Testing Paleoclassical Predictions Against Measured DIII-D Pedestal Profiles

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Outline

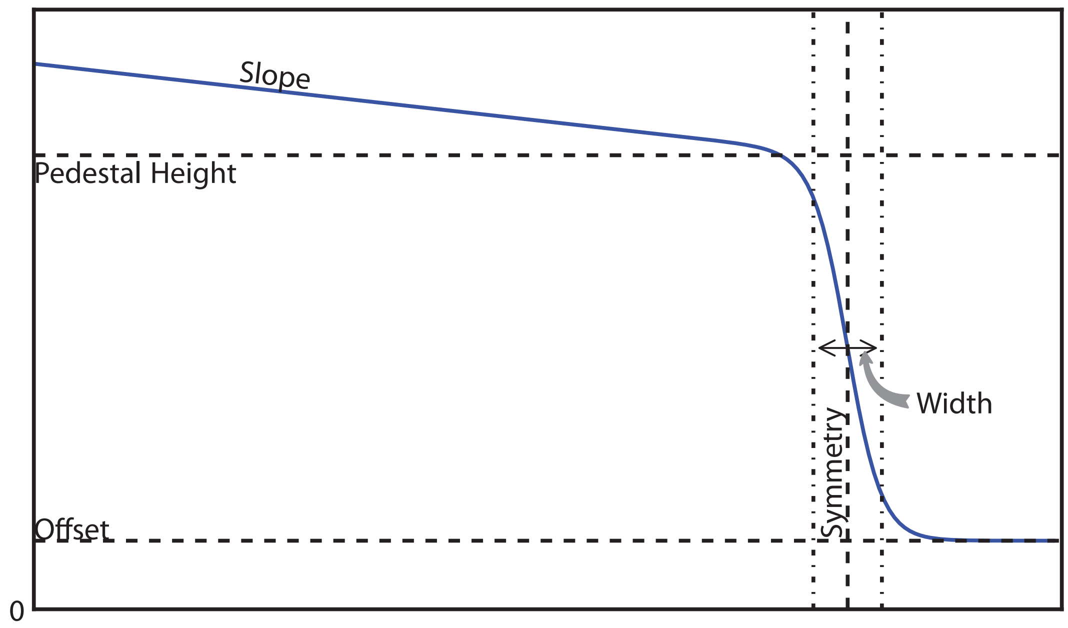
1. Description of database of experimental measurements
2. Description of the Paleoclassical pedestal model
3. Paleoclassical predictions for the whole database
4. Specific input and Paleoclassical profiles
5. Summary

Pedestal Database Measurements Come from a Variety of DIII-D H-mode Shots

- **Scans**
  - ρ_* scan for comparison with JET
  - EPED scaling tests
    - shape
    - q_{95}
    - β_p
  - ITER demo discharges
    - baseline
    - hybrid
    - steady state
- **Data sources**
  - n_e and T_e come from Thomson scattering
  - Z_{eff} comes from n_e and CER determination of Carbon density
  - Data averaged over ~ 80–99% phase of multiple ELM cycles

n_e and T_e Data are Fit by Modified Tanh
f_z Data are Fit by Spline

$$\text{fit} = \frac{\text{ped} - \text{off}}{2}\left[\frac{(1 + z^*\text{slo})e^{z} - e^{-z}}{e^{z} + e^{-z}}\right] + \frac{\text{ped} + \text{off}}{2}$$

