Testing predictions of electron scale ETG pedestal turbulence in DIII-D ELMy H-modes

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MIT PSFC seminar
May 3, 2019

Acknowledgements:
NERSC resources, DOE funding
A. Diallo, F. Laggner, P.B. Snyder
D.R. Hatch, M. Kotschenreuther

Overview / Summary

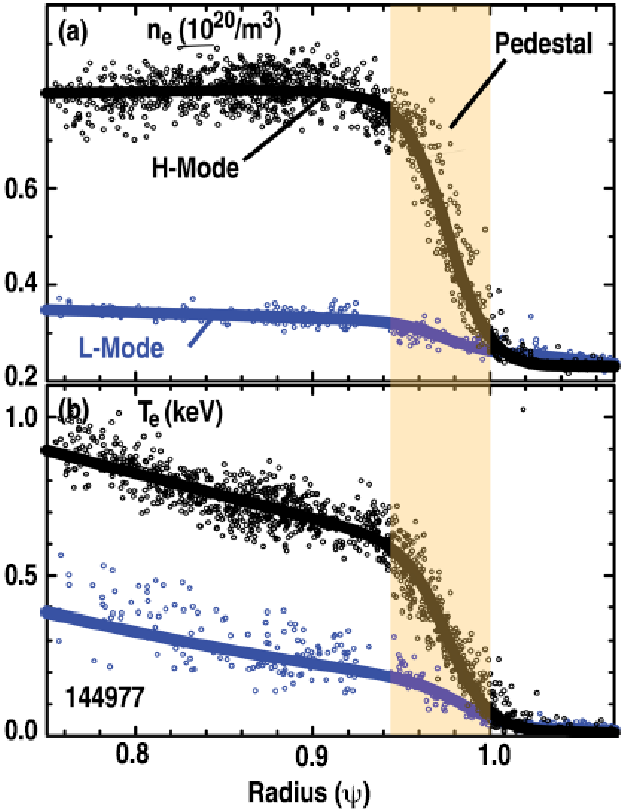
- *Linear* gyrokinetic analysis (CGYRO) suggests electron scale ETG turbulent transport may limit $\eta_e \sim \nabla T_e / \nabla n_e$ in some DIII-D ELMy H-mode pedestals

- Numerous *nonlinear* gyrokinetic simulations run to predict ETG transport, used to develop ETG pedestal transport model for use in predictive simulations

➢ ETG contributes to $\chi_{e,ped}$, but unlikely to be the only transport mechanism

➢ Neoclassical D_e plays non-negligible role in setting density profile

High confinement H-mode characterized by steep gradients in the edge "pedestal" region



A.W. Leonard (2014)

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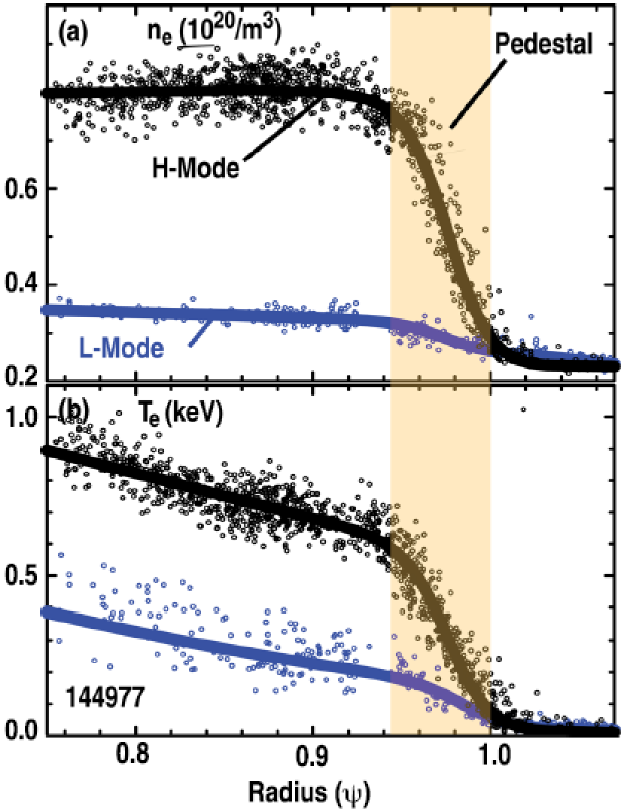

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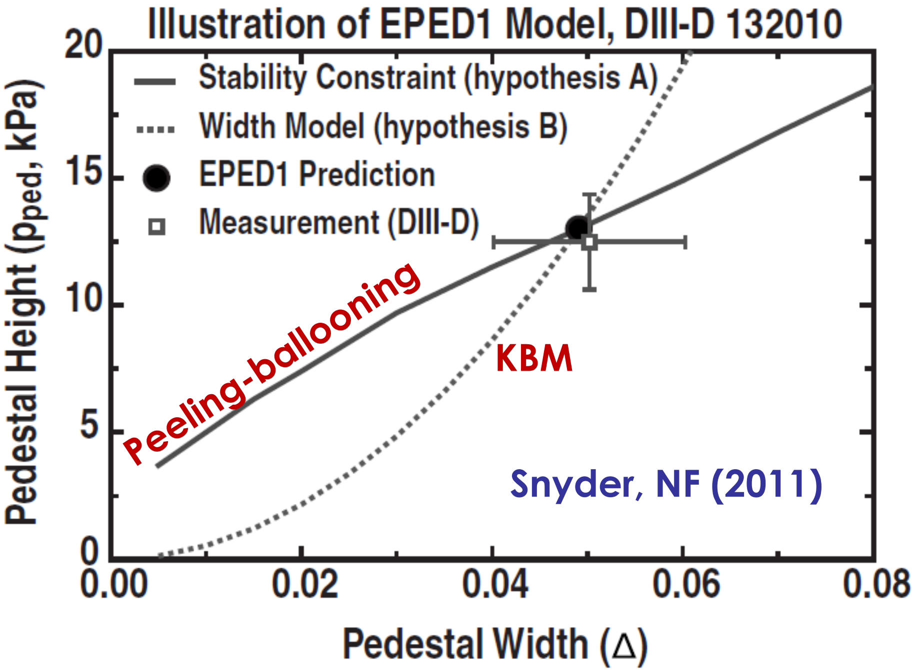
- **MHD stability [peeling-ballooning stability + KBM ∇p transport limit] provides valuable predictive model for pedestal pressure limit in <u>ELMy</u> H-modes**



Motivation: Understand what sets pedestal density & temperature structure to develop predictive capability

- **[MHD peeling-ballooning stability] + [KBM ∇p transport limit] provides valuable predictive model for pedestal pressure limit in ELMy H-modes [Snyder, NF 2011]**
  - Requires density as input
  - Can not predict n vs T inter-ELM dynamics (i.e. doesn't "know" about source strengths)
  - KBM predicts $D/\chi \sim 1$, whereas experiment often infers $D/\chi \ll 1$
  - Does not capture ELM-free scenarios or low aspect ratio NSTX scenarios

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Still need a transport model

- **KBM has a ∇p threshold, expected to be extremely stiff (~ large d[Q]/d[∇T])**
- **There are other instabilities that also have thresholds (typically ∇T and/or ∇n), with varying degrees of stiffness and varying D/χ**

An aside: The zoology of microinstabilities (& acronyms)

<u>Ion scales</u> ($k_\perp \rho_i \leq \sim 1$)

- **(ITG) Ion temperature gradient mode ($\sim \nabla T_i$)**
- **(TEM) Trapped electron mode ($\sim \nabla T_e$, ∇n_e)**
- **(PVG) Parallel velocity gradient mode ($\sim R\nabla\Omega$)**

Electrostatic modes

- **(MTM) Microtearing modes ($\sim \nabla T_e$, β_e)**
- **(KBM) Kinetic ballooning mode ($\sim \alpha \sim \nabla P_{tot}/B_\theta^2$)**

Electromagnetic modes

<u>Electron scales</u> ($k_\perp \rho_i >> 1$, $k_\perp \rho_e \sim 1$)

- **(ETG) Electron temperature gradient mode ($\sim \nabla T_e$)**

Electrostatic mode

- **Each *theoretical* instability is distinguished by:**
  - Scaling with parameters (a/L_T, a/L_n, β, ν, α, s, q, …)
  - Mode frequency (ion, electron diamagnetic direction)
  - Spatial structure (ballooning, tearing; ES, EM)
  - Partition of transport (Γ, Π, Q → D/χ, χ_φ/χ) ["transport fingerprint", UT-Austin]

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- **Hypothesis: A more complete transport model accounting for all instabilities and their thresholds / stiffness, coupled with MHD P-B, could provide a unified understanding for all H-mode/I-mode pedestal structures**

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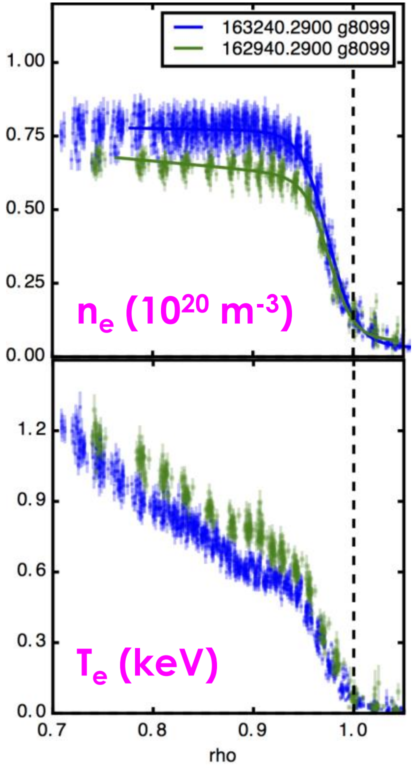
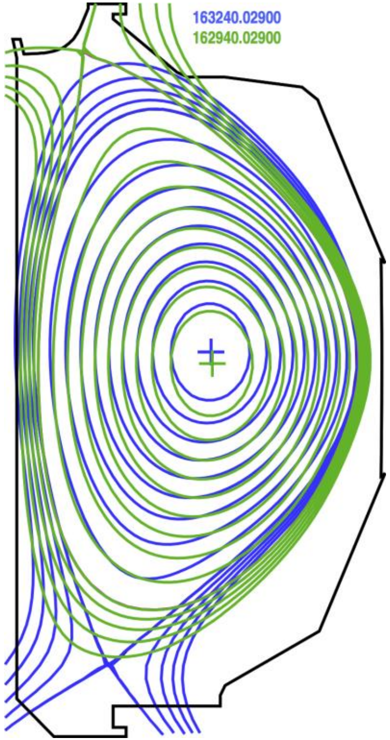
- **This talk: Use gyrokinetics (CGYRO) to predict theoretical microinstabilities and transport in DIII-D ELMy H-mode; compare with experimental interpretation using SOLPS-ITER → Begin developing ETG pedestal transport model as one component of a predictive model**

Investigating pedestal transport in two similar discharges with different edge particle source (baffling / cryopumping)





