition, and to higher required ion heat flux in hydrogen

[1]M. Bessenrodt-Weberpals 1993 *NF* **33** 1205
[2]P.A. Schneider 2017 *Nucl. Fusion* **57** 066003
[3]Garbet X. 2004 *PPCF* **46** 1351

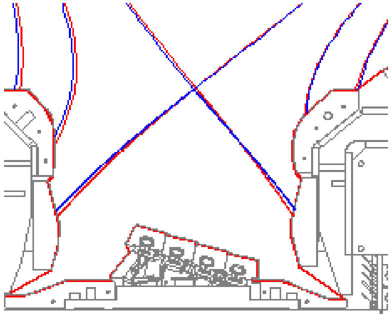
JET results: Isotope dependence of energy, momentum and particle confinement in JET-ILW

- **So far (to best of our knowledge) most comprehensive recent experimental effort to understand isotope effects in any tokamak**
- **Substantial and growing database in D and H**
- **Experimental design started in 2014/2015 to encompass Tritium and DT in 2020 (possibly He too)**

- **Deuterium & Hydrogen type I ELMy H-modes**, 171 samples B_T=1T, I_p=1MA ($q_{95} \cong 3$) and B_T=1.7T, I_p=1.4MA ($q_{95} \cong 3.7$)
  Mostly 'corner-corner (C/C)'
  Gas scans and power scans:
  Deuterium: 3.5MW≤ P_{NBI}≤17MW, only NBI
  Hydrogen: 5 MW≤ P_{NBI}≤10MW, 0 ≤ P_{ICRH}≤6.5MW
  Caveat: much worse particle confinement in H, few H/D pairs at same density



- **Deuterium & Hydrogen L-modes**, 20 samples
  B_T=2.9 T, I_p=2.5 MA, $\langle n_e \rangle \cong 3.1\times10^{19}m^{-3}$ NBI power scan only,
  20 samples,only NBI power scans 1.5MW≤ P_{NBI}≤9.5MW
  Divertor strike points on vertical tiles for highest P_{L-H}



Maggi PPCF 2018; Weisen IAEA 2018

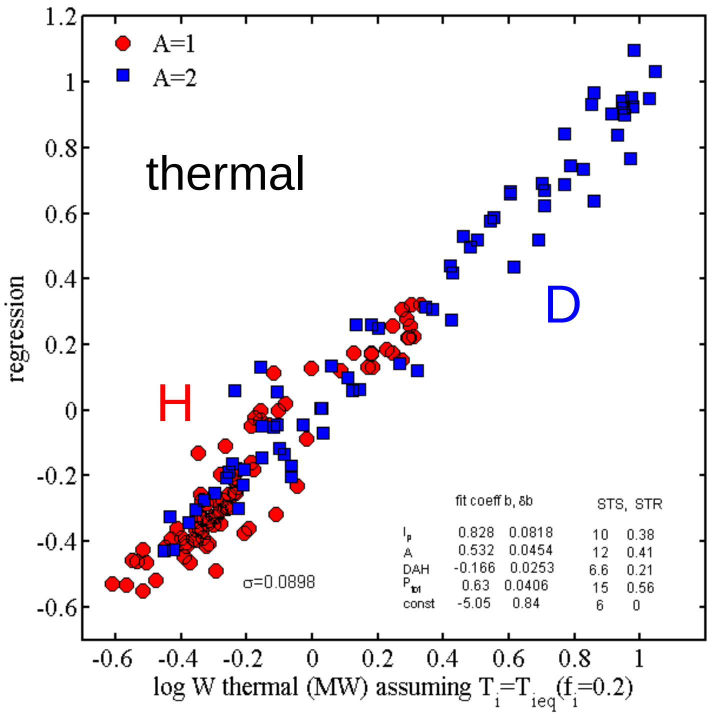
Isotope confinement in JET-ILW in type I ELMy H-modes

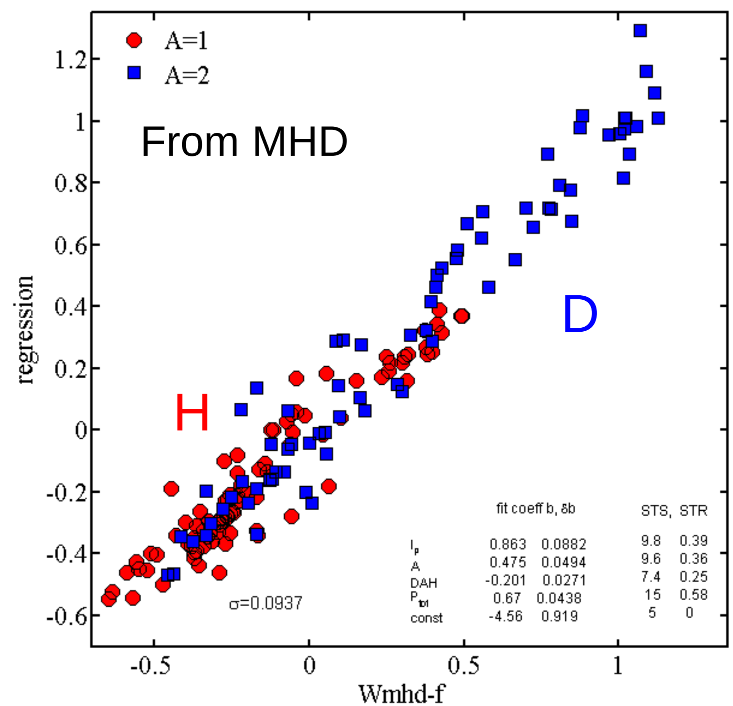
- Different regressions, using different assumption on T_i and regression parameters have yielded similar results $\tau_{Eth} \propto A^{0.4\text{-}0.5}$ in previous studies[1,2]
- Caveat: include $\langle n_e \rangle$, which is not a control parameter in JET Deuterium H-modes
- Instead we use proxies for edge particle source (Γ) from Balmer-alpha emission, together with heat source (P) and 2 confinement terms (A & I_p)

$$W_{th} \propto A^{0.53\pm0.05}\ I_p^{0.83\pm0.08}\ \Gamma^{-0.17\pm0.03}\ P^{0.63\pm0.04}$$

$$W_{mhd} \propto A^{0.48\pm0.05}\ I_p^{0.86\pm0.09}\ \Gamma^{-0.2\pm0.03}\ P^{0.67\pm0.04}$$

using proxy for T_i [2,3] corrected for fast ions





Much stronger than in JET-C!

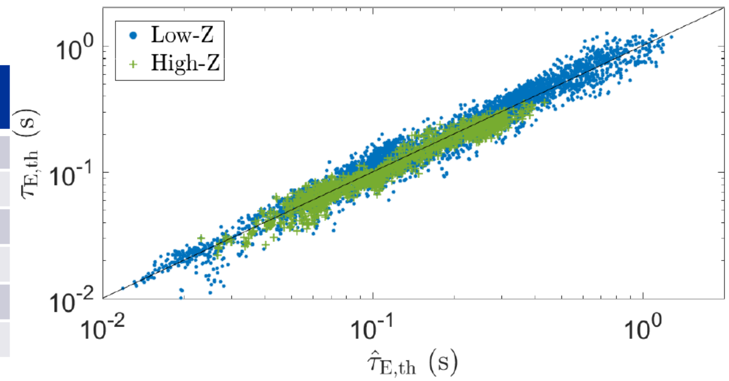
[1]Maggi, PPCF 2018
[2]Weisen IAEA 2018
[3]Weisen, NF subm.

Update to ITPA H-mode database and scaling

- Commonly used IPB98(y,2) has $\tau_E \propto A^{0.19}$ (ref 1)
- Revision[2], 2 decades after IPB98(y,2), includes isotope scan data from 'old' ASDEX, DIII-D, JET-C, **JET-ILW**, JFT-2M
- These devices individually have $\tau_E \propto A^{0.11}$ to $A^{0.78}$
- More refined data selection and regression methods than in 1998
- Several overall scalings (subsets, regression method and variables included), lead to a range of mass exponents, from $\tau_E \propto A^{0.1}$ to $A^{0.47}$

STD5 (ELMy + ELM-free)

Method	α_0	α_I	α_B	α_n	α_P	α_R	α_κ	α_ϵ	α_M	$\hat{\tau}_{10}$ (s)
OLS	0.049 ±0.002	1.1 ±0.02	0.085 ±0.020	0.19 ±0.02	−0.71 ±0.01	1.5 ±0.04	0.80 ±0.04	−0.043 ±0.046	0.25 ±0.03	2.7 ±0.1
WLS	0.040 ±0.002	0.99 ±0.03	0.11 ±0.02	0.29 ±0.02	−0.64 ±0.01	1.7 ±0.04	0.79 ±0.04	0.093 ±0.046	0.25 ±0.03	2.9 ±0.1
GLS	0.042 ±0.003	1.2 ±0.02	0.068 ±0.016	0.21 ±0.01	−0.78 ±0.01	1.6 ±0.03	0.88 ±0.06	−0.052 ±0.027	0.47 ±0.07	2.7 ±0.03