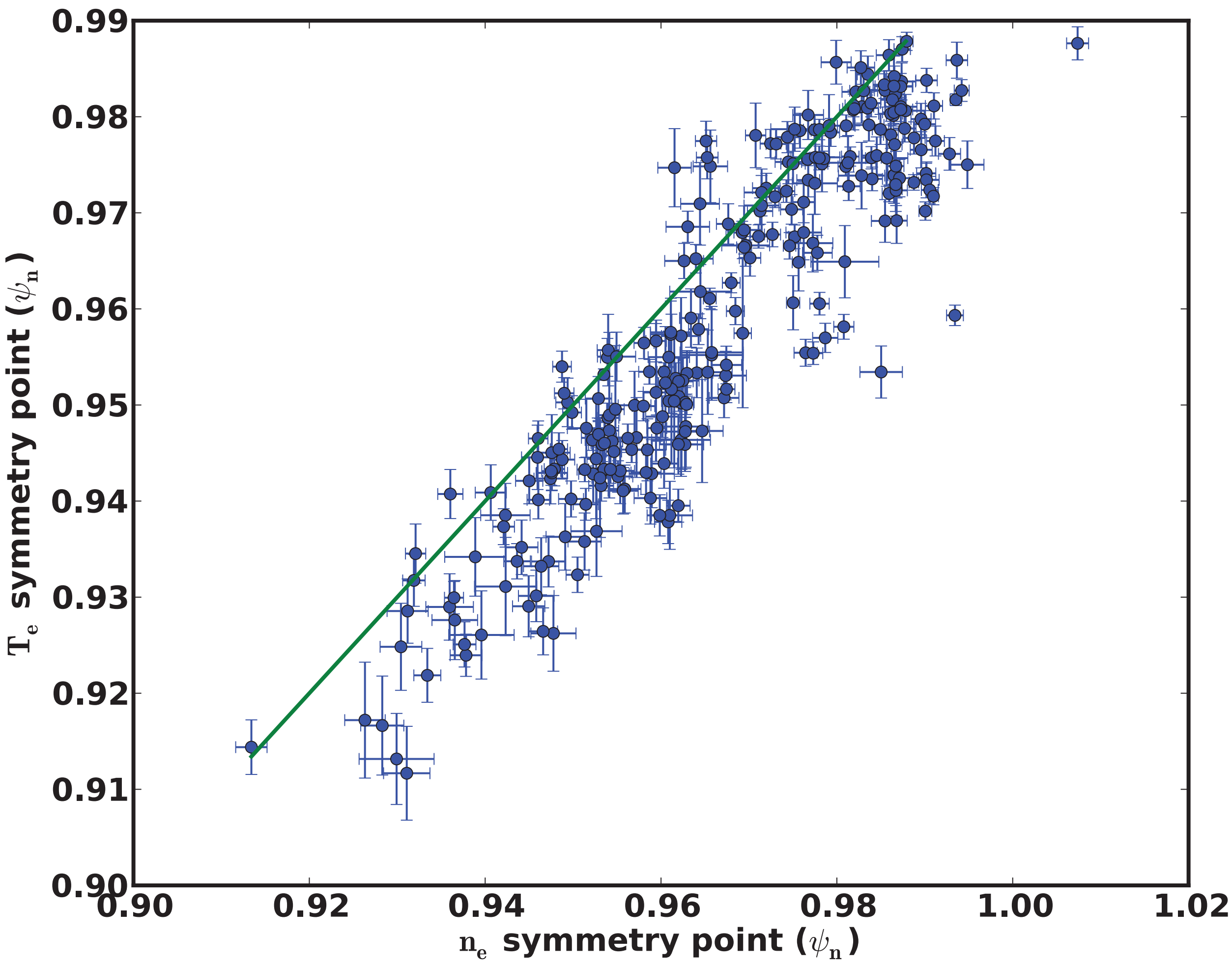


$$z \equiv 2\frac{\text{sym} - \rho}{\text{wid}}$$

$$\rho_T \equiv \text{sym}_{T_e}$$

$$\rho_D \equiv \text{sym}_{n_e}$$

n_e Tanh Symmetry Point Occurs Further Out for the Database than the T_e Symmetry Point



- **Green line indicates equality**
- **Local fueling may account for** $\rho_D > \rho_T$

Paleoclassical Diffusion, Proportional to Neoclassical Resistivity, is a Minimum Transport

- The main thrust of paleoclassical theory is that as poloidal magnetic flux diffuses outward, it carries with it particles and energy, which can be characterized by a single diffusion coefficient, $D_\eta \equiv \eta_{||}^{nc}/\mu_0$, where the resistivity is the parallel neoclassical resistivity
- In this study $\eta_{||}^{nc}$ is evaluated based on equations given in UW-CPTC 09-6R
- Because paleoclassical processes are only the minimum transport processes, they are only dominant in the steep gradient region of the pedestal where other processes are less dominant
- To compare the paleoclassical model of the electron pedestal to experimental measurements, we will evaluate Eqs. (1) & (2) (see next slide) at the symmetry point of the T_e tanh fit ρ_T

Paleoclassical Predictions in the Pedestal: n_e and ∇T_e

- **Electron density profile in the pedestal** [1]

$$n_e(\rho) \simeq \frac{a^2 \left(n_e D_\eta V'/\bar{a}^2\right)\Big|_a + \int_\rho^a \dot{N}_e \, d\rho}{a^2 \left(D_\eta V'/\bar{a}^2\right)\Big|_\rho} \qquad (1)$$

- **Electron temperature gradient** [2]

$$-\frac{dT_e}{d\rho} \simeq \frac{\hat{P}_e - (3/2)\dot{N}_e T_e}{(3/2)(V' D_\eta n_e a^2/\bar{a}^2)} \qquad (2)$$

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[1] UW-CPTC 10-6 Eq. (29)
[2] UW-CPTC 10-6 Eq. (35)

Definitions of Terms

$$\hat{P}_e \equiv -\left\{ \begin{array}{l} \text{electron heat flow through the separatrix} \\ + \displaystyle\int_\rho^a \frac{V'(\hat{\rho})}{M(\hat{\rho})+1} \left[Q_e^{net} - \frac{1}{V'} \frac{d}{d\rho} \left(\tfrac{5}{2} V' T_e \Gamma \right) \right] d\hat{\rho} \end{array} \right\}$$

$\Gamma \equiv$ particle flux

$$\dot{N}_e \equiv -\left\{ \begin{array}{l} \text{Particle flow through the separatrix} \\ + \displaystyle\int_\rho^a V'(\hat{\rho}) \langle S_n(\hat{\rho}) \rangle d\hat{\rho} \end{array} \right\}$$

$$V' \equiv \frac{d}{d\rho}(\text{volume})$$

$\langle S_n \rangle \equiv$ local particle source

$Q_e^{net} \equiv$ local electron heating

$$M \equiv \frac{1/(\pi R_0 q)}{1/(\pi \bar{R} q n_{max}) + 1/\lambda_e}$$ helical winding factor