I_P = 1.4 MA
B_T = (±) 2.1 T
P_{NBI} = 3 MW
β_N = 2
q_{95} = 3.7-4

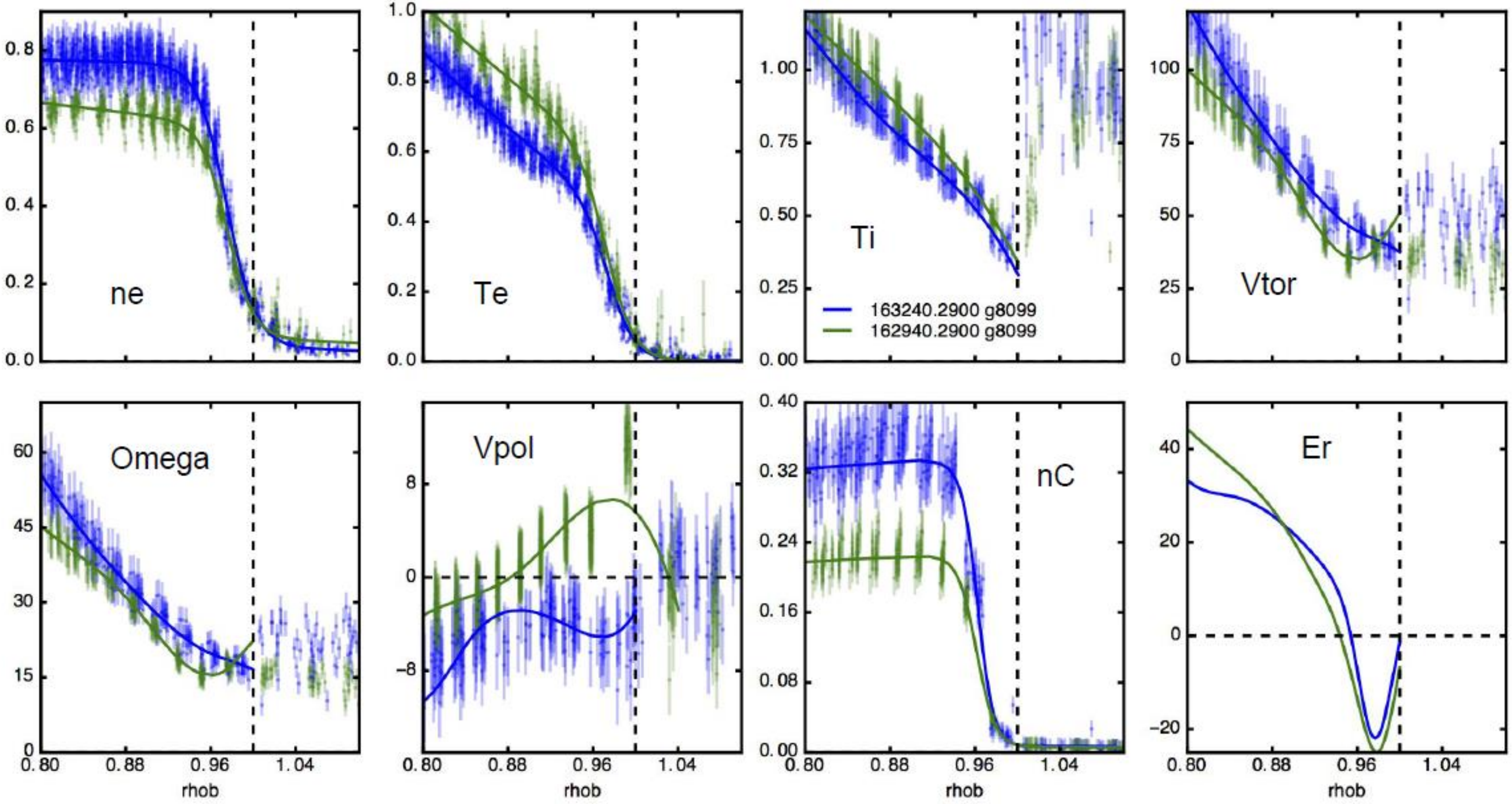
LSN – strike point on lower shelf (→open divertor)
USN – strike point in front of cryo baffle (→closed divertor)

Flipped B_T to maintain consistent ∇B divertor drifts

Very low/no gas fueling beyond recycling

- **USN closed divertor configuration leads to lower $n_{e,ped}$ due to lower source, higher $T_{e,ped}$ (Leonard IAEA 2016) → *what role does transport play*?**

Kinetic EFIT generated using high resolution edge profiles (ensemble from 80-99% of ELM cycle)



E_r calculated using measured $V_{tor,C}$, $V_{pol,C}$ & ∇P_C

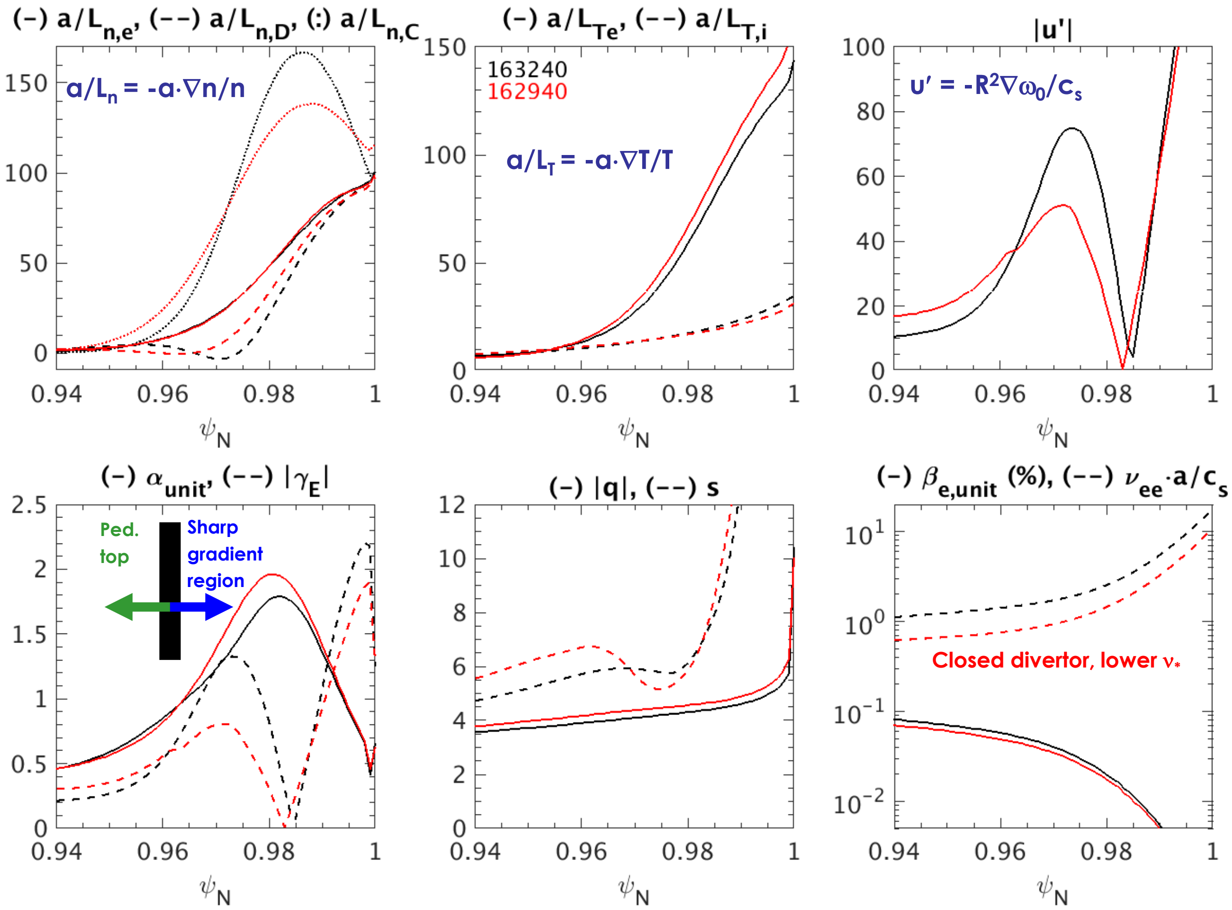
Using spectral, multiscale CGYRO code [Candy, JCP 2016] for scoping linear ion & electron scale instabilities

MODEL CHOICES

- **Uses rigorously derived low-ρ_* drift ordering of Sugama (1998, …)**
- **Numerical equilibrium using kEFIT (513×513) + 24 harmonic Fourier representation of flux surfaces [Candy, 2009]**
- **3 kinetic species (D,C,e)**
- **Sugama GK collision operator for all species [Candy, 2016; Belli, 2017]**
  - Pseudo-spectral in velocity space (v,ξ)
  - Well-suited for pedestal $\nu_e \cdot a/c_s \geq 1$
- **Fully electromagnetic (φ, $A_{||}$, $B_{||}$)**
  - EM effects important at high α/α_{KBM} in pedestal [Snyder, 2000; …]
- **Including finite u & u' (mach & γ_P; γ_E=0) in the low flow limit ~ O(M)**
  - Have also tested sonic $O(M^2)$ flow effects [Belli, 2018], possibly important for particle flux [Angioni; Buchholz, 2015]

- **Have tested numerical resolution requirements at each radius**
  - Large parallel resolution (n_θ) required for large gradients ($R/L_{T,n}$>>1)

Very strong normalized gradients (n, T and Ω) with large variation across pedestal



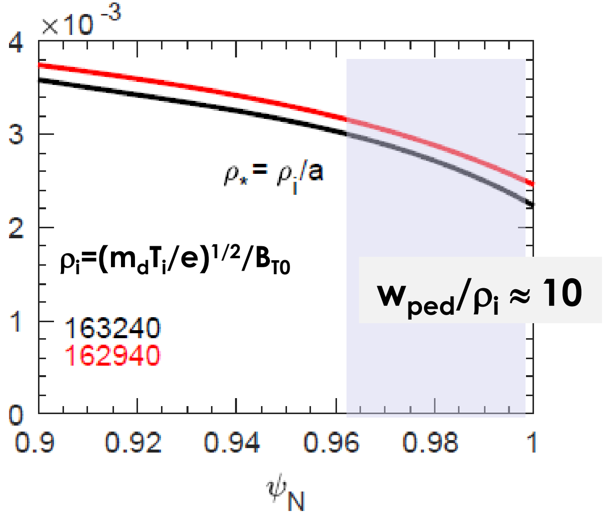
Validity of ion scale simulations in low-ρ_* ordering is questionable across steep gradient region

Across pedestal ψ_N>0.96

$\rho_{*i}=\rho_i/a \lesssim 1/300$

$\rho_i/\Delta_{ped} \approx 1/10$

$L_{c,r}/\Delta_{ped} \sim 0.5$ [assuming typical turbulence correlation length $L_{c,r} \sim 5\ \rho_i$]



- **Profile shearing (~n″, T″) may be important for ion-scales**
  - Can be tested spectrally in CGYRO, consistent within the framework of low-$\rho_*=\rho/L$ ordering
- **Thermal ion banana widths are comparable to pedestal width, orbit losses not captured**

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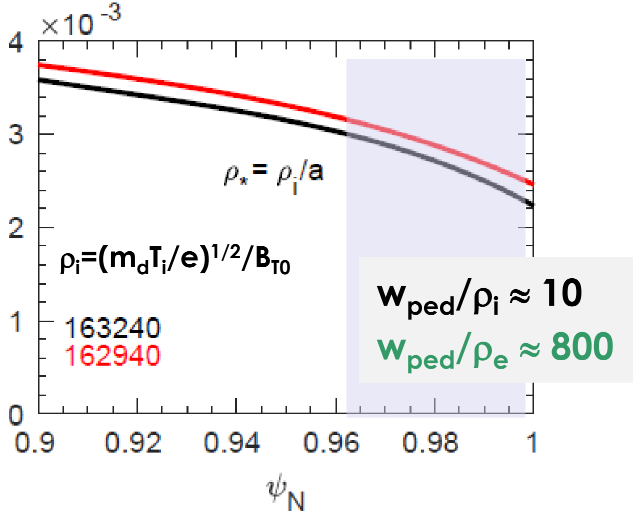

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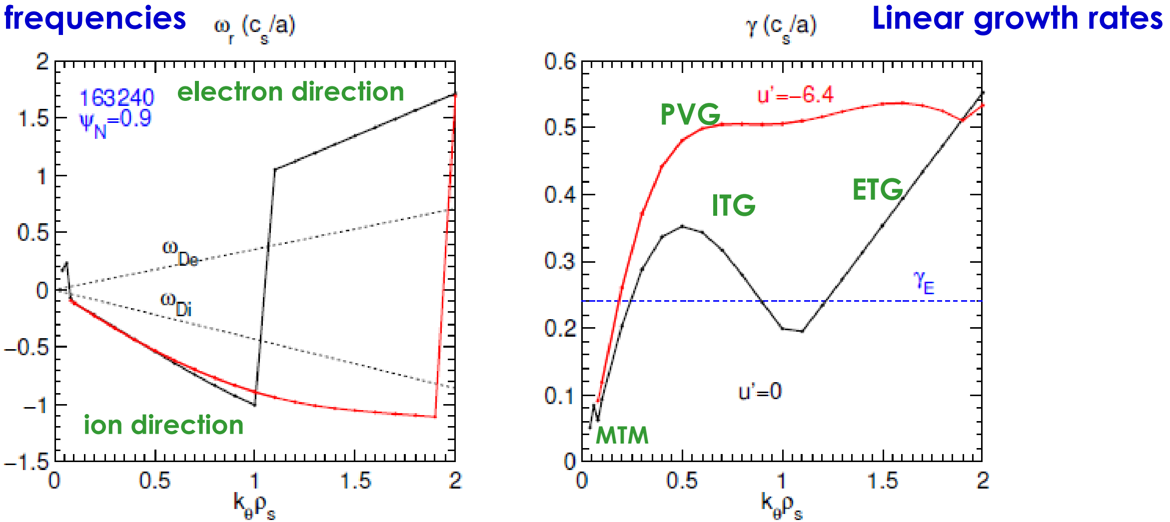
→ **Local, δf analysis sufficient for electron scale micro-stability / turbulence analysis ($\rho_e/a \lesssim 1/6000$)**