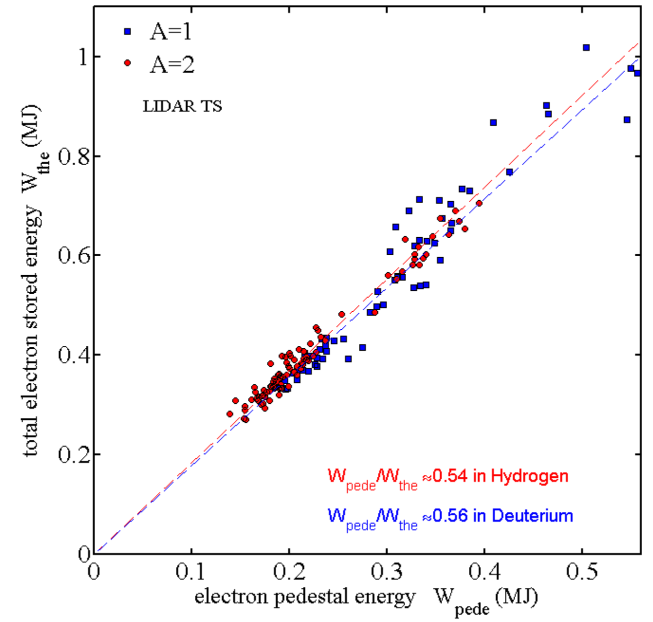


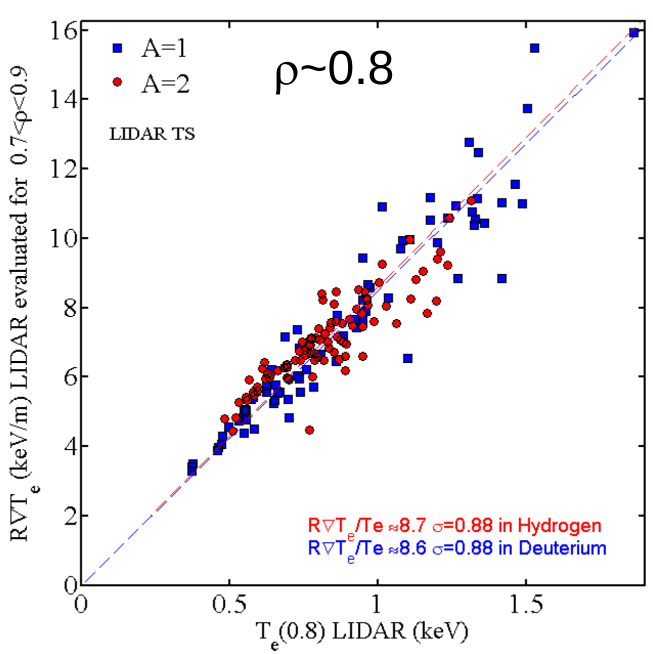
- **Isotope dependencies are poorly described by global multi-machine scalings!**

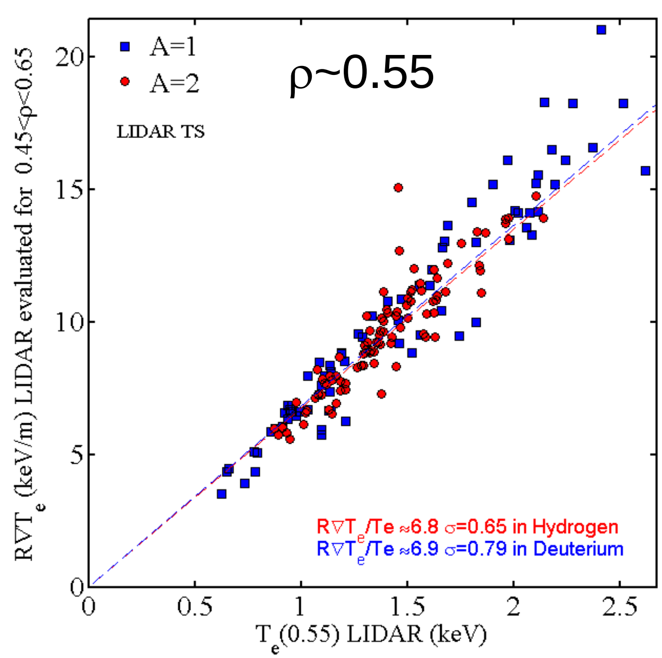
[1] ITER Physics basis, NF 1999, chapter 2 [2]Geert Verdoolaege, IAEA FEC 2018

Stiff temperature profiles: pedestal contribution to stored energy is constant

- We use $W_{pede}=1.5\, e\, n_e(0.9)T_e(0.9)\, V_p$ as a proxy for pedestal electron energy
- For each of the species, the ratio of electron pedestal to global electron stored energy is near constant for the whole dataset
- Consistent with profile stiffness:
  Global confinement reflects pedestal confinement
- W_{pede}/W_{the} and R/L_{Te} species-independent
  This is contrary to 2-term scaling from JET-C[1]





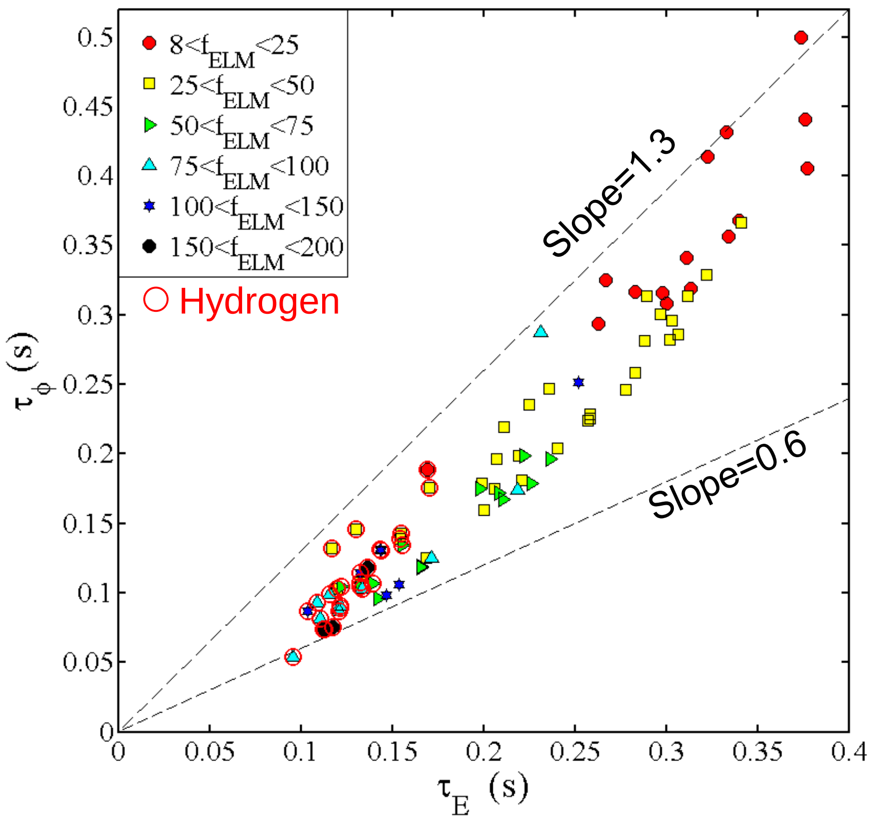


R/L_{Te} species-independent

[1]J.G. Cordey *et al* 1999 *Nucl. Fusion* 39 301

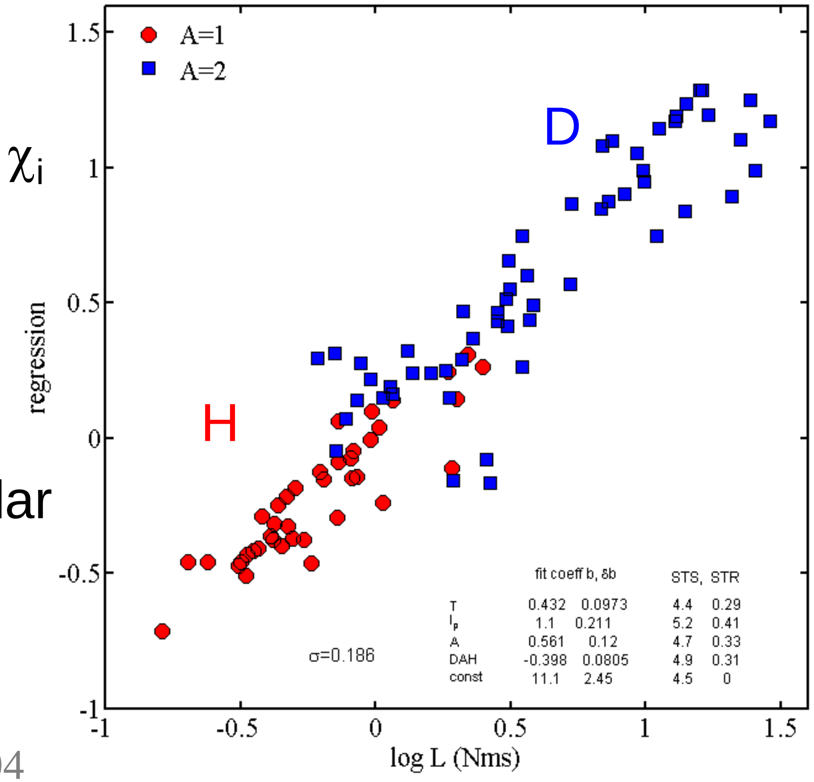
Momentum transport

- Momentum transport related to ion heat transport ($\chi_\phi \sim \chi_i$)
- Momentum in hydrogen much smaller than in Deuterium H-modes
- $0.6 < \tau_\phi / \tau_E < 1.3$ irrespective of species
- τ_ϕ / τ_E increases inversely with ELM frequency (and/or particle source, which anti-correlates with f_{ELM})



H-mode: Momentum confinement has strong dependence on isotope

- Large uncertainty in electron-to-ion equipartition prevents direct evaluation of χ_i and χ_e in most cases
- However momentum transport provides a direct indicator for transport in the ion channel
- Regression for angular momentum L similar to total thermal energy



$$L \propto A^{0.56\pm0.12}\, I_p^{1.1\pm0.21}\, \Gamma^{-0.4\pm0.08}\, T^{0.43\pm0.1}$$

$$W_{th} \propto A^{0.53\pm0.05}\, I_p^{0.83\pm0.08}\, \Gamma^{-0.17\pm0.03}\, P^{0.63\pm0.04}$$

- Significant, because momentum carried by ions only, no issue with equipartition with electrons:

⇒ strong mass scaling associated with ion transport (not electron transport)