$$n_{max} \equiv 1/\sqrt{\pi \delta_e |q'|/\bar{a}}$$

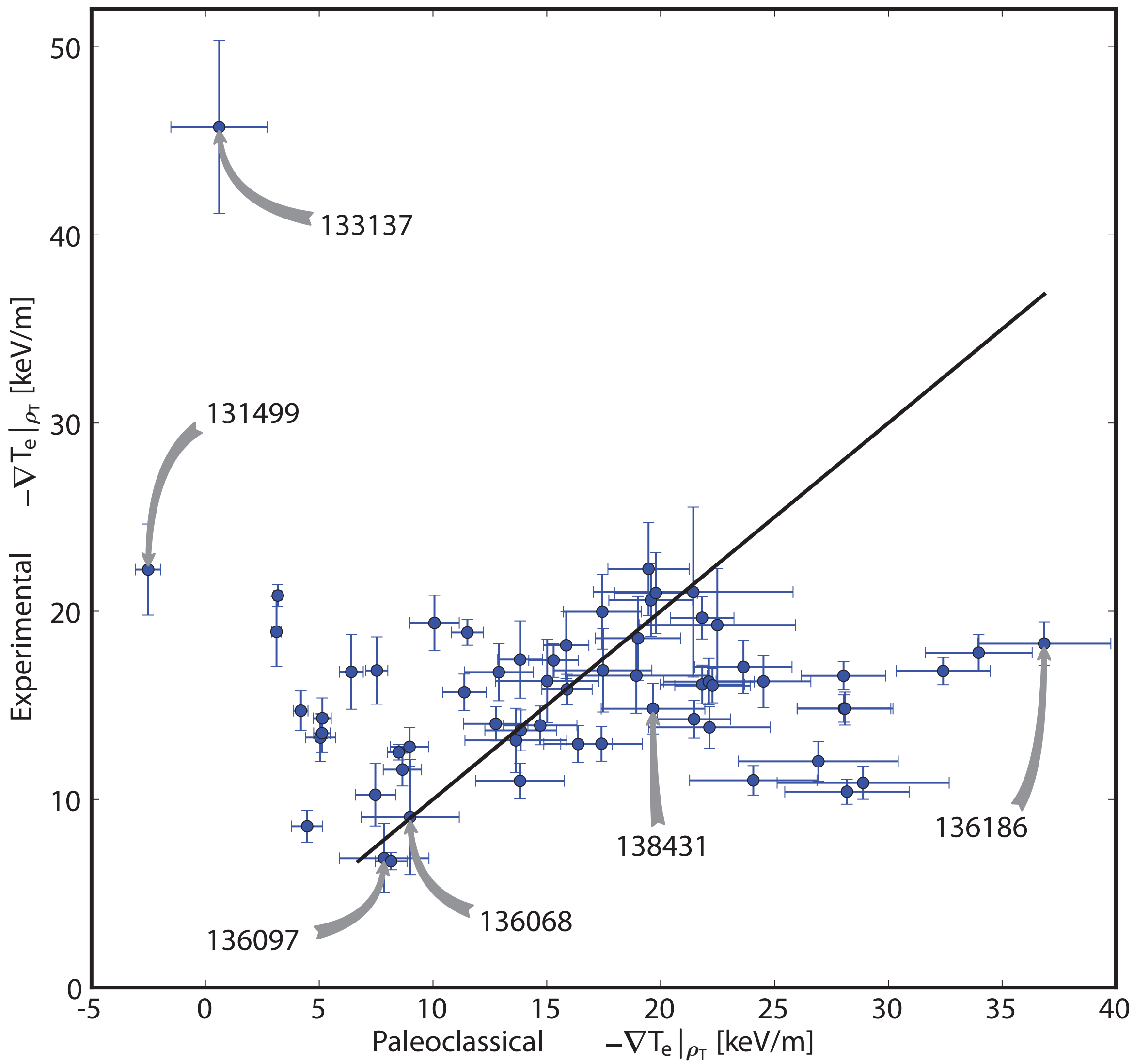
$$\lambda_e \equiv \frac{v_{Te}}{\nu_e}$$ Coloumb collision ‘mean free path’

$$\delta_e \equiv c/\omega_p$$

$$\bar{a} \equiv a \sqrt{\frac{\langle R^{-2} \rangle}{\langle |\nabla \rho|^2 / R^2 \rangle}}$$