Inside pedestal top region (ψ_N=0.90-0.97), strong rotation shear leads to broad spectrum of ITG-PVG instabilities with $\gamma_{ion} > \gamma_E$



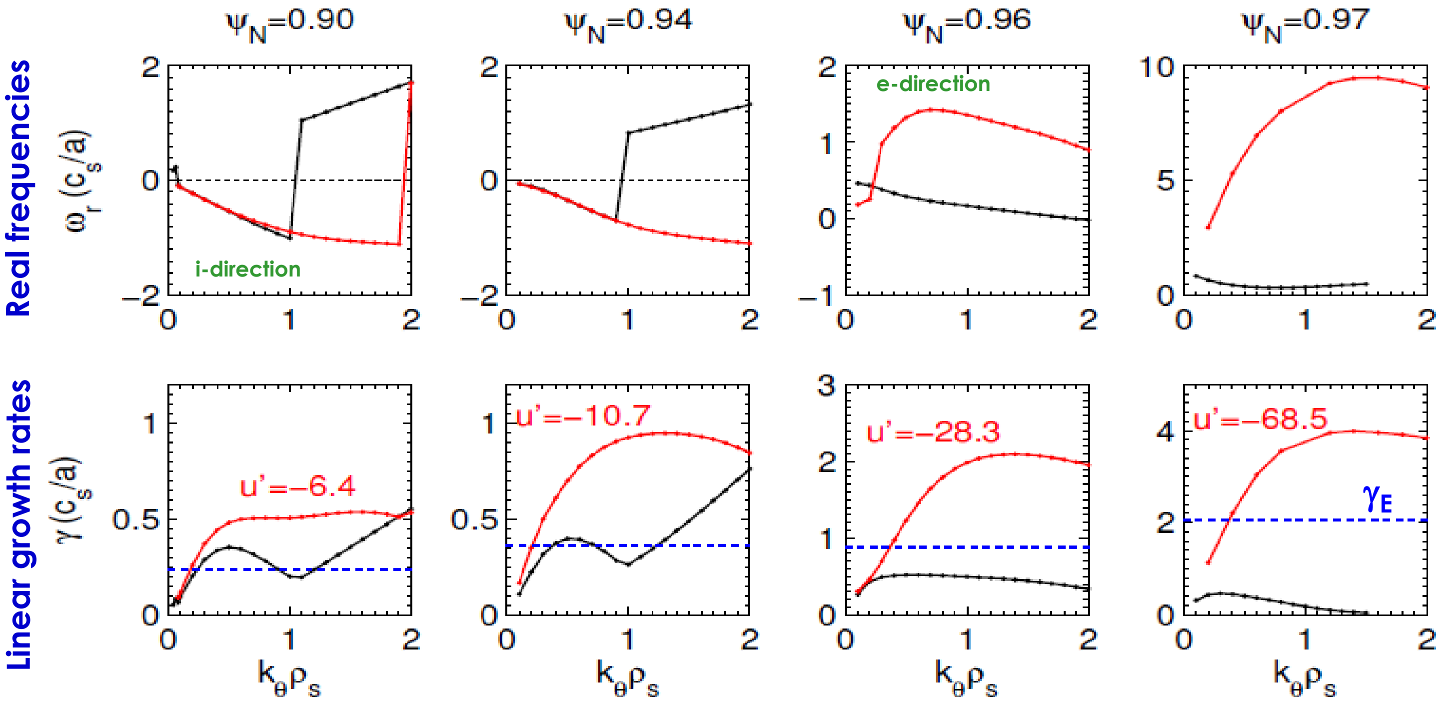
- **Traditional spectra of ITG-ETG found *when not including rotation shear***
- **Large rotation shear ($u' = -R^2\nabla\Omega/c_s = R/a \cdot \gamma_P$) significantly enhances growth rates**

$$R\nabla F_M \rightarrow [R/L_n + R/L_T \cdot (v^2/v_T^2 - 3/2) + (RB_T/R_0B) \cdot (v_{||}/v_T) \cdot u'] \cdot F_M$$

- **Leads to distinct Kelvin-Helmholtz / parallel velocity gradient (PVG) instability**
  [D'Angelo, 1965, Catto et al., 1973, …]

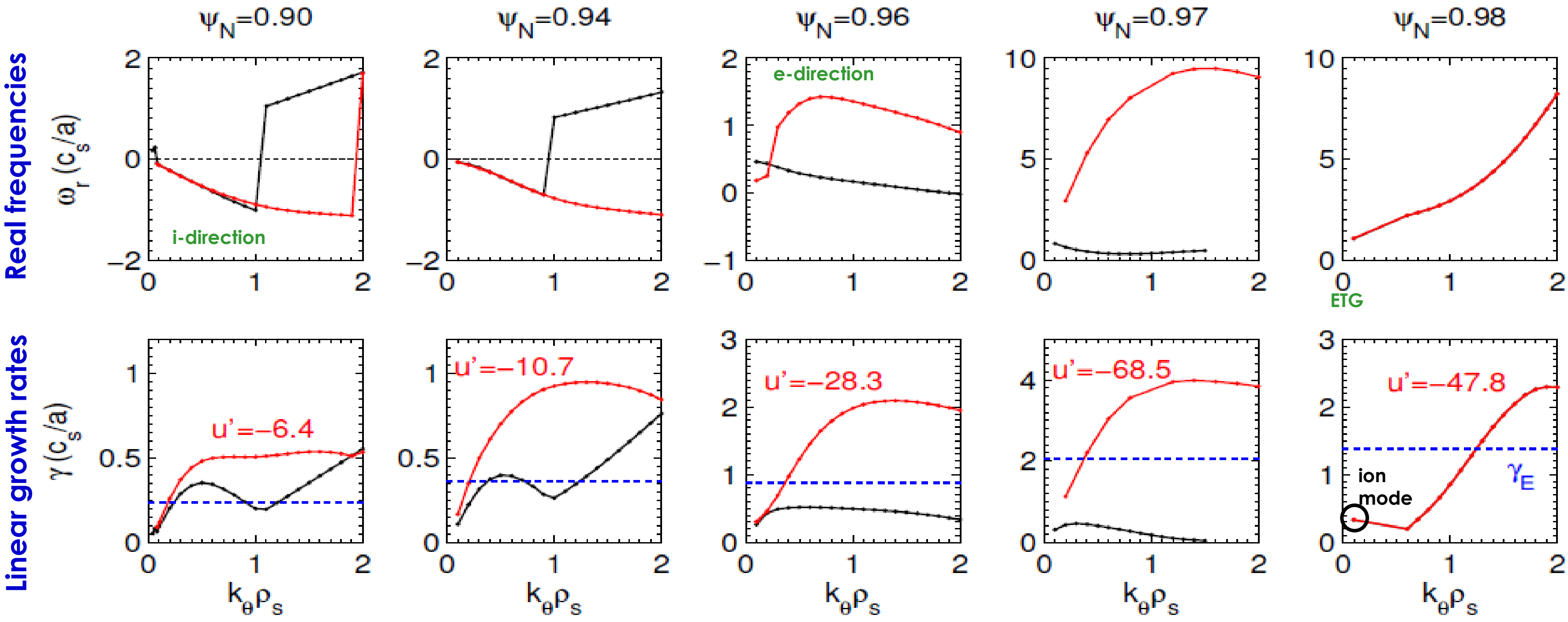
Very similar result moving to pedestal top (ψ_N=0.96-0.97);

- **Pedestal top**: strong drive from u′ with γ_{ion}>γ_E; modes transition from i-dia to e-dia ($a/L_{Te} > a/L_{Ti}$)



Very similar result moving to pedestal top (ψ_N=0.96-0.97); E×B shearing rate > $\gamma_{lin,ion}$ in sharp gradient region (ψ_N=0.98)

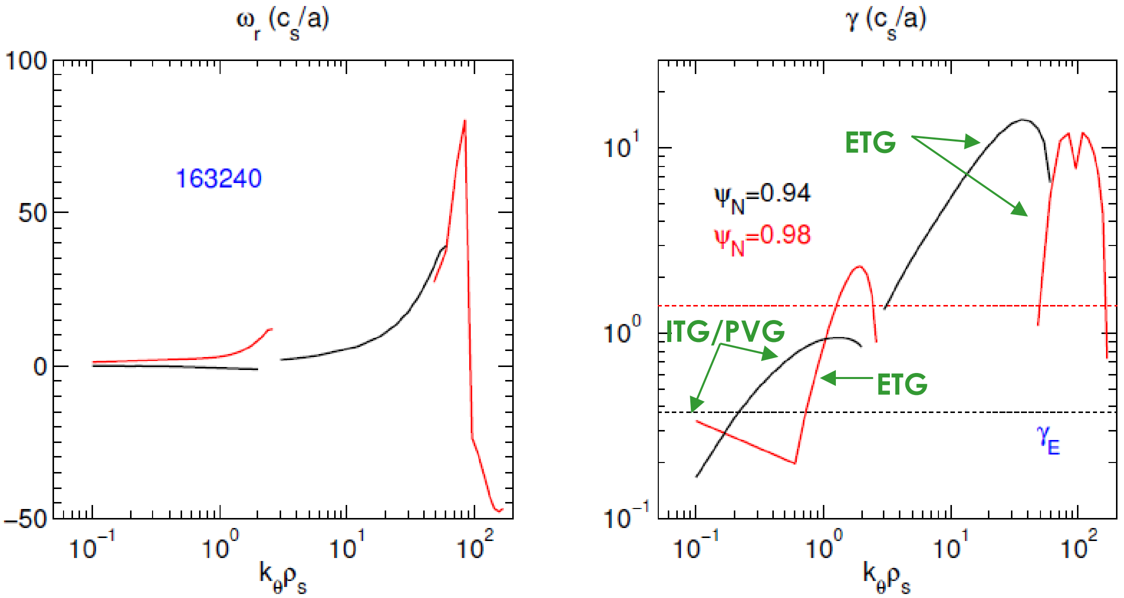
- <u>Pedestal top</u>: strong drive from u′ with $\gamma_{ion}>\gamma_E$; modes transition from i-dia to e-dia ($a/L_{Te} > a/L_{Ti}$)
- <u>Sharp gradient region (ψ_N~0.98)</u>: weak ion modes ($\gamma_{lin}<\gamma_E$), no enhancement from u′ where R/L_n > u′; electromagnetic effects stabilizing; sign of low k_y ETG



In the sharp gradient region (ψ_N~0.98): weak ion modes ($\gamma_{lin}<\gamma_E$), very broad spectrum of ETG