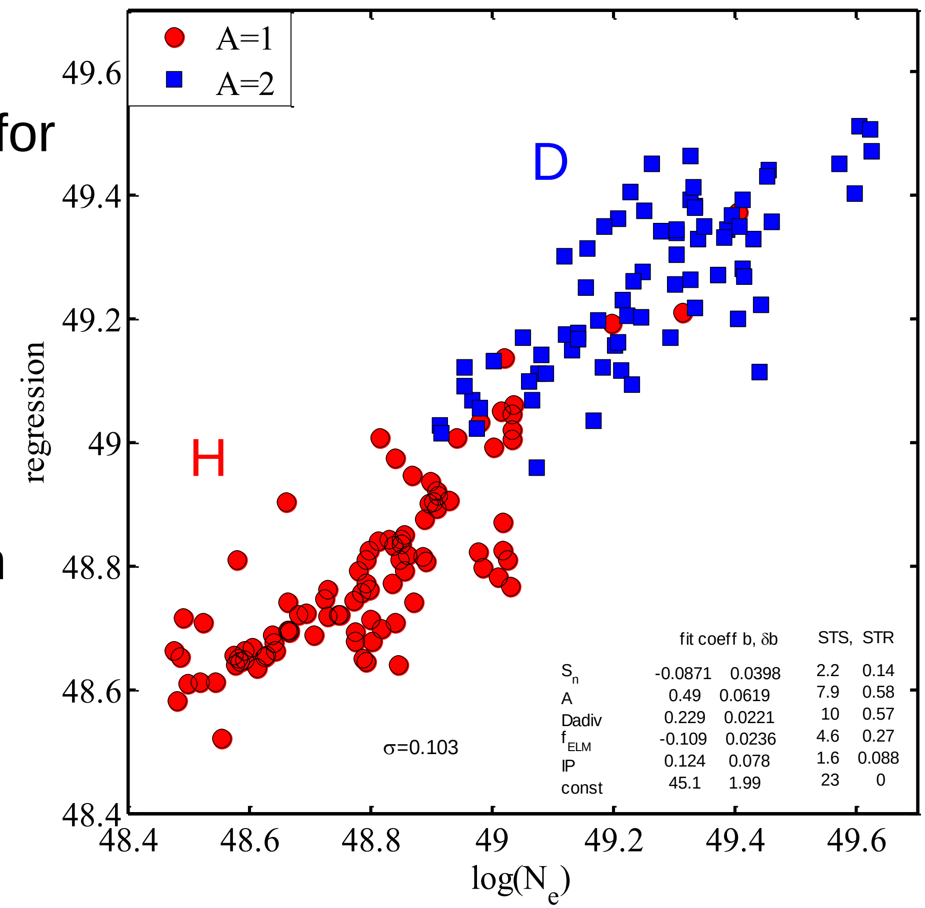
H-mode: particle confinement dependence strong

- $N_e = \int n_e dV$ total electron content
  Divertor Balmer-alpha Γ_{div} as proxy for edge source and NBI source S_{NBI}
- Regressions:

$$N_e \propto A^{0.49} \Gamma_{div}^{0.23} S_{NBI}^{-0.09} I_p^{0.12} f_{ELM}^{-0.11} \quad \text{or}$$

$$N_e \propto A^{0.68} \Gamma_{div}^{0.18}$$

- Strongest dependencies of N_e are on ion mass and divertor source
  I_p and power dependences weak or absent, core source influence weak…and negative! (likely reflects power effect)



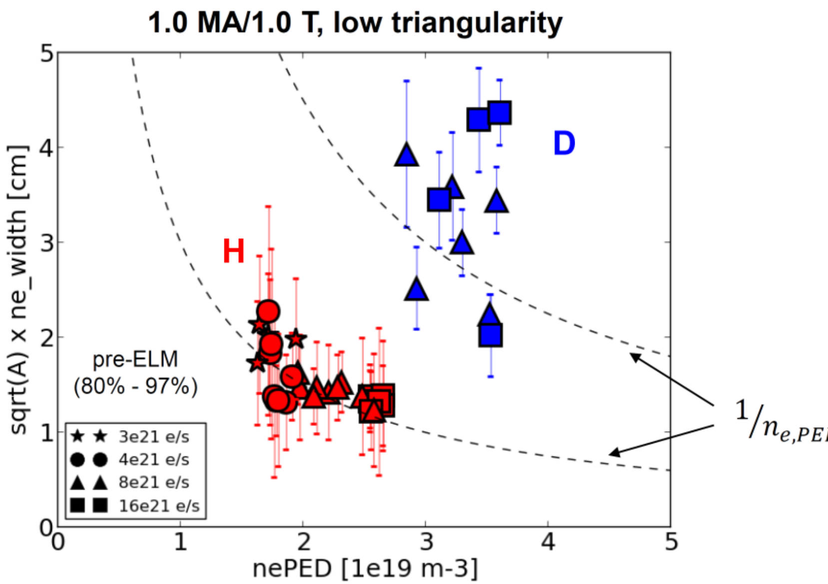
Energy, momentum & particle confinement have similar, strong isotope dependence

H modes: Pedestal widths not consistent with neutral penetration model

- The lower particle confinement in hydrogen is add odds with idea that the higher thermal velocity should make fuelling easier[1]
- ⇒ Transport more than overrides fuelling by neutrals
- Pedestal width model based on neutral penetration (Groebner 2002):

$$\Delta_{ne} \propto A^{-1/2}(T_{iped}/T_{eped})^{-1/2} n_{eped}^{-1}$$

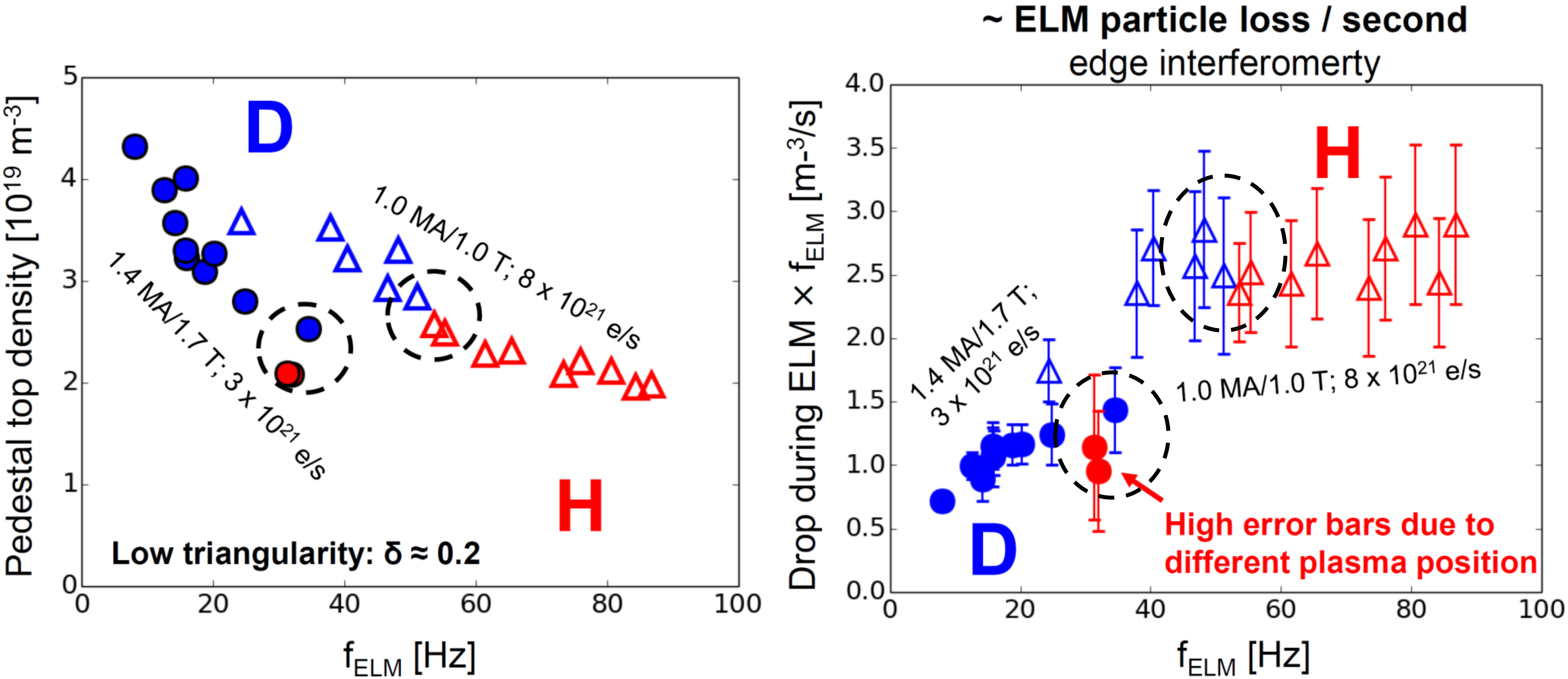
- This scaling is not followed anywhere in the dataset, even reversed at 1MA, 1T !
- Transport processes which override neutral penetral differences already at work in the pedestal!