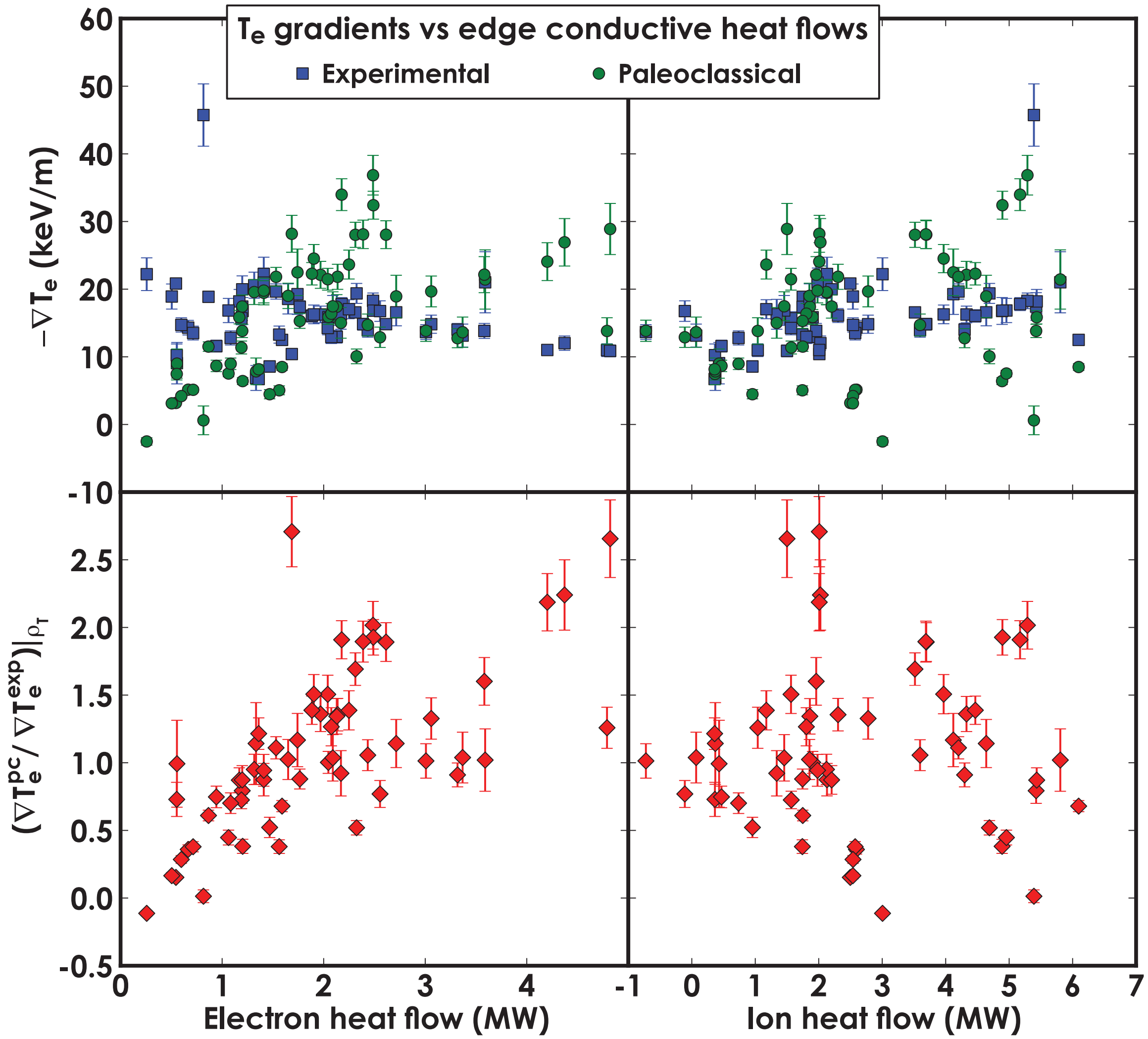
$a \equiv$ Minor radius

Across the Whole Database, Paleoclassical Predictions of $\nabla T_e|_{\rho_T}$ are Fairly Close to Experiment



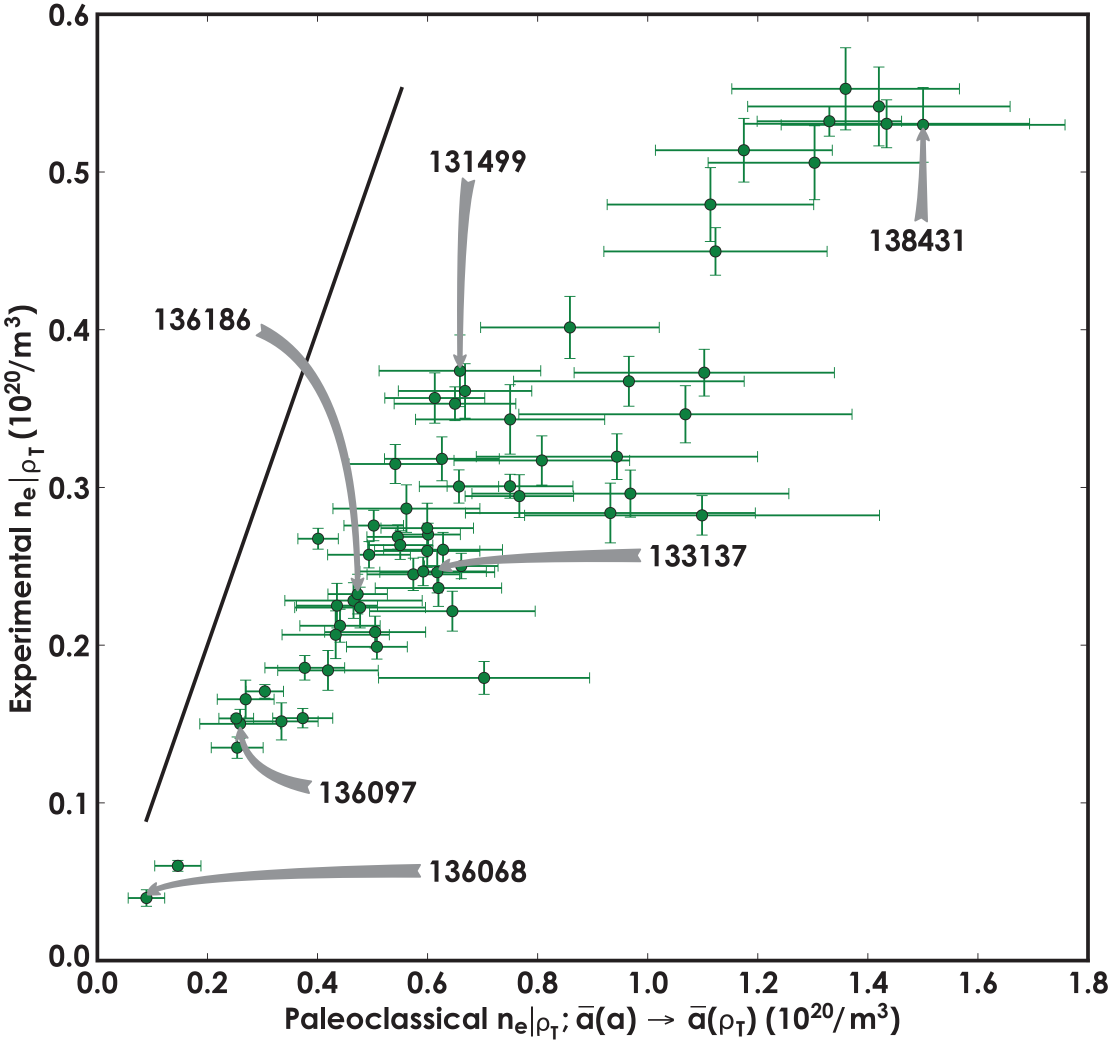
- **Paleoclassical predictions are in the ballpark of experimental gradients**
- **The line indicates equality**
- **avg($\nabla T_e^{pc}/\nabla T_e^{exp}$) = 1.1 ± 0.6**
- **Input & output profiles given on ensuing slides for labelled shots**