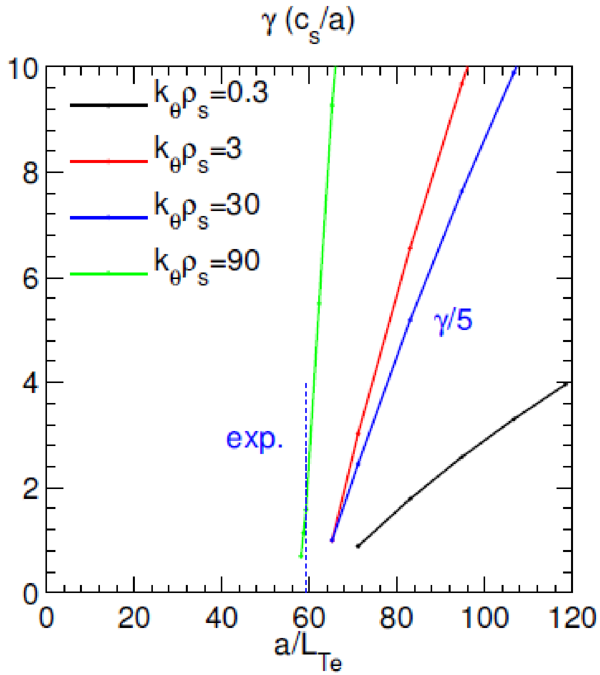
- **ETG extends to both $k_\theta\rho_s<1$ and $k_\theta\rho_s$ >100 for larger a/L_{Te} gradients (ψ_N=0.98)**
  - Predicted in AUG [Told, 2008; Hatch, 2015] and NSTX [Canik, 2013; Coury 2016]

- **Large low-k_θ / high-k_θ gap at ψ_N=0.98 eliminated w/ marginal ∇T_e increase (1.2 × a/L_{Te})**

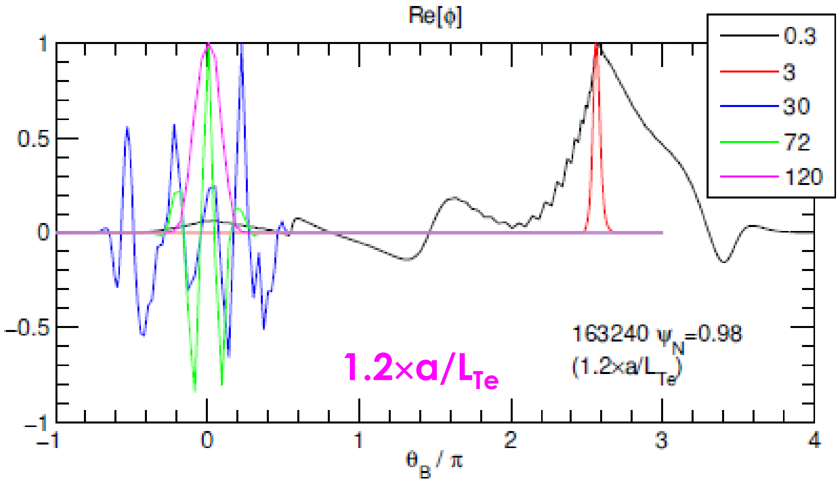


∇T_e near ETG threshold in the sharp gradient region (ψ_N=0.98)

- **a/L_{Te} sitting near ETG threshold for <u>broad</u> range of wavenumbers $k_\theta\rho_s$=0.3-90 (n≈90-26,000)**

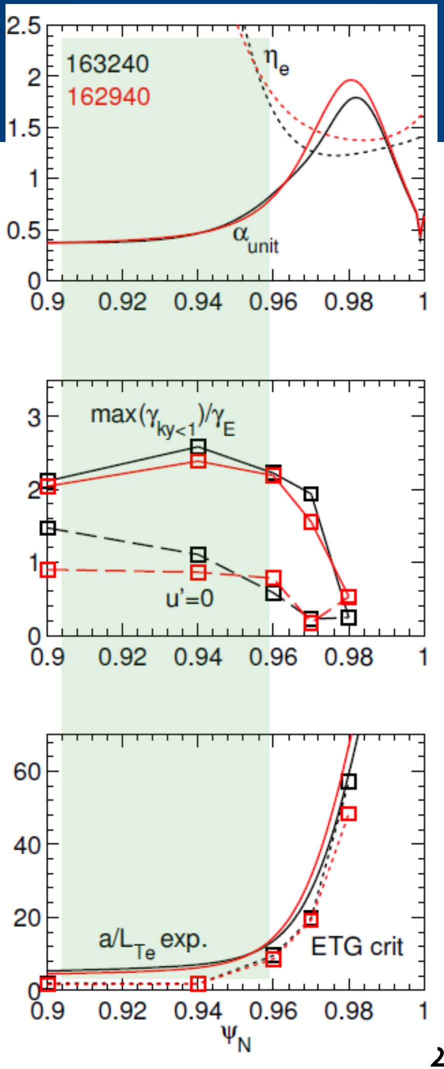


- **Large gradient drive excites fine parallel structure, high-order eigenfunction states (e.g. [H. Chen, L. Chen, 2018])**
- Lower $k_\theta\rho_s$ modes peaking around X-points (N_{int}*2π +/- 0.6π)
- Highest $k_\theta\rho_s$~120 follows more traditional ballooning shape



Linear summary

- **Pedestal top (ψ_N=0.9-0.97)**
  – ITG/TEM/PVG modes with growth rates larger than E×B shearing rate ($\gamma_{lin,ion}>\gamma_E$) → expected to dominate transport



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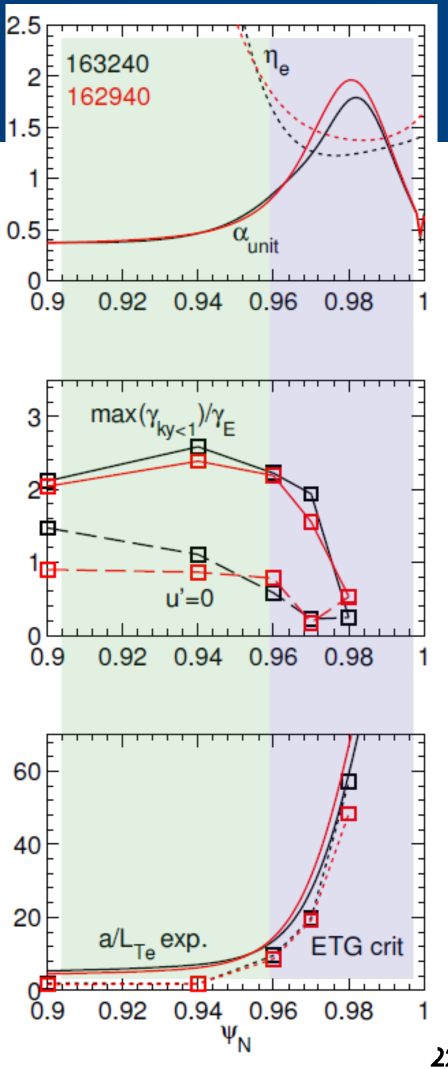
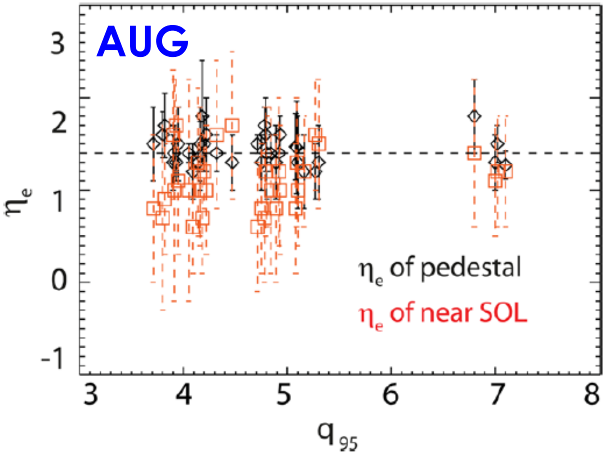
- **Sharp gradient region (ψ_N = 0.96-0.98)**
  - Ion modes become weak, expect to be suppressed by E×B shearing (γ_E > $\gamma_{lin,ion}$) + non-local profile-shearing (ρ_i/L_T~0.5)
  - ∇T_e follows ETG threshold, η_e = (a/L_{Te}) / (a/L_{ne}) ~1.2-1.5
  - Expected for larger R/L_n (e.g. Jenko, 2001, 2009):

$$\left(\frac{R}{L_{Te}}\right)^{crit}_{ETG} = \mathrm{Max}\left[\begin{matrix}(1+Z_{eff}T_e/T_i)(1.3+1.9\,s/q\,)(\cdots)\\ C\cdot R/L_n\end{matrix}\right]$$



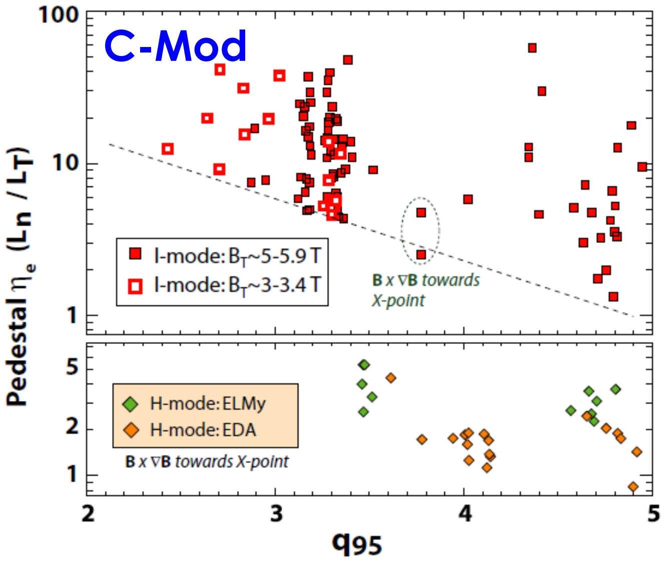
Some experimental evidence for the relevance (or not) of η_e in contributing to pedestal structure

- η_e~1.5-2 (ELMy H-mode)



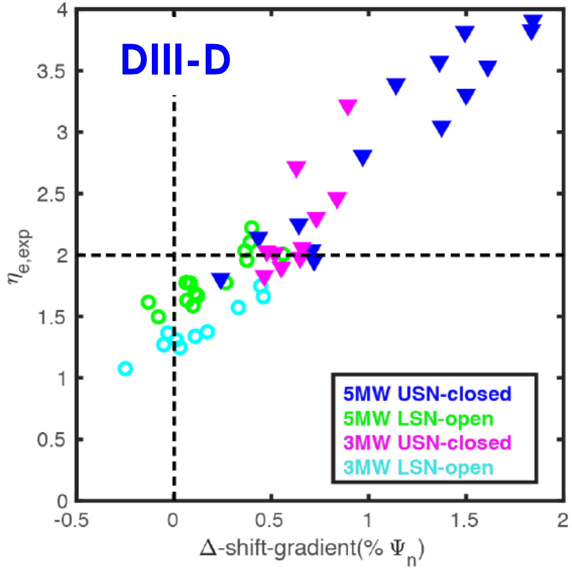
H.J. Sun (2015),
J. Neuhauser (2002)

- η_e~1-2 (EDA H-mode)
- η_e~2-4 (ELMy H-mode)
- Even larger for I-mode



D.G. Whyte (2010),
J.W. Hughes (2002)

- η_e varying with divertor closure / fueling / detachment (ELMy H-mode)



H.Q. Wang (2018)

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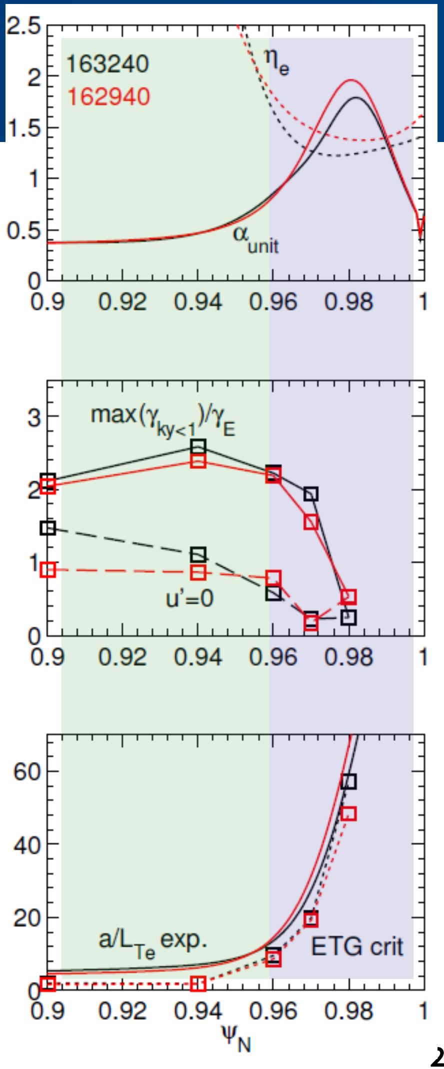
- **Can ETG transport alone account for pedestal structure and changes as source changes? → Lets test single-scale nonlinear ETG theory where drift-ordered GK is valid**