[1]L. Horvath, submitted NF 2019
[2]Groebner PoP 2002

H-mode: ELMs alone cannot explain differences in density between H and D

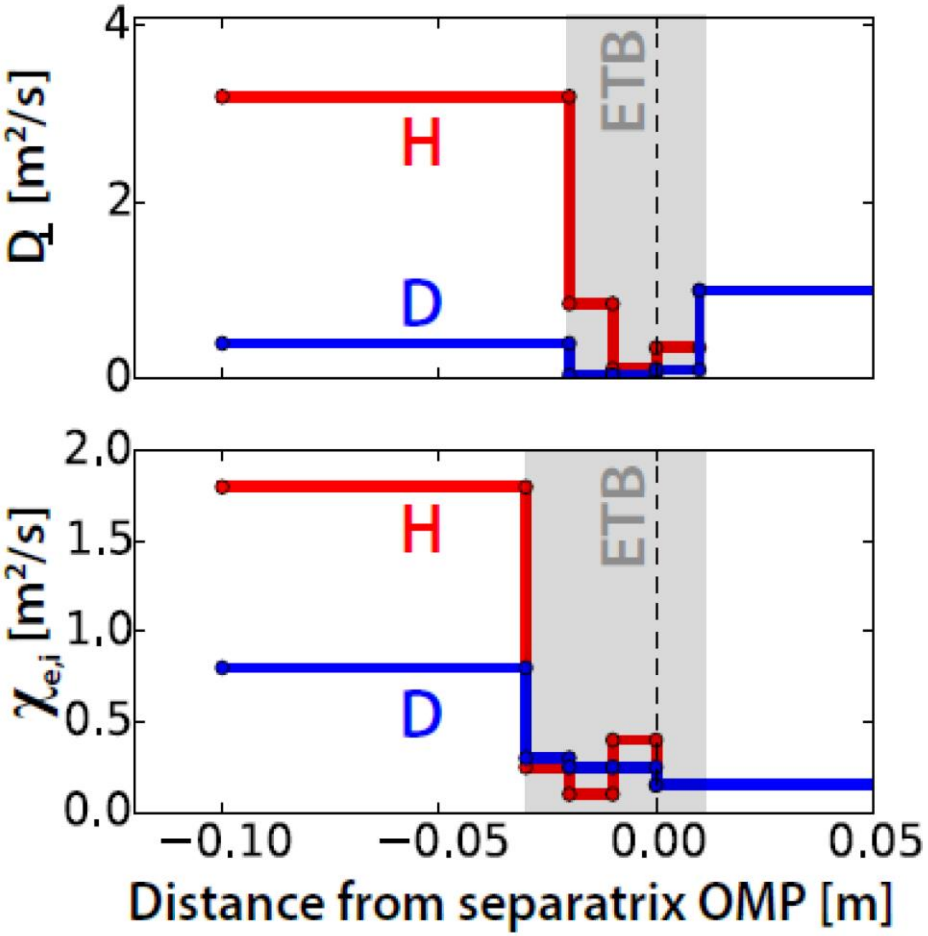
- Type I ELMs more frequent in H than D from same gas rate & power
- Pedestal density decreases with f_{ELM}
- However for f_{ELM}>40Hz, ELM particle loss/ELM decreases and time average losses $\delta n \times f_{ELM}$ saturate
- $\Rightarrow$ ELMs alone cannot explain differences in density between H and D



L. Horvath, submitted NF 2019

EDGE2D/EIRENE simulation confirms larger edge & pedestal inter-ELM transport in hydrogen

Interpretative EDGE2D/EIRENE modelling of measured n_e and T_e profiles



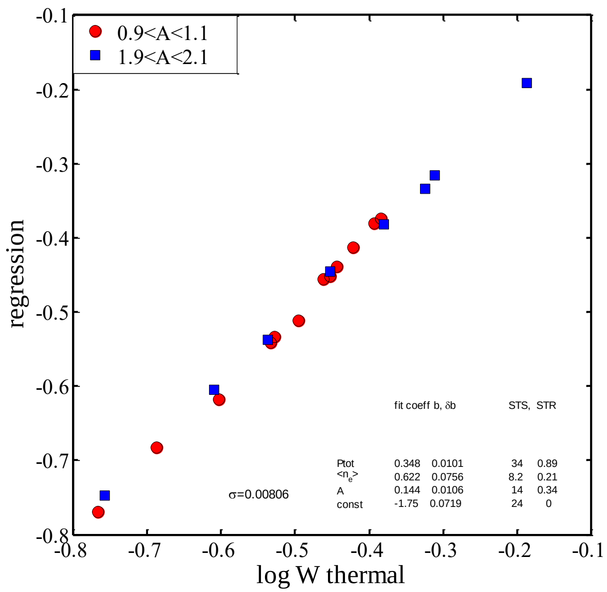
- Very little impact of neutral penetration (faster for H than for D) on n_e, T_e profiles
- Larger derived anomalous transport coefficients in H than in D
  - In particular, $D_\perp$ larger in H also in ETB
- Larger inter-ELM P_{sep} required in H than in D to maintain similar p_{PED}

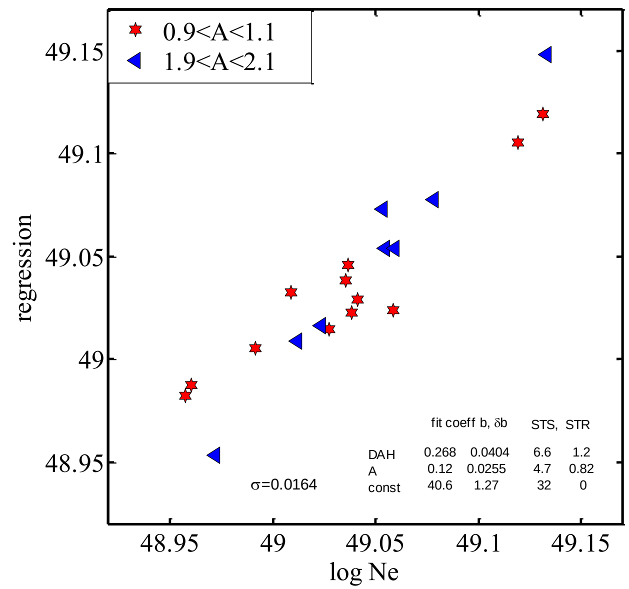
L. Horvath, submitted NF 2019
L. Horvath, HMWS, Shanghai 2019

#91554 (H), #84793 (D): 1.4 MA / 1.7T – similar W_{TOT} [10MW(H), 4.5MW(D)], Γ_{gas} ~ 3x 10^{21} e/s

L-mode : energy isotope dependence weak

- B_T=2.9 T, I_p=2.5 MA, $\langle n_e \rangle \cong 3.1\times10^{19} m^{-3}$ NBI power scans in D and H





- R/L_{Te} ≈const, as H-modes
- Measured $T_i \sim T_e$
- Robust regressions without and with n_e

$$W_{th} \propto A^{0.15} P^{0.37} \; or$$
$$W_{th} \propto A^{0.14} P^{0.35} \langle n_e \rangle^{0.62}$$
$$N_e \propto A^{0.12} \Gamma_{main}^{0.27}$$

- GK analysis shows dominant mode is ITG in core (*Maggi PPCF 2018*)
- Is weak isotope dependence due to weak ExB in L-mode (micro-pedestal?)

Isotope identity experiments satisfy scale invariance

- An H/D dimensionless L-mode identity pair in $\rho*$, β, $\nu*$ and q was successfully created by scaling the dimensional parameters as required for identity:

$$I_P, B_T \propto A^{3/4}; n \propto A, T \propto A^{1/2}$$

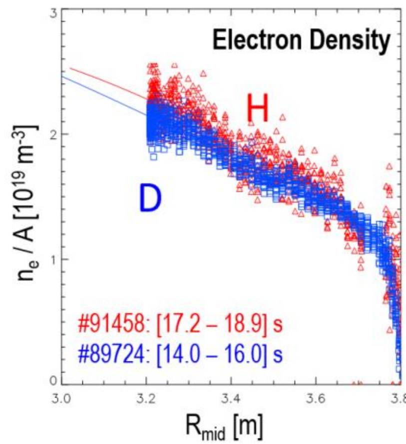
- Scale invariance was achieved, i.e. the pair had identical normalised confinement time [1]

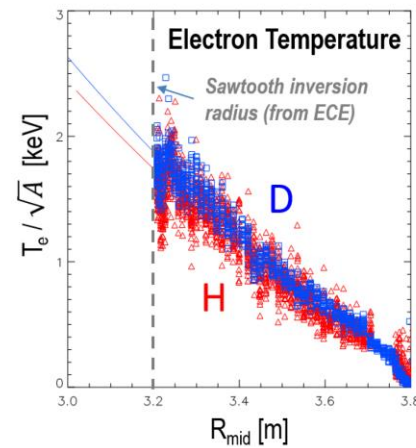
$$\omega_{ci}\tau_{Eth} \propto B_T\tau_{Eth}/A$$

- This is consistent with ion scale transport **in core** depending on $\rho*$, β, $\nu*$ and, within errors, no additional isotope dependence
- Mach number not matched, but likely did not play important role here
- H-mode pair also created in JET-C[2] and JET-ILW(to be confirmed), but in JET-ILW careful matching of ELM frequency was necessary

Food for thought: If scale invariance is achieved, isotope sensitive physics (e.g. E×B shear) is also matched (e.g. matching Mach numbers) or is unimportant.

Pulse #	**#91458**	**#89724**
Isotope	H	D
Time interval [s]	17.2 – 18.9	14.0 – 16.0
B_T [T]	1.74	2.95
I_P [MA]	1.44	2.46
P_{abs} [MW] (±10%)	2.56	6.24
$P_{abs}/B_T^{5/3}$ [MW/T$^{5/3}$]	**1.02**	**1.03**
Z_{eff} (±10%)	**1.4**	**1.35**
$\tau_{E,th}$ [s] (±10%)	0.155	0.19
$B_T\ \tau_{E,th}$ / A [T/s]	**0.27**	**0.28**





[1]Maggi, NF 2019 [2]Cordey PPCF 42 2000 A127

Mixed species plasmas

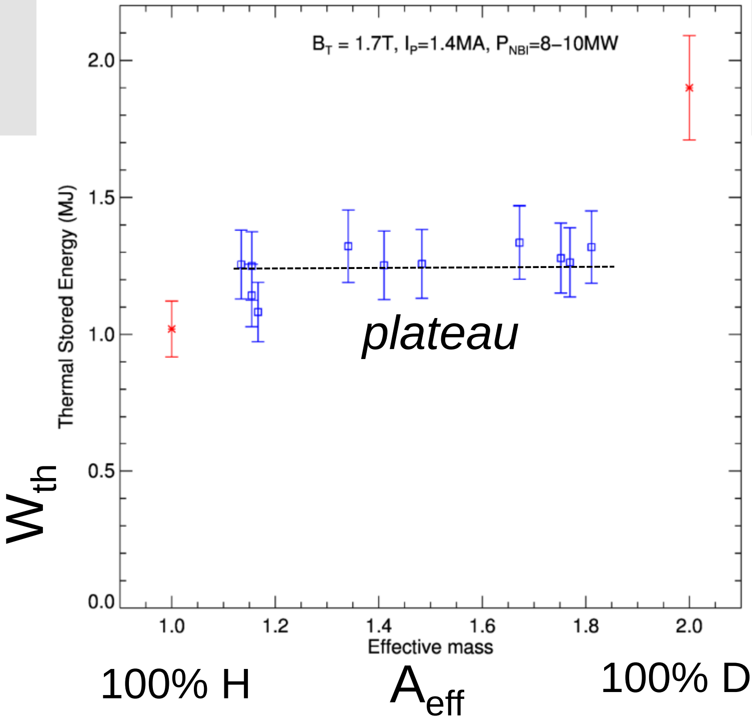
- NBI heated H/D mixed ELMy H-modes[1]
- These show that confinement doesn't increase linearly with the effective atomic mass