T_e Predictions for Whole Database Show Dependence on Edge Electron Heat Flow



- **Experimental ∇T_e and paleoclassical predictions of ∇T_e seem to be tracking differently with edge power**
- **Best agreement for moderate electron power flows**

Across the Whole Database, Predictions of $n_e|\rho_T$ Overshoot Experimental Measurements



- $\bar{a}(\rho > \rho_T) \rightarrow \bar{a}(\rho_T)$
- **The line indicates equality**
- $\text{avg}(n_e^{pc}/n_e^{exp}) = 2.3 \pm 0.5$
- **Input & output profiles given on ensuing slides for labelled shots**

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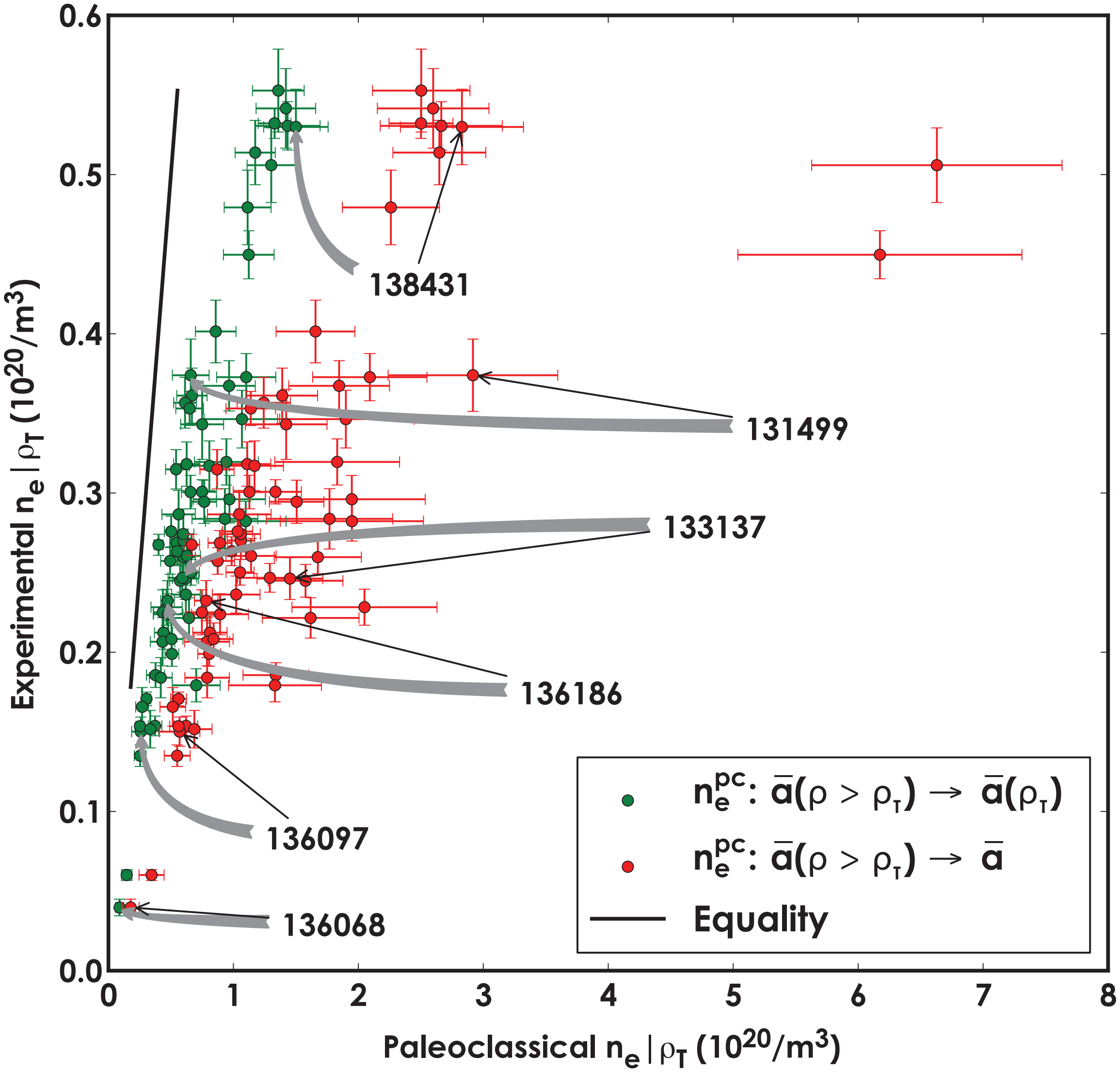
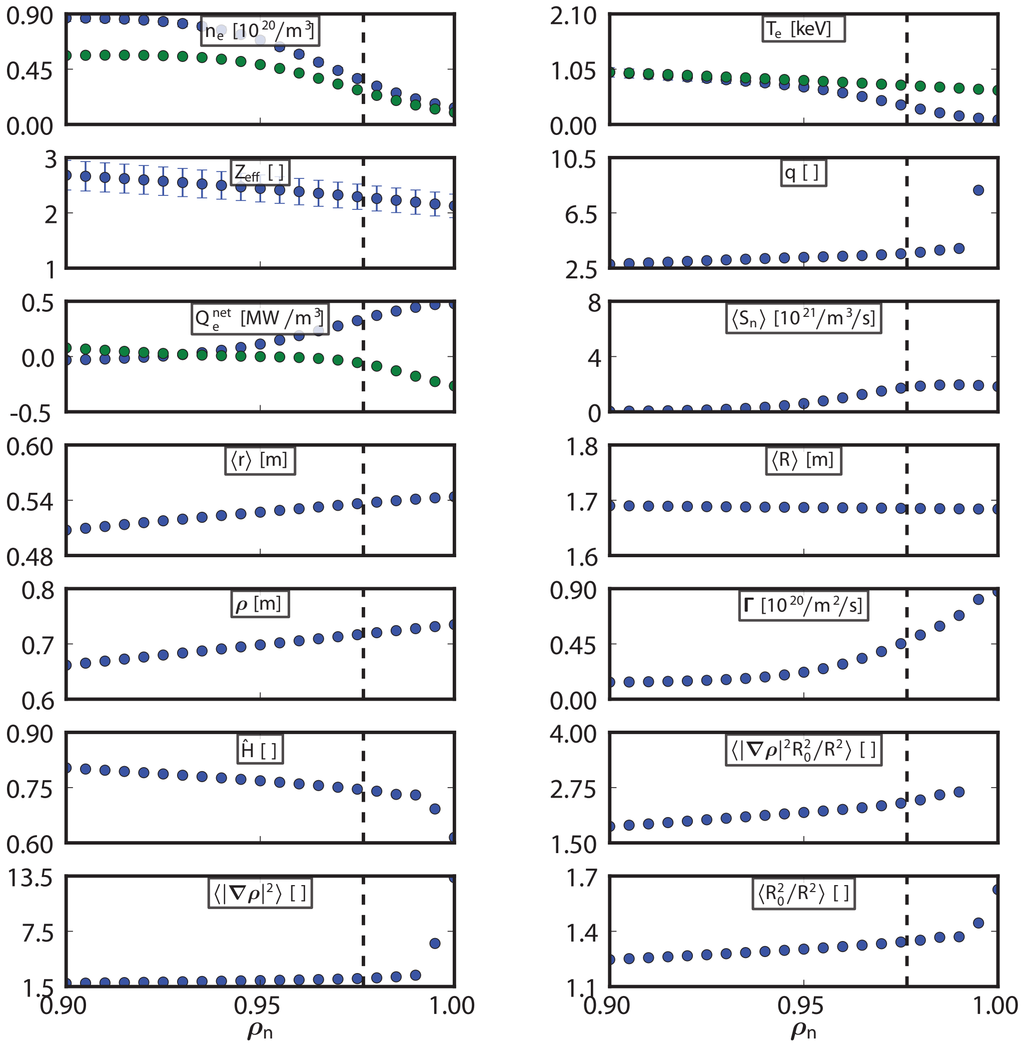
n_e Predictions for Whole Database Depend Greatly on $\bar{a}$ at Edge



- Definition of n_e^{pc} depends on $\bar{a}(a)$ in constant of integration
- $\bar{a}$ varies more than physically reasonable outside $\rho_n \approx 0.985$
- PC/XP Ratio:
  - 4.9 ± 2 (edge $\bar{a}$)
  - 2.3 ± 0.5 (symmetry $\bar{a}$)

Input Profiles: Shot 131499, Low ∇T_e^{pc}
Suspicious that Edge Ion Heat Flow ≫ Elec. Flow