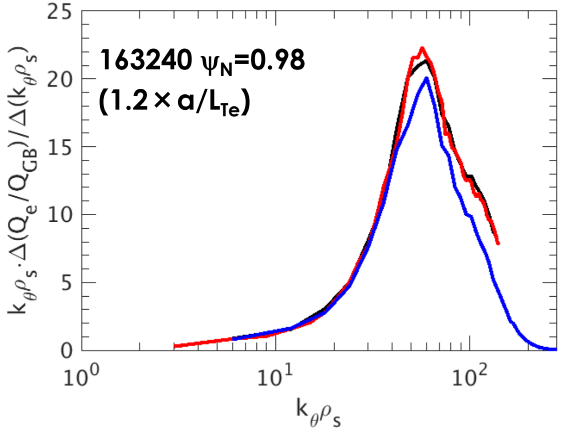
Nonlinear ETG simulations saturate with spectral peak at $k_\theta\rho_s$~50; turbulence peaks near outboard mid-plane (not X-point)

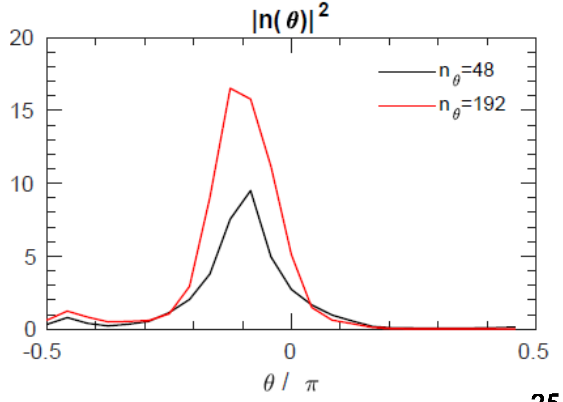
- **Peak at $k_\theta\rho_s$~50 much larger than typical core ETG simulations ($k_\theta\rho_{s,peak}$~10-15)**
  - Converged with perpendicular grid parameters

- **Fluctuations peak near outboard mid-plane (not X-point) → $(k_\theta\rho_s)_{peak,\theta=0}$ ~ 10 (similar to core)**
  - $(k_\theta)_{\theta=0}$ / k_θ = $[(d\nu/d\theta) / \kappa]$ = 0.2 for field-aligned ($\alpha = \varphi - q\nu$) flux coordinates

- **Features similar to those predicted in pedestal of AUG [Hatch, NF 2015] and NSTX [Canik, TTF 2016]**

Electron heat flux spectrum density (area-preserving)





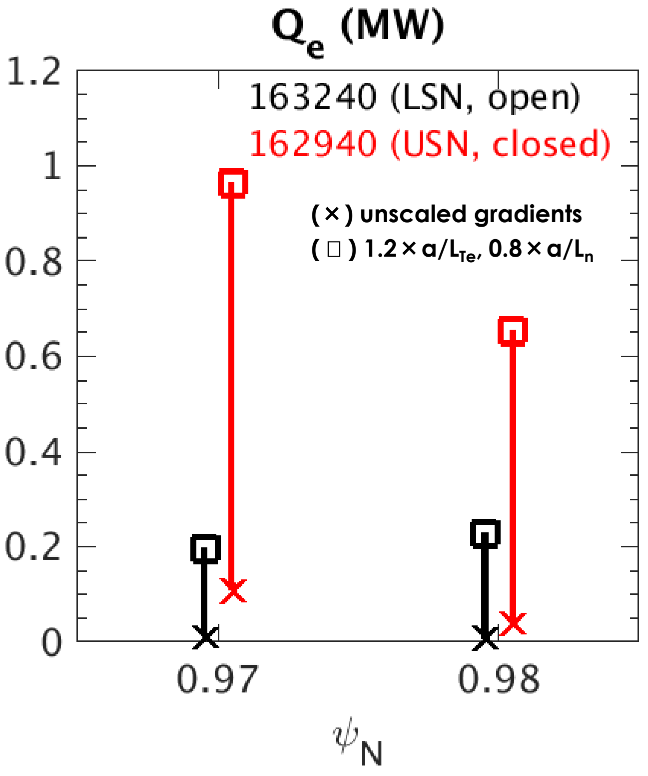
Nonlinear ETG simulations predict Q_e~0.2-1.0 MW using 20% scaled gradients

$Q_{e,ETG}$ < 0.1 MW (base gradients)
Q_{eETG} = 0.2-1 MW (20% scaling in ∇n & ∇T)

$Q_{i,NEO}$ = 0.7 MW

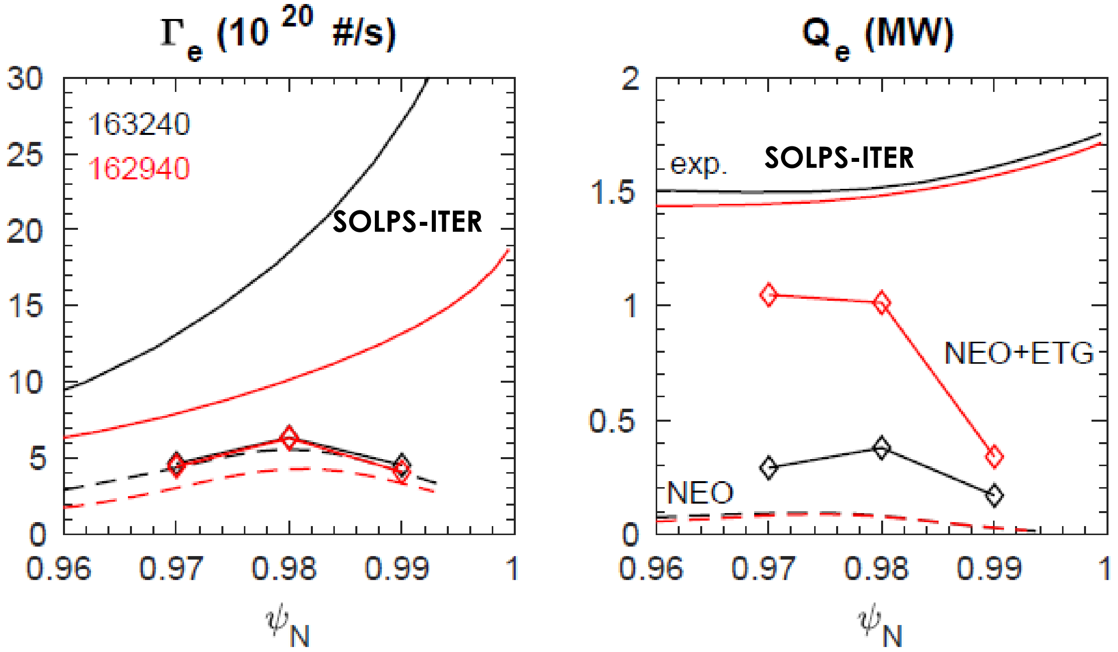
$Q_{e+i,TRANSP}$ = 2.8 MW

- **Q_{ETG} + Q_{NEO} accounts for 30-60% of experimental Q_{e+i}** (using scaled ∇n_e, ∇T_e)



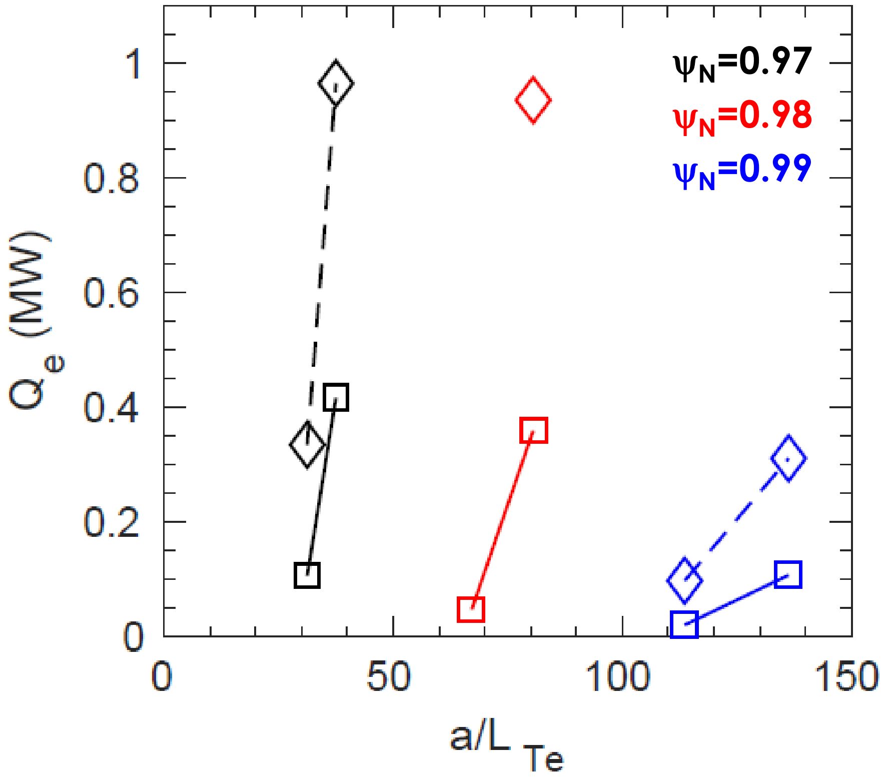
ETG (scaled gradients) + NEO recovers some, not all, of electron particle and thermal transport inferred from SOLPS-ITER

- Γ_e and Q_e agreement closer for closed divertor case
- Neoclassical Γ_e >> ETG Γ_e
- ETG + NC does not appear to account for all Γ_e & Q_e
- $(D_e/\chi_e)_{SOLPS}$ ~ 0.05-0.1



Let's invert the problem → predict profiles for given target fluxes, but we need transport model…

Additional simulations run to identify key dependencies with a/L_{Te} and a/L_{ne}

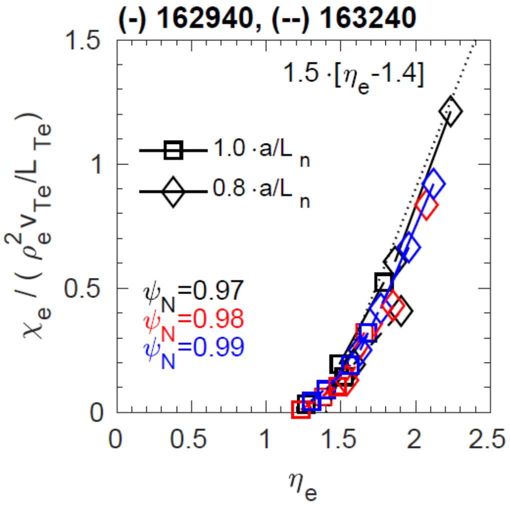


- **Wide variation in predicted transport depending on density and temperature gradients**

(solid) 1.0 × $a/L_{n,exp}$
(dash) 0.8 × $a/L_{n,exp}$

$\chi_{e,ETG}$ vs η_e overlap when using ETG-relevant electron gyroBohm (expected in "slab" limit, $L_{T,n}/R << 1$)

- **~O(1) $\rho_e^2 v_{Te}/L_{Te}$ indicative of slab ETG transport, smaller than ~O(10) found for toroidal ETG [Jenko, Dorland 2000, 2002]**



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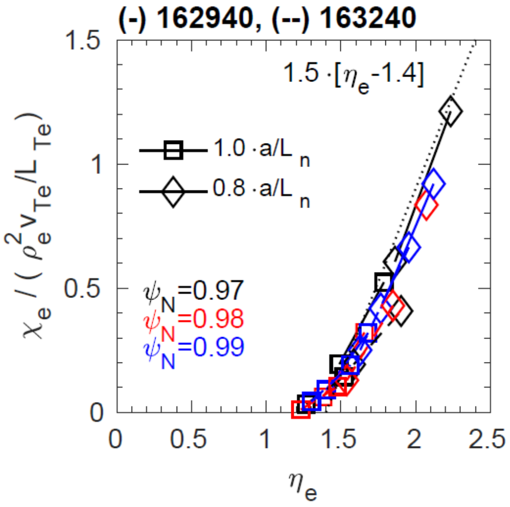