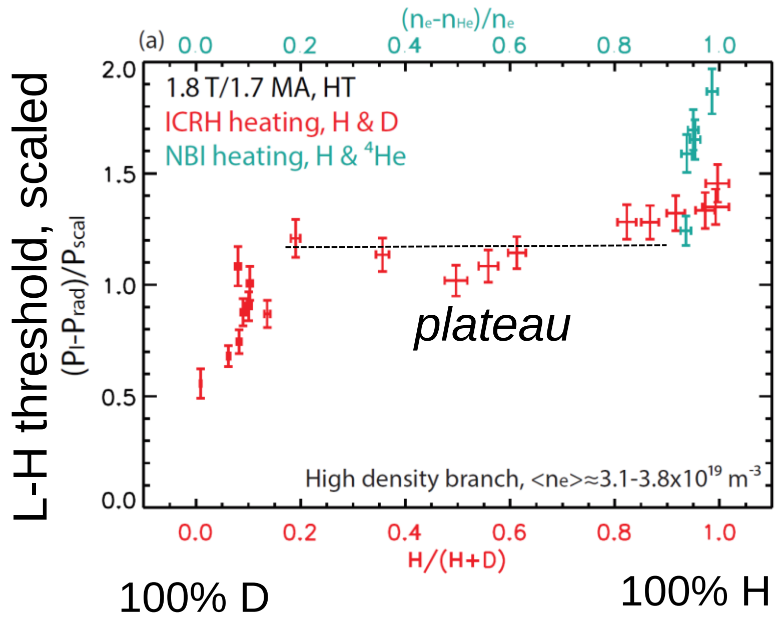
$$A_{eff}=\sum n_i A_i/\sum n_i$$

- Instead, a plateau of near constant confinement time appears for $1.2<A_{eff}<1.8$ (further exploration needed)

- Plateau is reminiscent of plateau in L-H threshold power observed in different set of experiments[2] (ICRH). Behaviour may be linked to general observation that quality of H-modes improves with $P/P_{L\text{-}H}$

- Fast isotope mixing observed



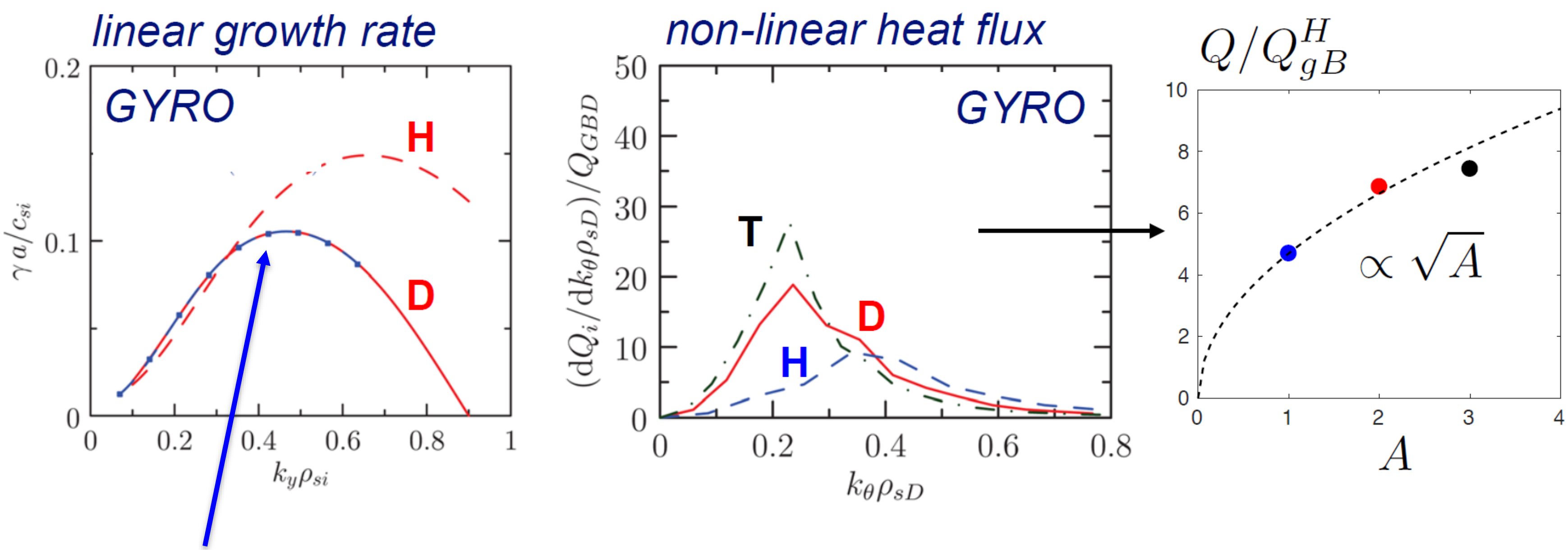


[1]D. King et al, EPS 2019, to be published in NF
[2]Hillesheim et al, IAEA FEC 2018

Overview of isotope transport effects (1)

- Local limit, electrostatic, adiabatic electrons, no collisions or flows: GyroBohm scaling $\chi_i \propto \gamma_i \rho_i^2$

$$\gamma_i^{\max} \propto \frac{1}{\sqrt{A}} \qquad \chi_i \propto \frac{\sqrt{A}}{Z^2}\chi_H$$



H growth rate rescaled to D

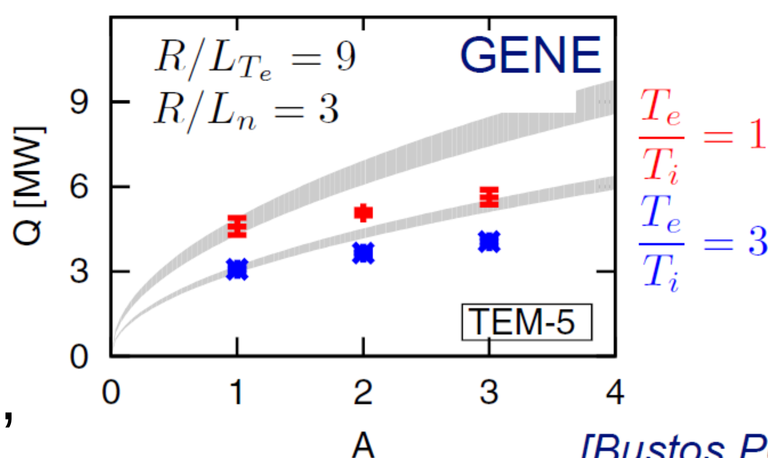
Pusztai et al, Phys. Plasmas **18**, 122501 (2011)

Overview of isotope transport effects (2)

- Effects which can modify the mass scaling:
  - kinetic electrons
  - collisions
  - background flows (ExB shearing, PVG)
  - electromagnetic fluctuations
  - finite system size effects (profile shearing)
  - flux-driven (avalanches)
  - Boundary condition+profile stiffness

- **Kinetic electrons**
  - Increase of γ/c_s at high $k\rho_i$ with A, for ITG and ETG[1]
  - Reduce Zonal Flow damping for higher A affects TEM at $T_e \geq T_i$
  - $\Rightarrow$ A scaling of Q still positive, but reduced

NL heat flux



[Bustos PoP'15]

Overview of isotope transport effects (3)

- **Electron ion collisions**

$$\nu_{\rm eff} \sim \frac{\nu_{ei}}{\gamma^{\rm nocol}} \propto \sqrt{A}$$ → TEM stabilisation at high isotope mass

Broadening of density profiles at high isotope mass and high $\nu_{\rm eff}$

C. Angioni POP 2018 082517

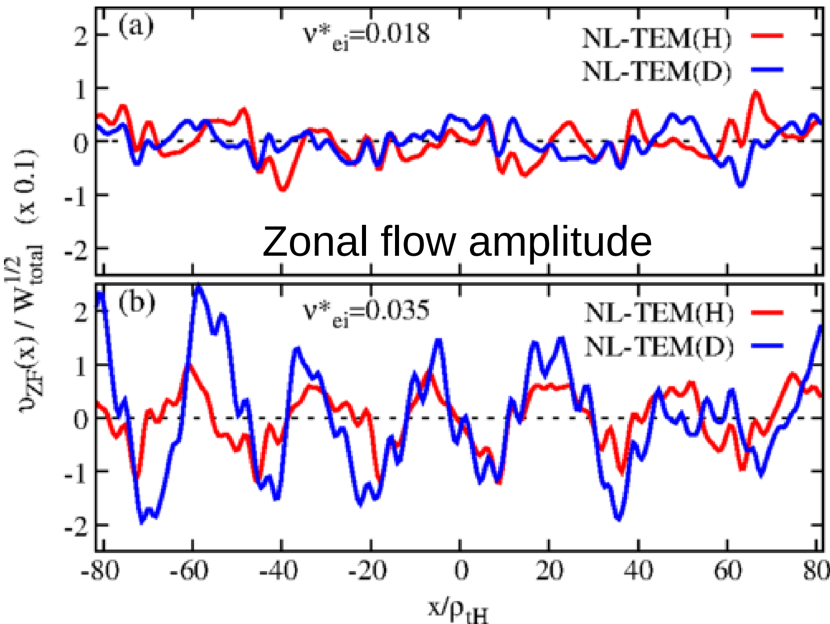
- **Ion-ion collisions**

$$\nu_{ii} = \frac{n_i Z_i^2 e^4 \ln \Lambda}{4\pi\epsilon_0 m_i^2 v_{\rm thi}^3} \propto A^{-1/2}$$