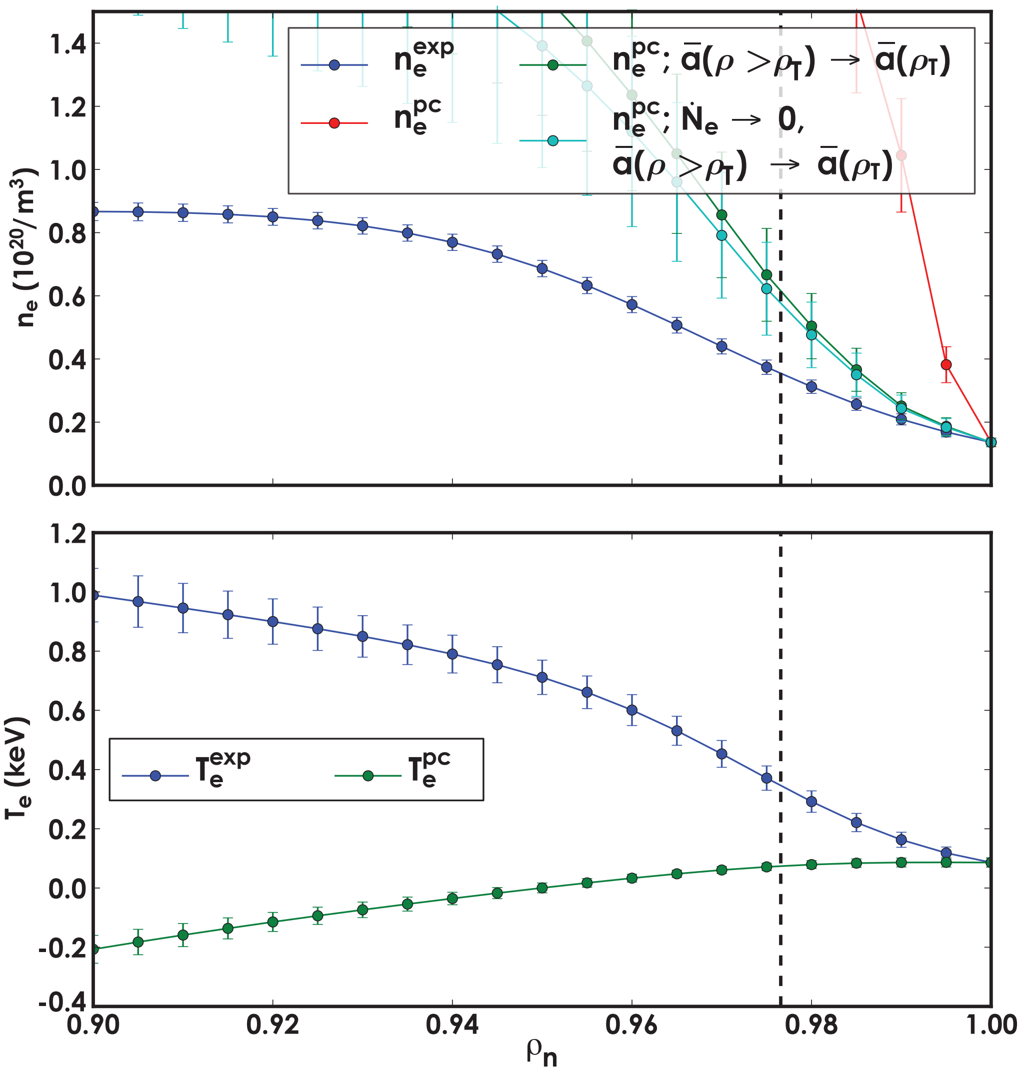


- **Ion quantities shown in green**
- **Vertical line is ρ_T**
- **Scalar inputs:**

  Bt0=-1.9T
  R0=1.7 m
  edge_elec_cond_energy_flow = 0.26 MW
  edge_ion_cond_energy_flow = 3 MW
  edge_part_flow = 4.4 x 10^{21}/s

- **Shot 133137 is similar**

Paleoclassical Predictions: Shot 131499, Low ∇T_e^{pc}



- **Eq. (1) is sensitive to $\bar{a}$ at the edge**
- **The local source term $\dot{N}_e$ is not a large contributor**
- **Vertical line is ρ_T**
- **Values ρ_T:**

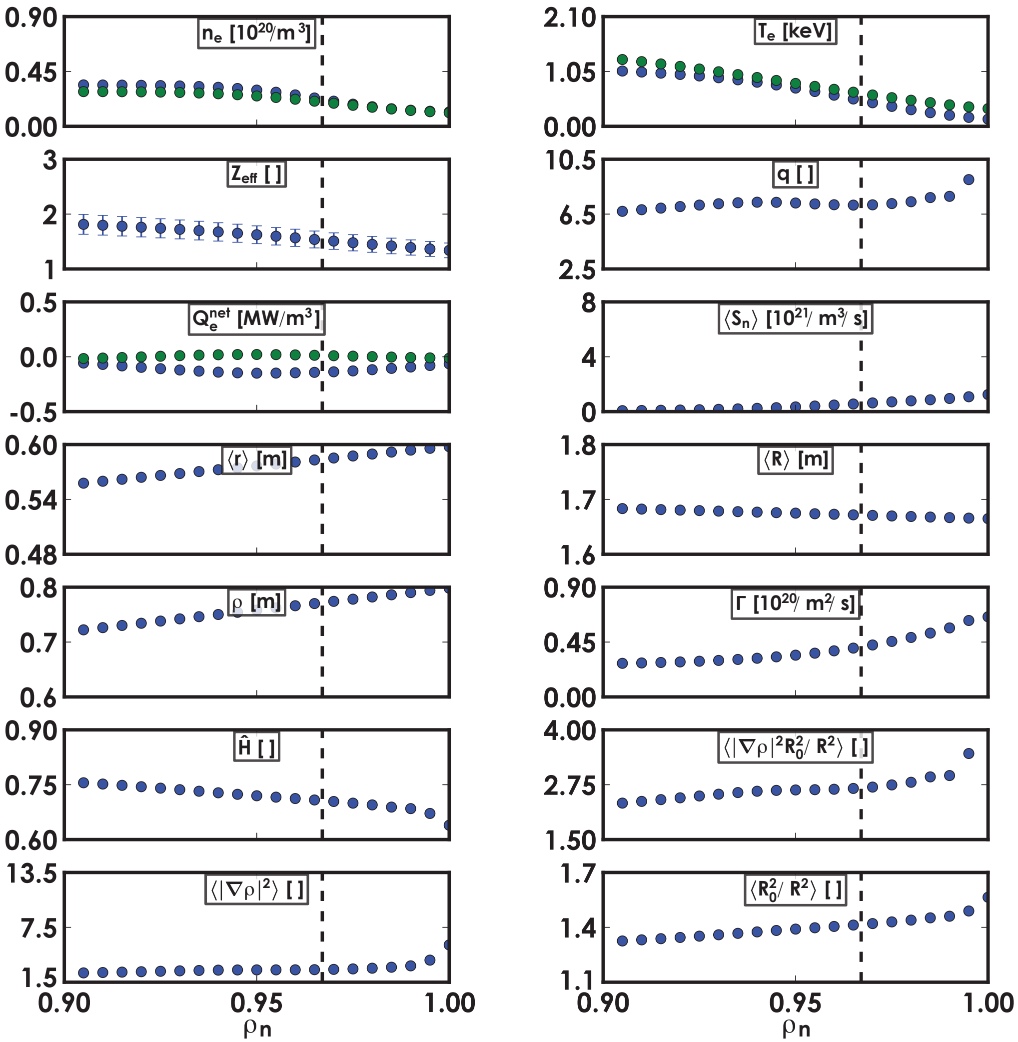
  $n_e^{exp}|_{\rho_T} = 0.37 \pm 0.023$