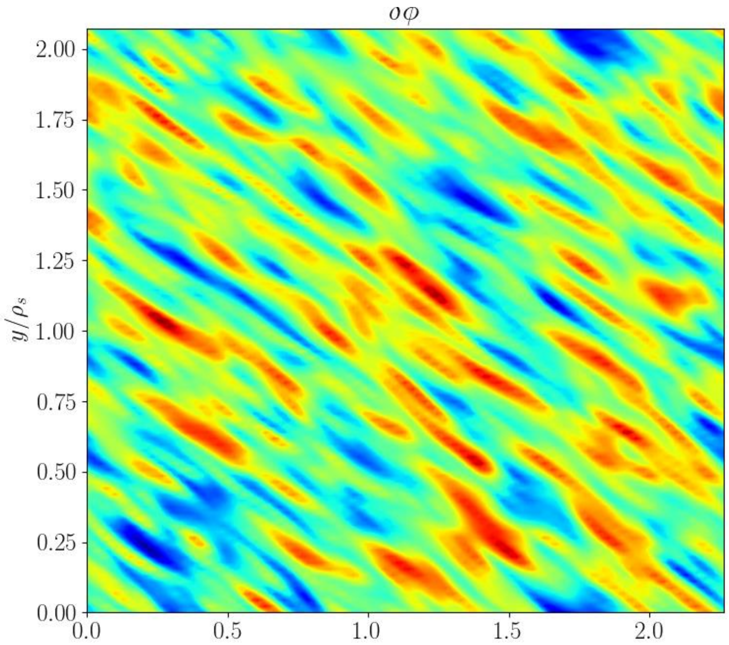

Eddies closer to isotropic than "streamers" (L_x~6 ρ_e < 15 ρ_e typical for core "streamers")

Strongly titled from large γ_E and s

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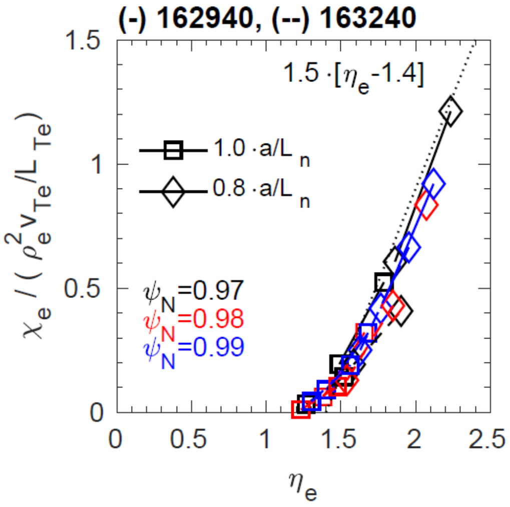
- **Slab saturation explained by "Cowley secondary" instability [Cowley 1991] → zonal flow driven by primary instability modes**
  - Cowley secondary + high R/L → large $k_{||}$, demands high parallel resolution (n_θ=[48,144,192] for ψ_N=[0.97,0.98,0.99])



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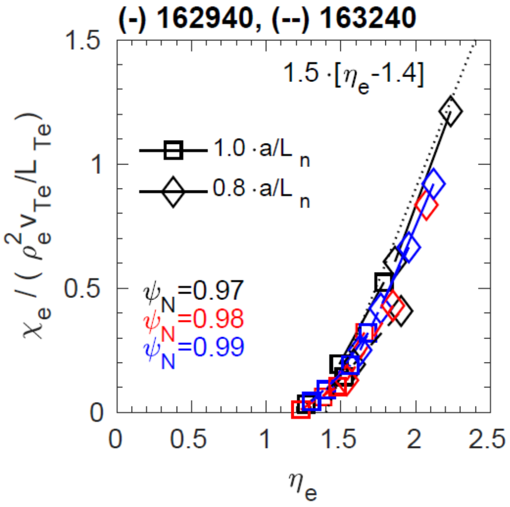
- **Can infer a very simple reduced slab-ETG pedestal transport model**



Regime of applicability:
R/L_{ne} >> 1

$$\chi_{e,ETG} = 1.5 \cdot [\eta_e - 1.4] \cdot \left(\frac{a/L_{Te}}{60}\right) \cdot \left(\frac{\rho_s^2 c_s}{a}\right)$$

Similar to GENE sims for AUG H-mode (Jenko, 2009)

$\chi_{e,ETG}$ vs η_e overlap when using ETG-relevant electron gyroBohm (expected in "slab" limit, $L_{T,n}/R \ll 1$)

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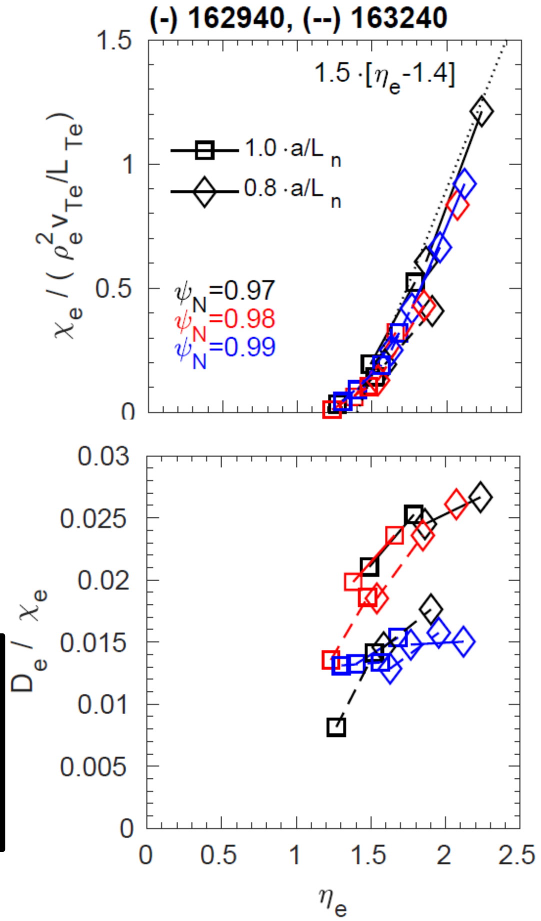

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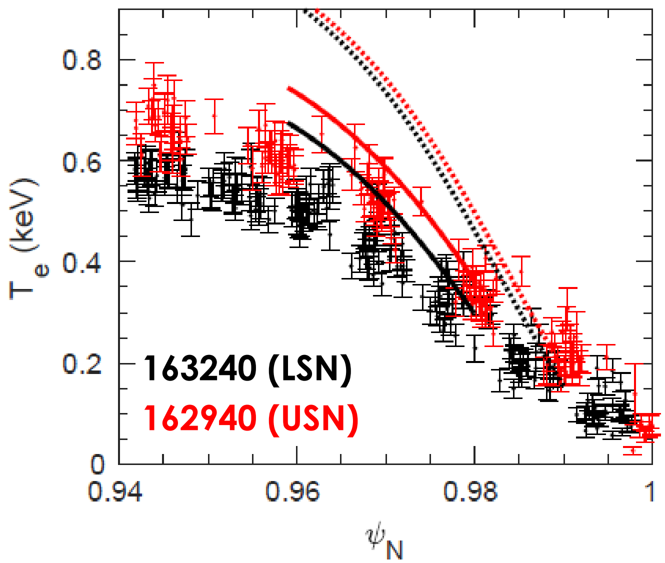
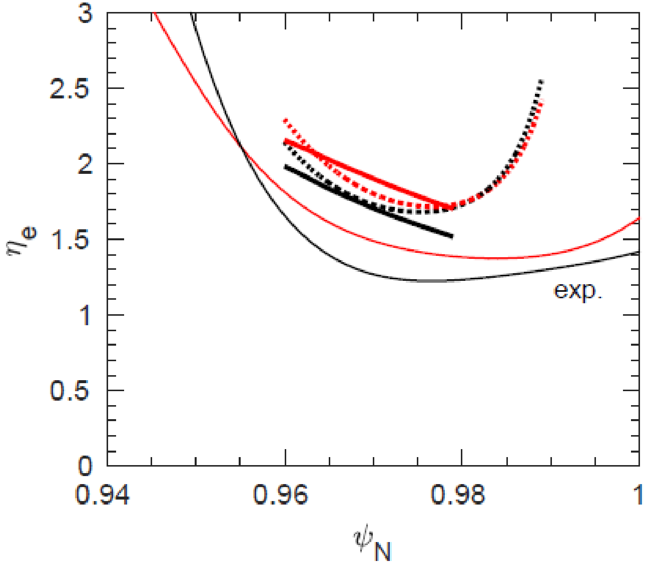
$$\chi_{e,ETG} = 1.5 \cdot [\eta_e - 1.4] \cdot \left(\frac{a/L_{Te}}{60}\right) \cdot \left(\frac{\rho_s^2 c_s}{a}\right)$$

$$D_{e,ETG} = 0.02 \cdot \chi_{e,ETG}$$

ETG transport model slightly over-predicts T_e (for fixed n_e); captures increase in T_e with lower n_e

- **Captures increase in T_e and η_e with lower n_e (but mostly because $T_{e,BC}$ larger)**
- **Slight over-prediction of T_e; gets worse if we move boundary out to $\psi_{N,BC}$=0.99**
  - Difficult to overcome falling gyrobohm coefficient $Q_{GB} \sim T_e^{5/2}$



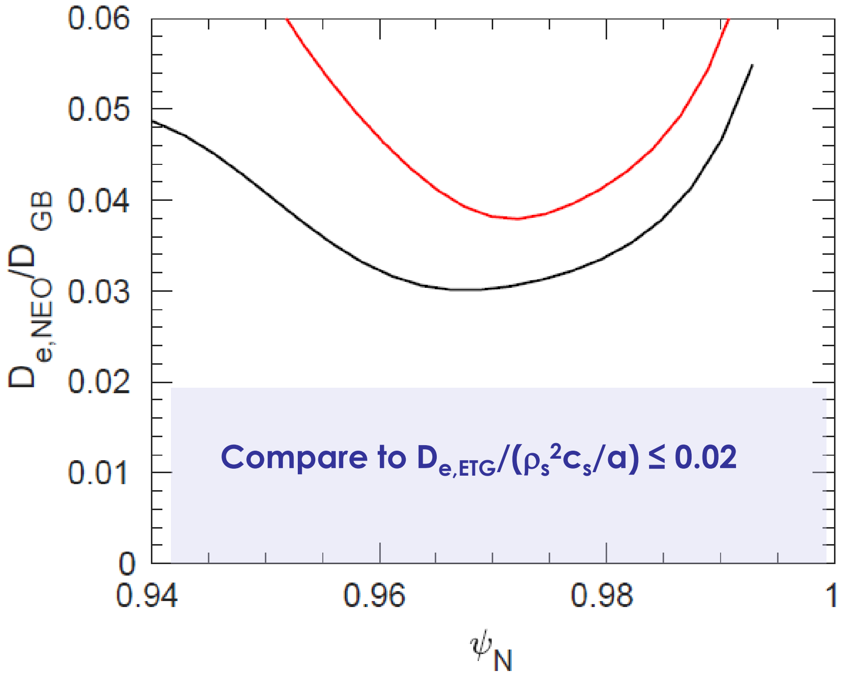


- **Want to predict n_e & T_e simultaneously to see if sensitivities of transport with gradients improves / degrades agreement**

To predict n_e, need to include neoclassical particle transport (larger than ETG contribution)

In the following n_e + T_e predictions, we use:

- **SOLPS-ITER Γ_e & Q_e for target fluxes**
- **Assumed constant $D_{e,NC}=0.05 \cdot D_{GB}$**