Zonal flow damping increases with A & collisionality:

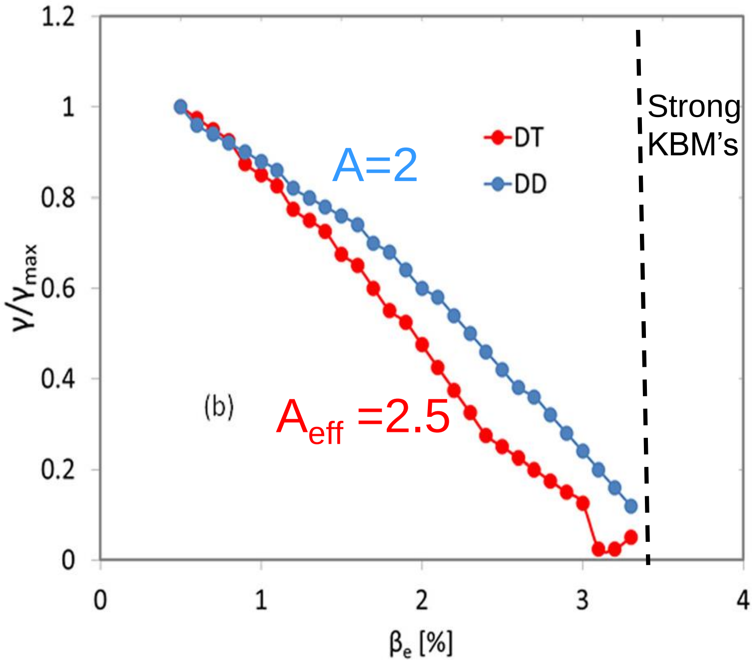
- Nakata, PRL 2017, in TEM regime ⟶

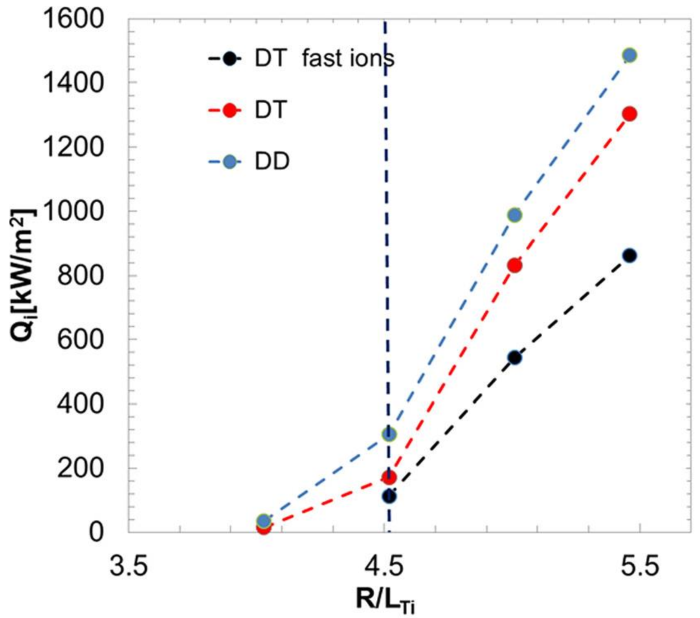
- Oberparleiter EU-US TTF Sept 2018 in ITG regime



Overview of isotope transport effects (4)

- **Electromagnetic stabilisation** stronger for larger ion mass
- Linear e.m. GENE results for ITER hybrid parameters, fixed ion pressure & ion collisionality, shows growing difference with β_e in as KBM transition is approached[1]
- Effect is compounded by fast ion electromagnetic stabilisation (α particles), leading to significant de-stiffening in non-linear simulations[1]





[1] Garcia et al, Phys. Plasmas **25**, 055902 (2018)

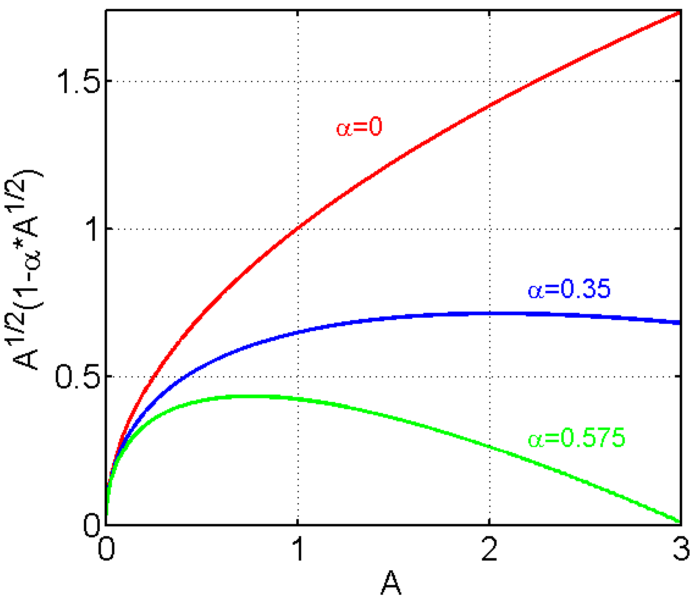
Overview of isotope transport effects (5)

- **E×B shearing**, QL, assuming underlying transport is gB:

$$\chi_i \sim \chi_{gB}[1-\alpha_E\frac{\gamma_E}{\gamma_{\max}}] \longrightarrow \boxed{\chi_i \sim \chi_{gB}^H\sqrt{A}[1-\alpha_E\frac{\gamma_E}{\gamma^H_{\max}}\sqrt{A}]}$$

$\gamma_{max} \propto \gamma^H_{max} v_{thi} \propto \gamma^H_{max} A^{-1/2}$ $\quad \alpha_E \sim 1$

- $\Rightarrow$ opportunity to break gB scaling, depending on $\alpha=\alpha_E\gamma_E/\gamma^H_{max}$



$$\gamma_E = \omega_{E\times B} = \frac{RB_\theta}{B}\frac{d}{dr}\left(\frac{E_r}{RB_\theta}\right)$$

$$\simeq \frac{T_i}{Br_n}\frac{d\ln(RB_\theta)}{dr} + \frac{1}{B}\frac{d(V_{\varphi i}B_\theta)}{dr} - \frac{1}{B}\frac{d}{dr}\left(\frac{T_i}{r_n}\right)$$

NC terms species-independent, i.e. $\alpha=\alpha_E\gamma_E/\gamma^H_{max} \propto A^0$

$\Rightarrow$ Stabilising term can reduce, reverse gB scaling

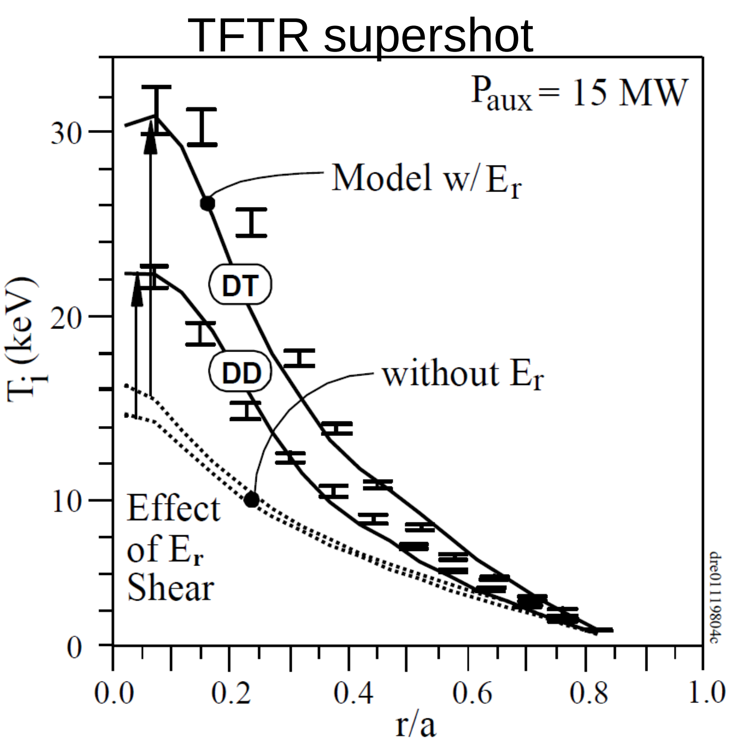
Overview of isotope transport effects (6)

- **E×B shearing**, QL, assuming underlying transport is gB:

$$\chi_i \sim \chi_{gB}[1 - \alpha_E \frac{\gamma_E}{\gamma_{\max}}] \longrightarrow \chi_i \sim \chi_{gB}^H \sqrt{A}[1 - \alpha_E \frac{\gamma_E}{\gamma_{\max}^H}\sqrt{A}]$$

$\gamma_{max} \propto \gamma^H{}_{max} v_{thi} \propto \gamma^H{}_{max} A^{-1/2}$ $\alpha_E \sim 1$

- $\Rightarrow$ opportunity to break gB scaling, depending on $\alpha = \alpha_E \gamma_E / \gamma^H{}_{max}$