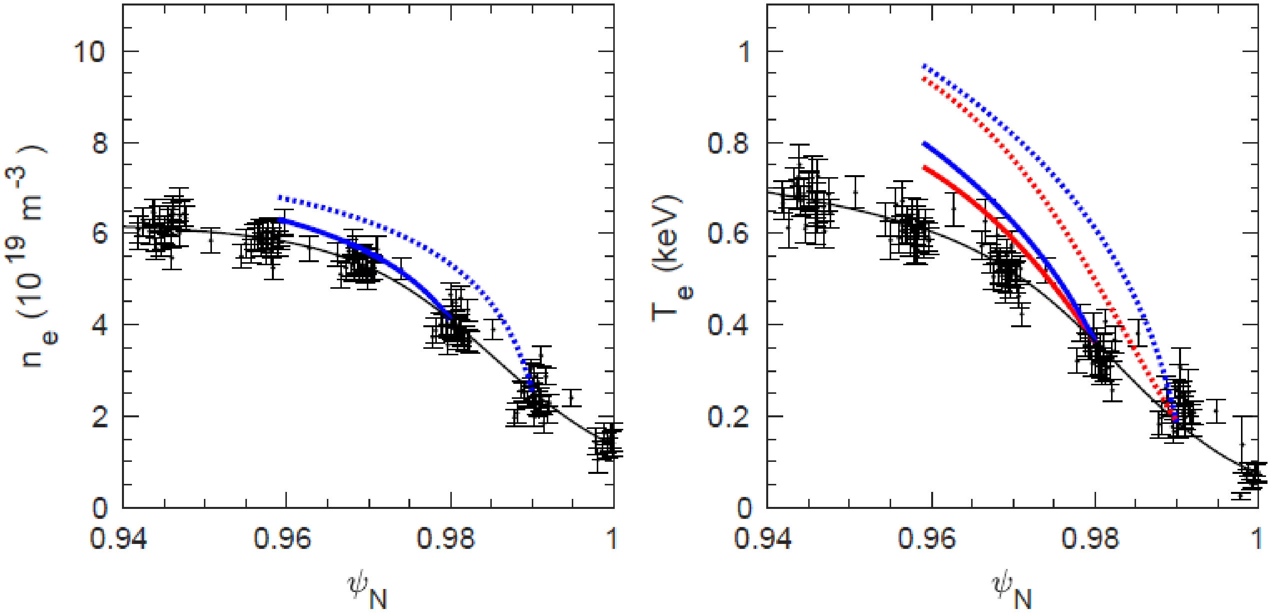
n_e & T_e predictions for closed divertor discharge similar to T_e only prediction

- $n_{e,pred}$ ~ $n_{e,exp}$ (dominated by neoclassical Γ_e)
- Similar T_e over-prediction, gets worse as BC moved outward

<u>162940 (closed divertor)</u>

(red) T_e only prediction

(blue) n_e & T_e prediction



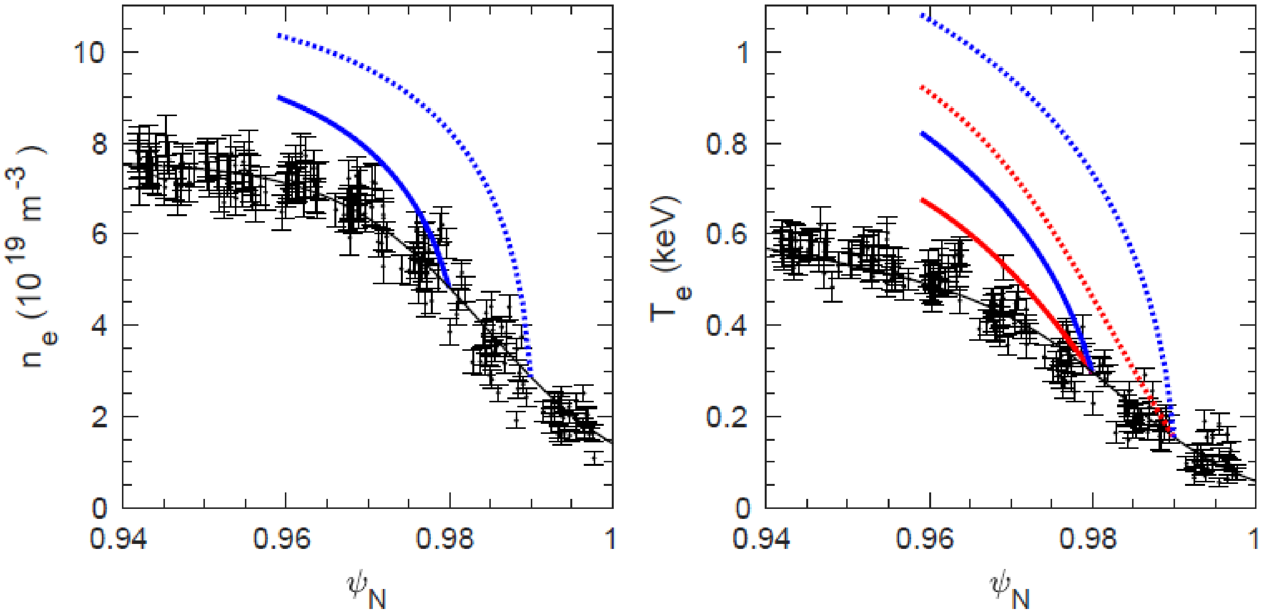
Much larger over-prediction for open divertor discharge (larger edge particle source)

- $\Gamma_{e,open\text{-}divertor}$ ~double the closed divertor case → gives much larger $n_{e,pred}$ and corresponding $T_{e,pred}$

163240 (open divertor)

(red) T_e only prediction

(blue) n_e & T_e prediction



Much larger over-prediction for open divertor discharge (larger edge particle source)

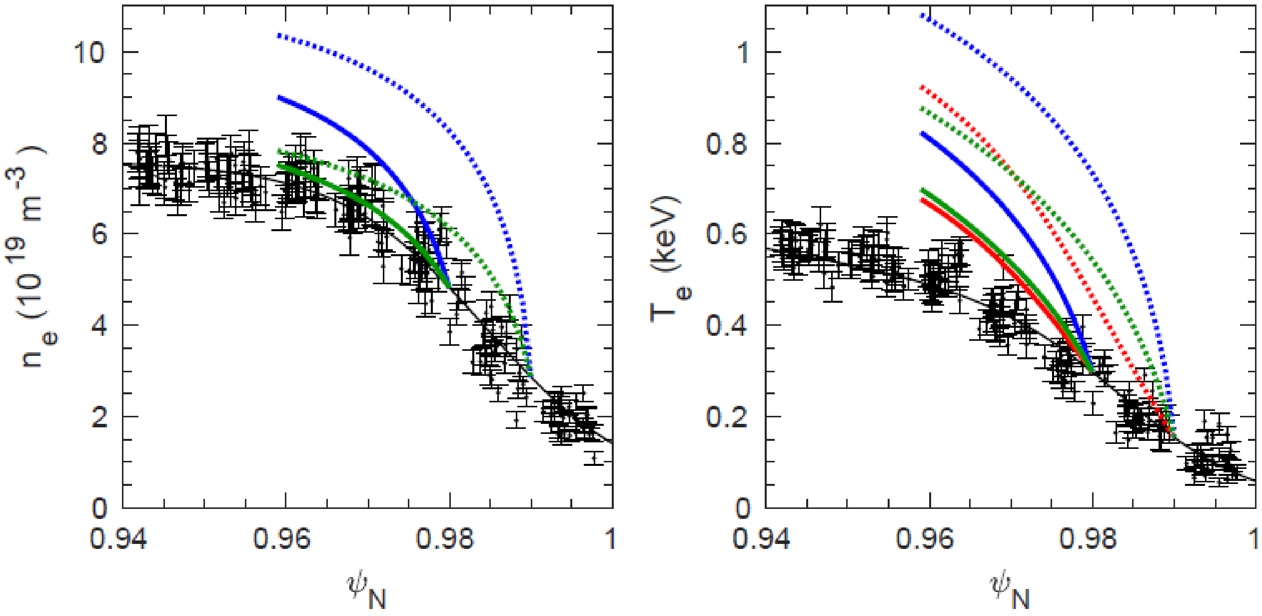
- $\Gamma_{e,open\text{-}divertor}$ ~double the closed divertor case → gives much larger $n_{e,pred}$ and corresponding $T_{e,pred}$
- Improved agreement if we use $\Gamma_{e,closed\text{-}divertor}$

<u>163240 (open divertor)</u>

(red) T_e only prediction

(blue) n_e & T_e prediction

(green) n_e & T_e prediction ($\Gamma_e = \Gamma_{e,closed\ divertor}$)



Plenty of uncertainties to investigate

- **Sensitivity to T_i (e.g $T_d < T_c$ as in some main ion CX measurements [Haskey, 2018])**
  - Slab ETG not very sensitive: reducing T_i/T_e=[1.47,2.45]→1 for ψ_N=[0.98,0.99] reduces $Q_{e,ETG}$ ~20%
  - Lower $T_{i,sep}$ / larger $\nabla T_{i,ped}$ increases neoclassical ion heat flux ($Q_{i,NEO}$ doubles for T_d=T_e)
  - Expect some impact on collisional coupling (Q_e / Q_i partition)

- **SOLPS-ITER analysis needs further validation and sensitivity tests to boundary conditions (may change inferred sources / fluxes)**

- **Need to self-consistently evaluate NEO and collisional exchange in the profile predictions**
  - ETG-model has been added to TGYRO, will test soon

- **More careful accounting for inter-ELM time-dependence in analysis and modeling**

Summary

- ***Linear*** **gyrokinetic analysis (CGYRO) suggests electron scale ETG turbulent transport may limit $\eta_e \sim \nabla T_e/\nabla n_e$ in some DIII-D ELMy H-mode pedestals**

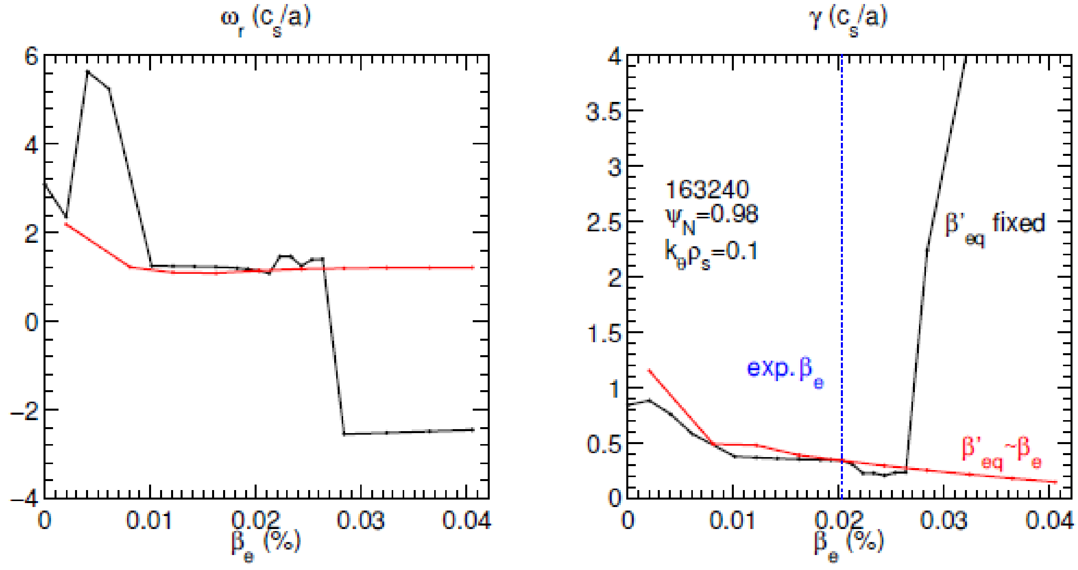
- **Numerous *nonlinear* gyrokinetic simulations run to predict ETG transport, used to develop ETG pedestal transport model**
  - This is one of a few necessary pieces of a pedestal transport model

- **ETG contributes to $\chi_{e,ped}$, *but unlikely to be the only transport mechanism***
  - Ion-scale turbulence may contribute (simulations in progress)
  - Evidence for QCFs, recently interpreted as MTM [Diallo 2015, X. Liu, 2018 thesis]
  - Recent analysis suggests ion-scale turbulence becomes increasingly important for increasing pedestal widths w/ρ_i>10 [Kotschenreuther, 2017]) → Similar result found in wide-pedestal grassy-ELM regime analysis [A. Ashourvan]

- **Neoclassical D_e plays non-negligible role in setting density profile**
  - Any additional transport mechanism must likely satisfy D_e/χ_e<<1 for these shots (e.g. MTM)

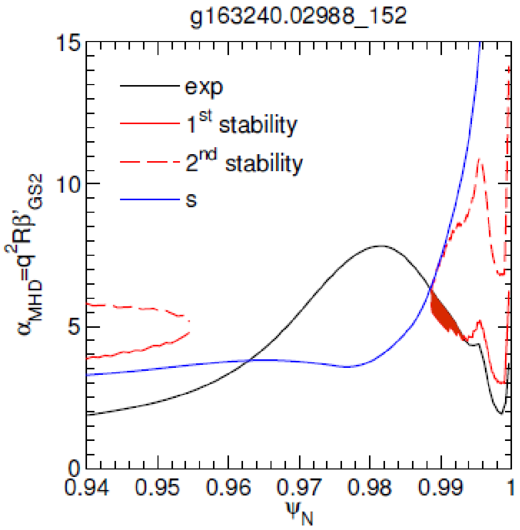
Electromagnetic effects stabilizing at ψ_N=0.98

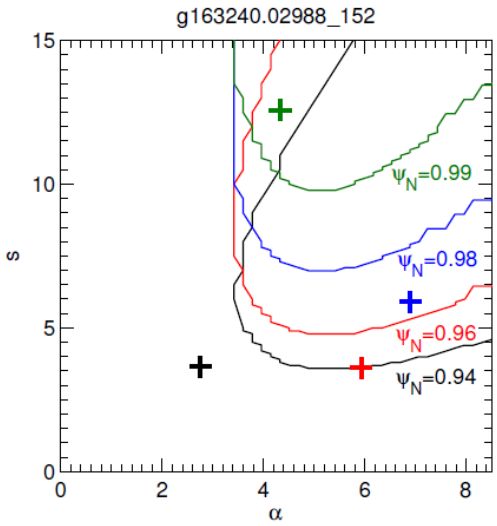
- **EM effects are stabilizing to ion scales modes in sharp gradient region**
- **β_e scans show ψ_N=0.97-0.98 is 15-20% below KBM threshold**
  - 2nd stable if one varies $\beta'_{eq} \sim \beta_e$
  - Consistent with ideal infinite-n MHD ballooning simulations (next slide)



Small region in lower half of pedestal is sitting near ideal MHD infinite-n ballooning threshold

- **Ideal MHD calculations (via '*ball*') indicate lower half of pedestal near infinite-n ballooning stability boundary**
  - Only $\Delta\psi$=0.005 surpasses threshold (out of $\Delta\psi_{ped}$~0.03)
  - Region of sharpest gradient (ψ_N=0.98) is 2nd stable

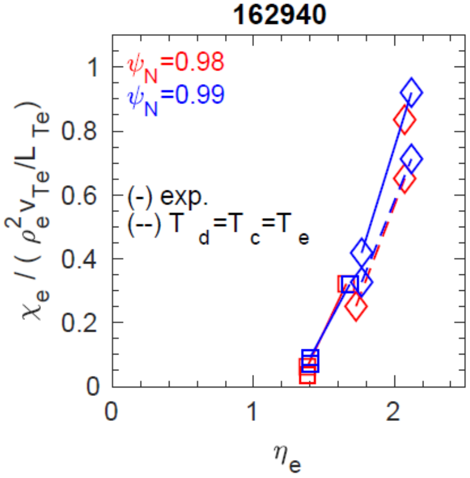


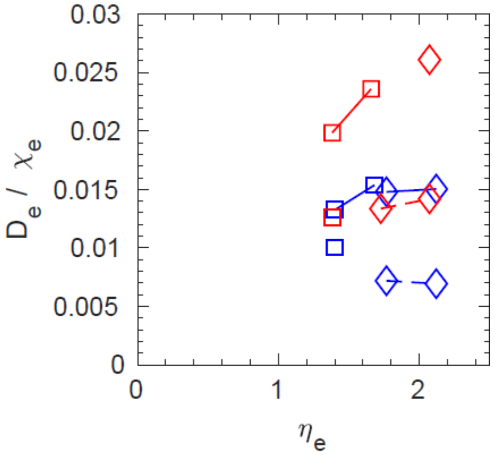


- **Finite-n effects can remove 2nd stability [Snyder …]**

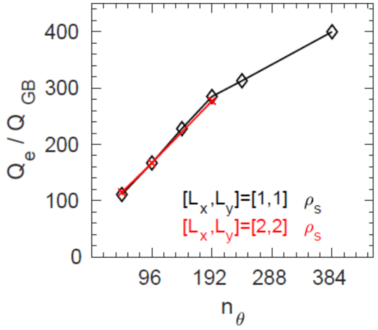
Testing $T_d=T_c=T_e$ in CGYRO NL ETG simulations (162940)

- **Don't expect T_e/T_i to strongly influence slab ETG (need to revisit old theory papers)**
  - Reducing T_i/T_e=[1.47,2.45]→1 for ψ_N=[0.98,0.99] reduces $Q_{e,ETG}$ ~20%
  - Also lowers D_e/χ_e ~ 50%





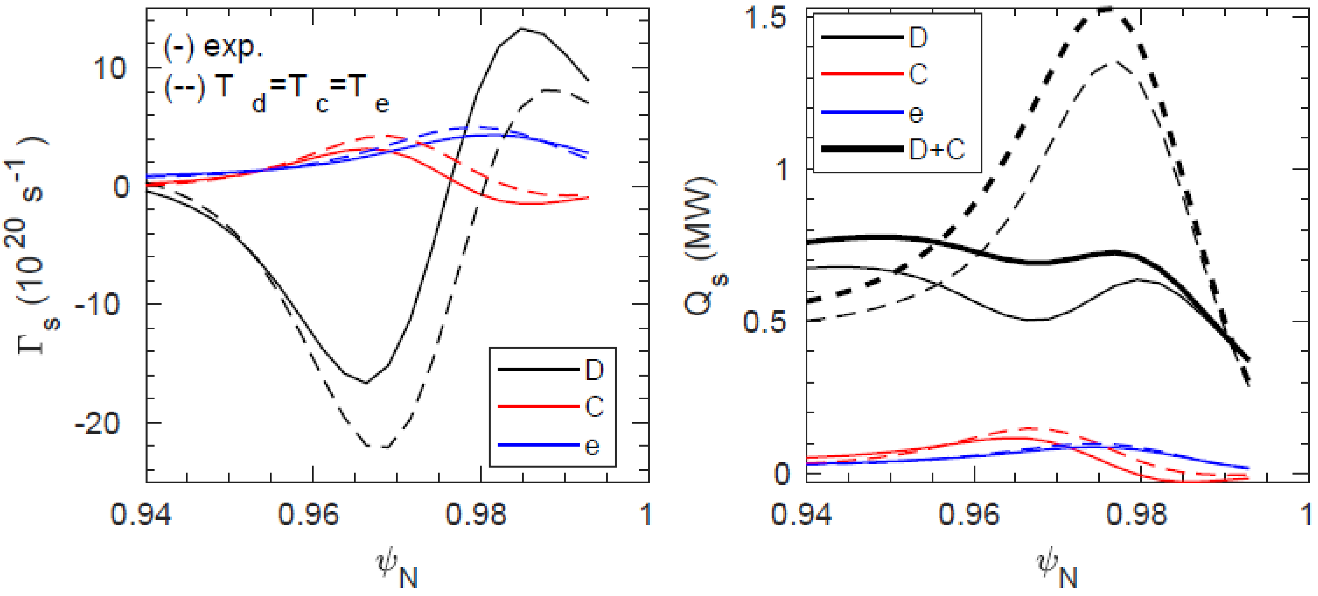
- **Have also continued with resolution tests – going to n_θ=384 (ψ_N=0.99) gives additional 30% increase →**



➢ **~30% uncertainty in leading coefficient of transport model**

Testing $T_d=T_c=T_e$ in NEO simulations (162940)

- **$Q_{i,NC}$ ~ doubles (0.5-0.7 MW → 1-1.5 MW)**

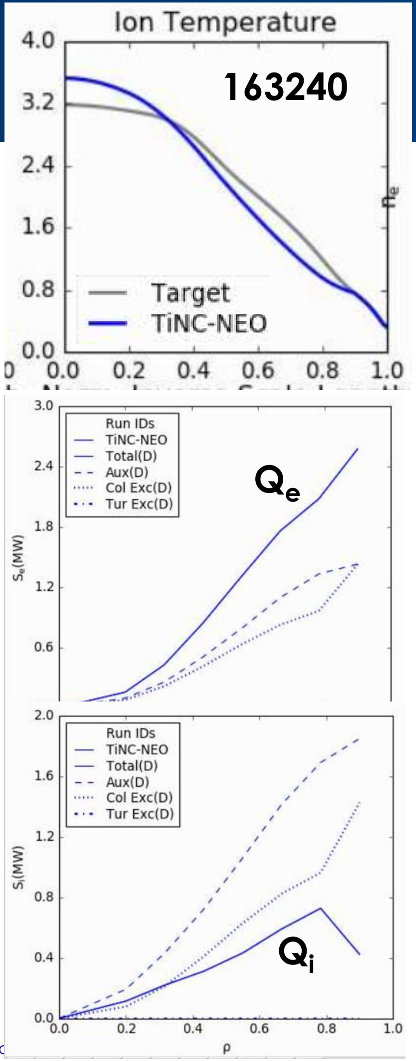


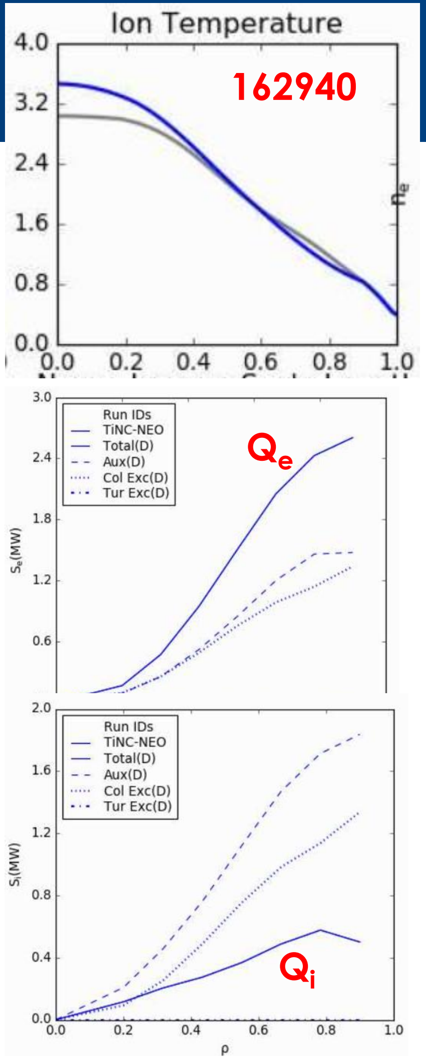
NC alone accounts for core Q_i

- **Predictions of T_i-only using NEO+TGYRO (within OMFIT)**

- **Using fixed T_e, ne, geometry …**
- **Only $\chi_{i,NEO}$ (with dynamic energy exchange) gives $Q_{e,0.9}$~2.5 MW**
  - Larger than the ~1.5 MW used in above SOLPS-ITER analysis

- **Perhaps this is an underpowered discharge (3 MW /)**





Using simple transport solver to predict profiles

- Fixed equilibrium, T_i (and n_e, in this example)
- Use Q_e from SOLPS-ITER as target flux
- Set $T_{e,BC}$ to match experimental T_e fit at ψ_N=0.98 (or 0.99)

- Evaluate:

$$Q_{e,target} = Q_{e,model}(T_e, \nabla T_e\ ;\ n_e, \langle \nabla V \rangle, B_{unit}, a)$$

at cell center $(i+\frac{1}{2})$ to solve for T_e^{i+1}, e.g.

$$T_{e,mid} = \frac{(T_e^{i+1}+T_e^{i})}{2}$$

$$a\nabla T_e = \frac{(T_e^{i+1}-T_e^{i})}{d\left(\frac{r}{a}\right)}$$

- Not updating i→e collisional energy exchange