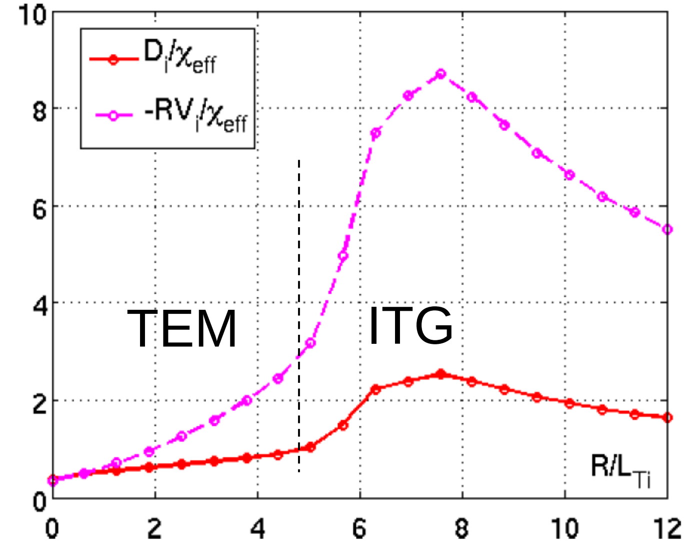


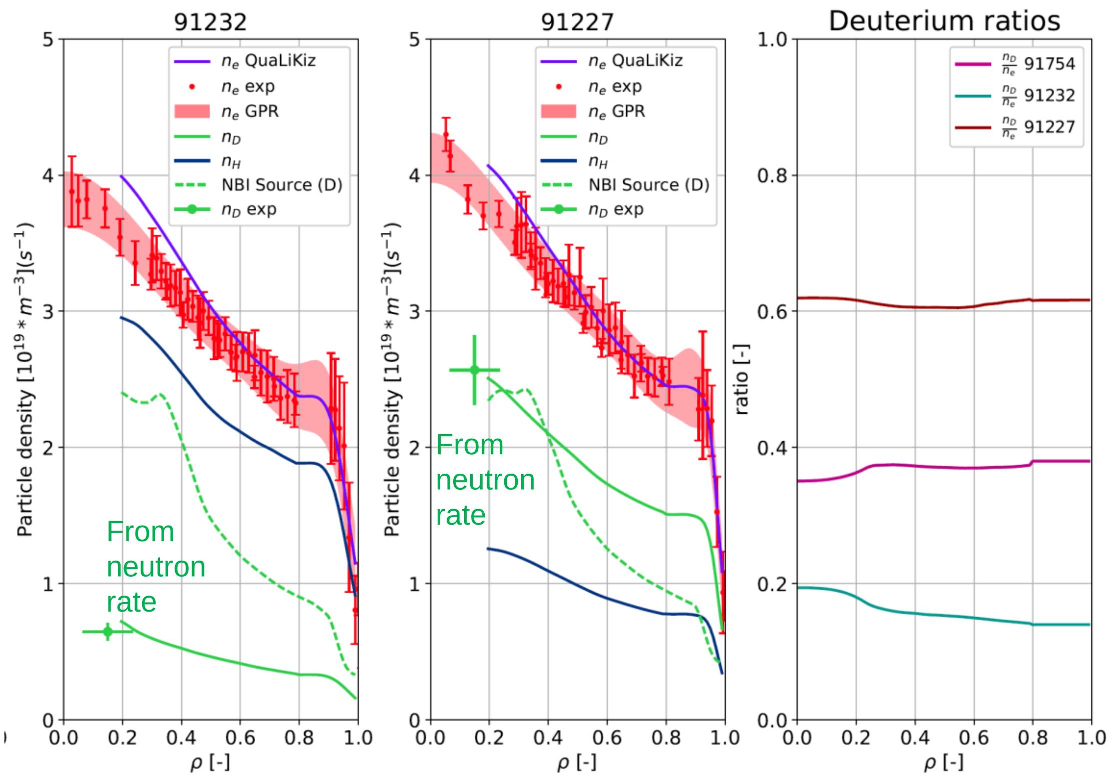
- E×B shearing used to explain strong confinement scaling ($\tau_E \propto A^{0.85}$) with A in TFTR L-modes & supershots[1,2]
- Caution: In 1998 the community was not aware of many other transport effects, e.g. fast ion β electromagnetic stabilisation!
- **Strong sheared poloidal rotation also in ITB's and ETB's: may be a key ingredient to explain pedestal confinement scaling with A.**

[1] Scott IAEA-CN-64/A6-6, 573
[2] Ernst PRL 81 (1998) 2454

Mixed species plasmas: fast isotope mixing

- Experiments with core NBI fuelling of one species into a background plasma of another, edge-fuelled species show isotope ratio equilibration at time scales similar to the energy confinement time, with $D \sim 2 * \chi^{eff}$ observed[1].
- ⇒beam fuelling only slightly (<10%) modifies the core isotope ratios.
- Fast mixing basic property of ITG's (TEM slower)[2]





- Experiments successfully modelled by GK modelling using Qualikiz[2,3]
- Similar observations with peripheral D pellet injection (ρ_{inj}~0.8) into H plasma[4]
- Fast isotope mixing greatly facilitates isotope ratio control

[1] M. Maslov NF 2018 076022
[2] C. Bourdelle *NF* 2018 076028
[3] M. Marin, to be published in NF
[4] M. Valovic NF 2019, 106047
[5] D. King et al, EPS 2019, to be published in NF

Physics based modelling

- Discussed several (not all) transport effects depending on A
- Mostly act counter to gyroBohm scaling

- ⇒ **Should not be surprised to see global and local scaling to be non-gB or anti-gB !**

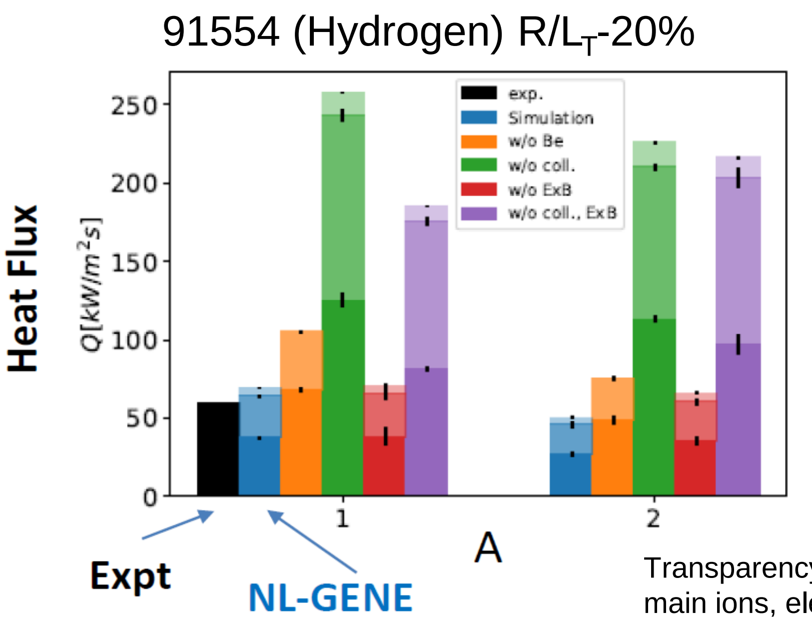
- However the isotope dependent transport effects do not occur in isolation, they coexist and interact non-linearly

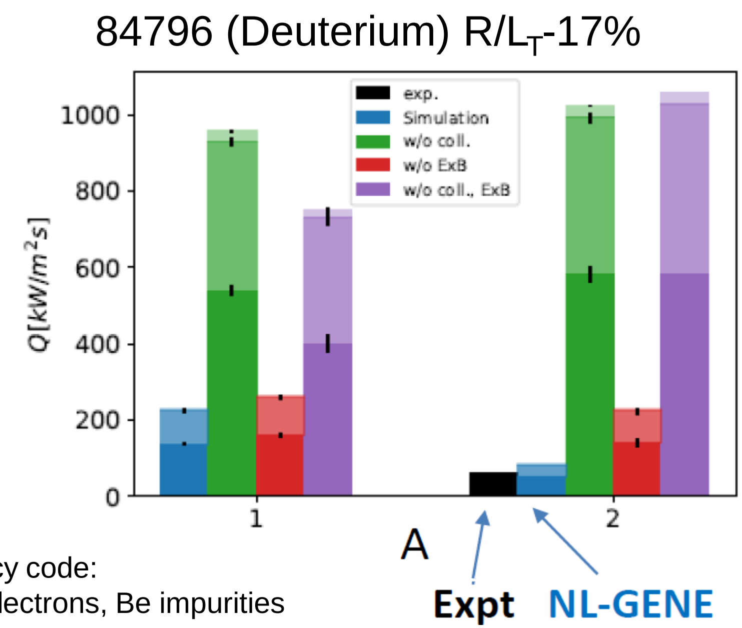
⇒ **Physics based (& integrated) modelling is required to account comprehensively for transport physics and for operational circumstances linked with ion species**

JET-ILW : Nonlinear local GENE simulations reverse gyroBohm scaling

- H-mode pair (H&D) with P_{aux}=10MW, non-linear, flux-tube, ρ=0.5, assuming A=1 & 2
- Absolute heat fluxes reproduced if ∇T_e reduced by ~20% [1]
  - collisions are included (most important)
  - dilution by Be impurities included
  - E×B shear included

note that omitting E×B makes little difference for H, but important for D





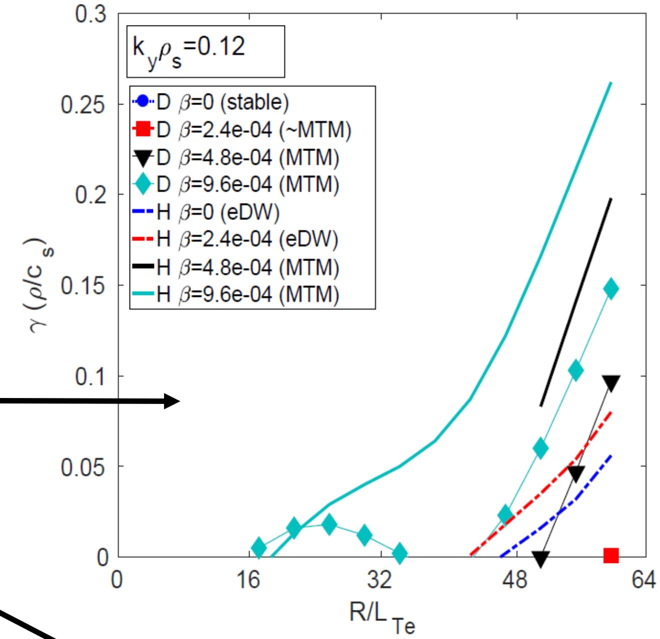
Transparency code:
main ions, electrons, Be impurities

- NL GENE also successful in L-mode[2], gB deviations mostly from E×B and collisions
- However QL flux driven modelling exhibits only weak ExB contributions in L and H-mode[3-5]. Efforts are underway to resolve the differences

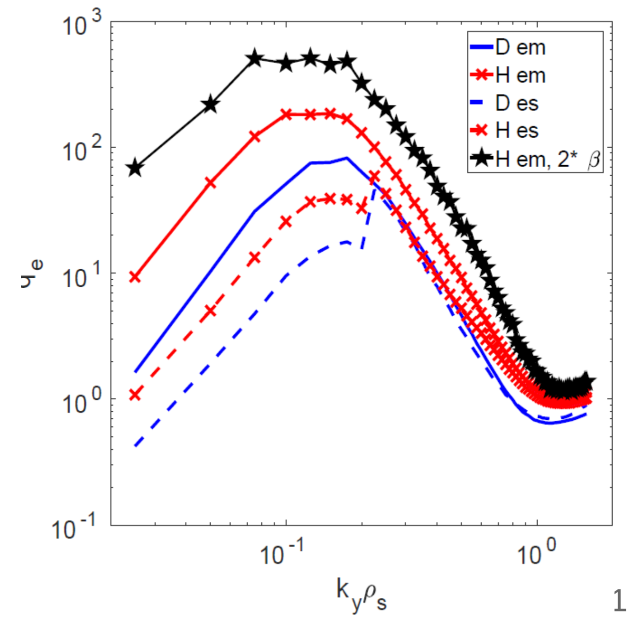
[1] Oberparleiter, EU-US TTF 2018 [2] J. Garcia *et al* 2019 *NF* **59** 086047
[3]Casson et al, IAEA-CN-258, TH/3-2 (2018) [4] Maggi, NF 2019 , [5] Maggi, PPCF 2018

Progress with GK edge modelling

- GENE simulations of L-mode edge in JET-ILW and AUG exhibit mass dependence[1]
- Electron drift modes unstable because parallel stabilising contribution $\gamma_{//}$ is reduced at the high collisionality characteristic of the edge
- Lower thresholds in R/L_{Te} in hydrogen, based on NL simulations, especially at high β_e



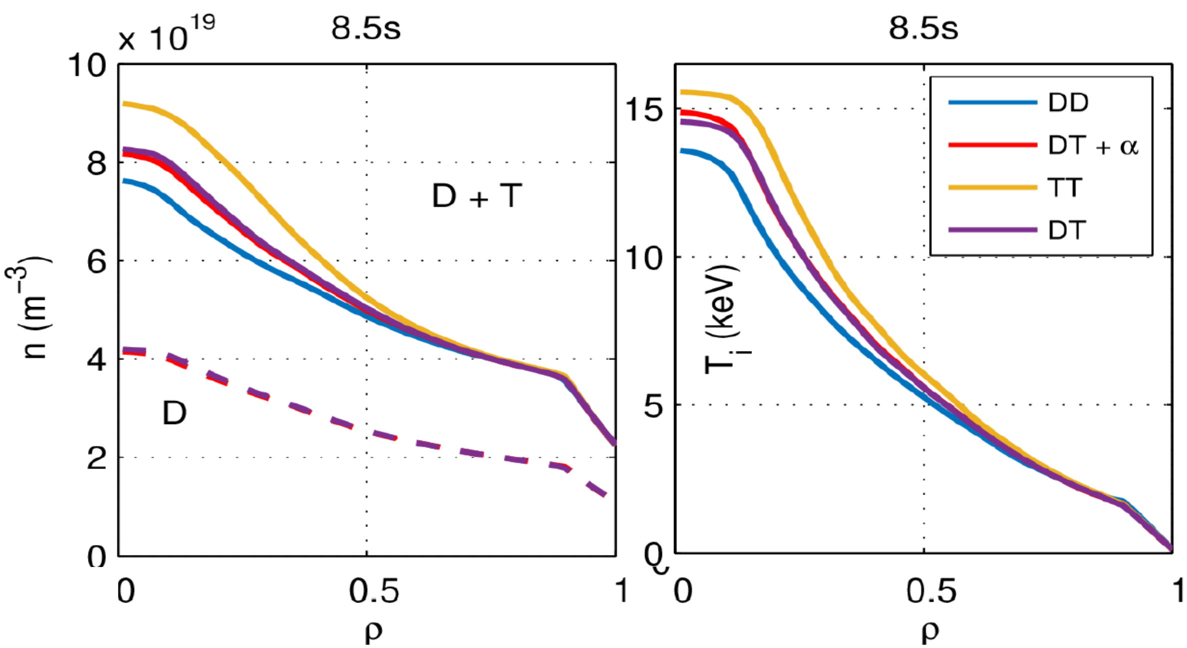
- Strong couling to low $k_y\rho_s$ in NL simulations, well below expectation from linear stability $\Rightarrow$ cannot approximate by QL models
- Lowest $k_y\rho_s$ more unstable in hydrogen, contribute strongly to transport.
- These low $k_y\rho_s$ modes have MHD-like properties despite being well below linear MHD limit
- Threshold for e-m effects $\beta^* = \beta_e (qR/L_\perp)^2 \approx 1$; $\beta^* > 1$ for JET and AUG parameters $\Rightarrow$ cannot be ignored
- General properties likely apply to H-modes pedestal too (to be studied), probably amplified by the stronger E×B stabilisation for the heavier species.



[1]N. Bonanomi, accepted NF 2019

Integrated modelling for JET DTE2 (2020)

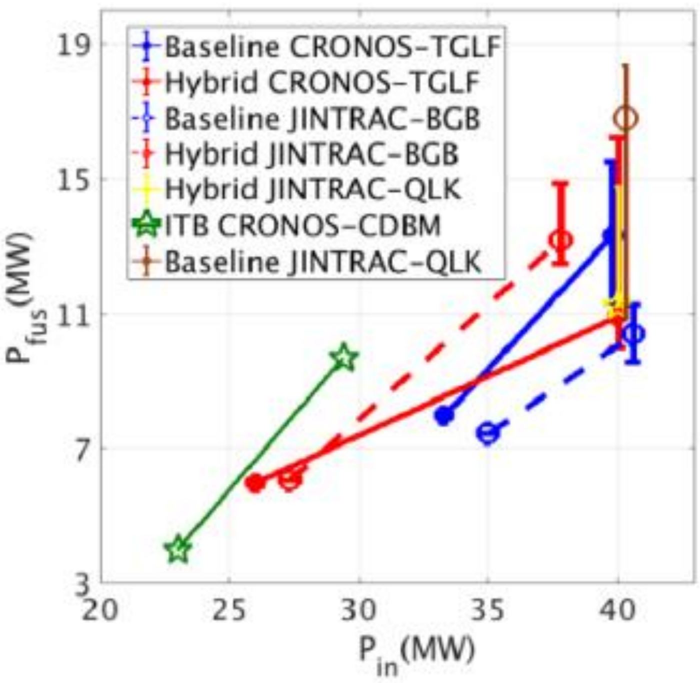
- Complex ongoing task – isotope effects are (only) part of the story
- Example: Hybrid plasma, JINTRAC with Qualikiz, E×B shear (for r<0.5), NEO, adhoc mimic of e-m stabilisation, no pedestal scaling with isotope
  ICRH deemed to heat ions to 80% (e.g. 3He minority)
- Core T_i,T_e higher in DT and pure T (labelled ‘TT’)
  …but $n_e(0)$ higher too ⇒ impurity accumulation worse
  … alpha’s appear to partly mitigate accumulation
- Not clear if higher pedestal in DT, T helpful, if it only raises n_{eped} , not T_{iped},T_{eped}



Casson et al,
IAEA-CN-258,
TH/3-2 (2018)

Integrated modelling for JET DTE2 (2020)

- A summary of integrated modelling predictions with various models shows that the target power (15MW) for DTE2 can be achieved[1]
- **These so far have only partial or imperfect implementation of isotope effects**, yet simulations show improvements in DT and full T over D plasmas.
- **No isotope effect has so far been implemented for the pedestal**, which determines the boundary conditions for the simulations



- **The combined isotope effects may be stronger than modelled so far, but may not necessarily all concur to maximising fusion power**, especially if they lead to higher operating densities instead of higher temperatures in DT plasmas.

[1] J. Garcia *et al* 2019 *Nucl. Fusion* **59** 086047
[2] Saarelma et al Plasma Phys. Control. Fusion 60 (2018) 014042

Conclusion: Validation challenges

- Many (most?) isotope sensitive physics elements identified
- These usually occur simultaneously, with mutual interactions

$\Rightarrow$ bewildering range of results

$\Rightarrow$ need to take all into account $\Rightarrow$ need integrated modelling

$\Rightarrow$ need to (in)validate understanding and physics elements in codes

$\Rightarrow$ need experiments that are sensitive to separate physics elements (e.g. only ExB shear stabilisation or only fast ion effects) AND experiments with simultaneous/synergetic processes

$\Rightarrow$ Need to identify unsatisfactory physics understanding (in)validate and improve, return to validation cycle

- **The upcoming pure T and DT campaigns will provide unique and irreplaceable opportunities to perform such experiments and (in)validate our physics understanding. (please contribute)**

Herein lies the true value of the JET T and DT campaigns!

Empty

Classical Summary

- **No such thing: «isotope scaling law»**

Type I ELMy H-mode:

- Isotope dependence of ion transport, but no unique scaling independent of device and conditions
- Nonlinear local GK calculations (GENE) reverse gyroBohm scaling in ITG thanks to collisions, ExB shear and impurities …
- Global confinement scaling with isotope mass starts at edge/pedestal, propagated to core by profile stiffness, **additional isotope effects occur in the core**

L-mode:

- Weak dependence of global energy / particle confinement on isotope
- Stronger dependence in TFTR – stronger ExB effect, but why?

Take home:

- Non/Anti-GB behaviour is introduced by physics beyond simple QL models, such as ExB shear stabilisation, kinetic electrons, finite beta, collisions…
- (In)validation of physics elements in codes (and elements still to be introduced) essential for progress, requires further work in different isotopes (and ions ^{4}He)