  $n_e^{pc}|_{\rho_T} = 0.66 \pm 0.15$

  – $\nabla T_e^{exp}|_{\rho_T} = 22 \pm 2.4$

  – $\nabla T_e^{pc}|_{\rho_T} = -2.5 \pm 0.55$

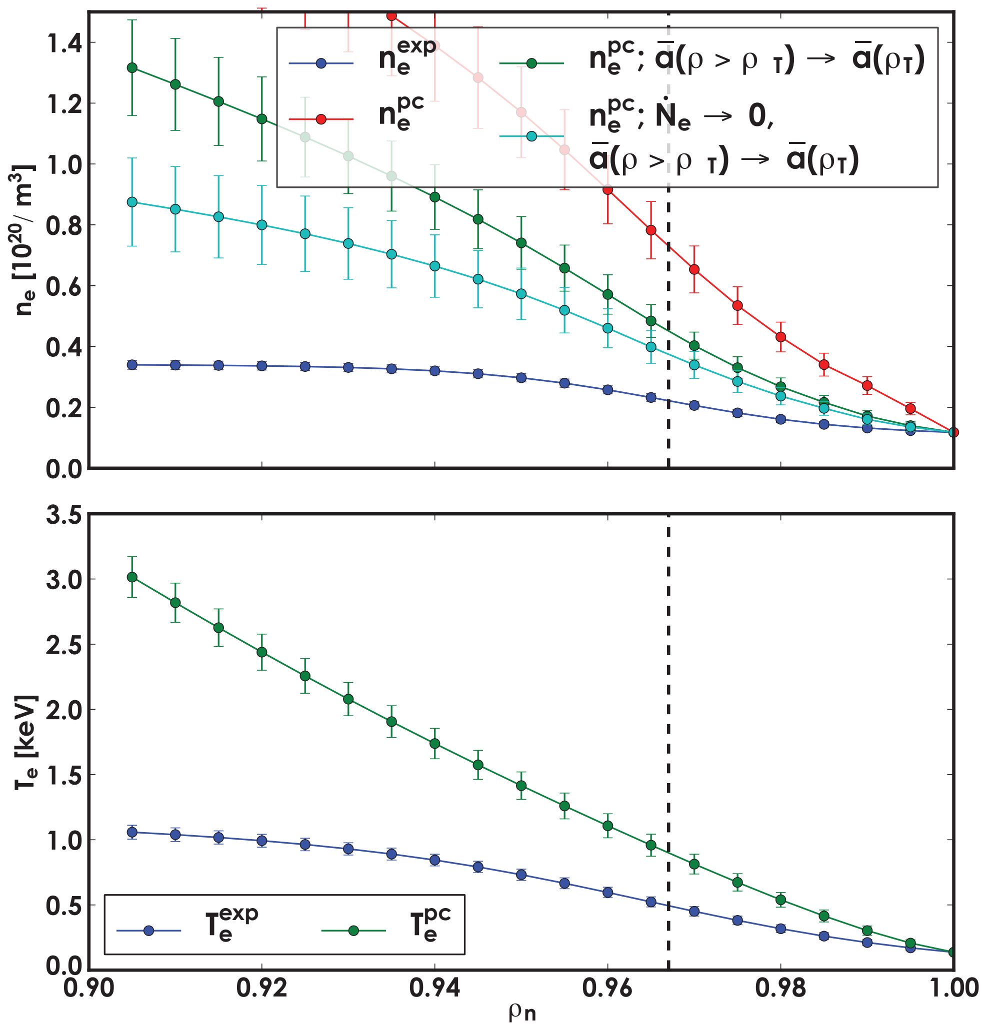
Input Profiles: Shot 136186, High ∇T_e^{pc} High q, Low $\hat{s}$



- **Ion quantities shown in green**
- **Vertical line is ρ_T**
- **Scalar inputs:**

Bt0= -2 T
R0 = 1.7 m
edge_elec_cond_energy_flow = 2.5 MW
edge_ion_cond_energy_flow = 5.3 MW
edge_part_flow = 3.6 x 10^{21}/s

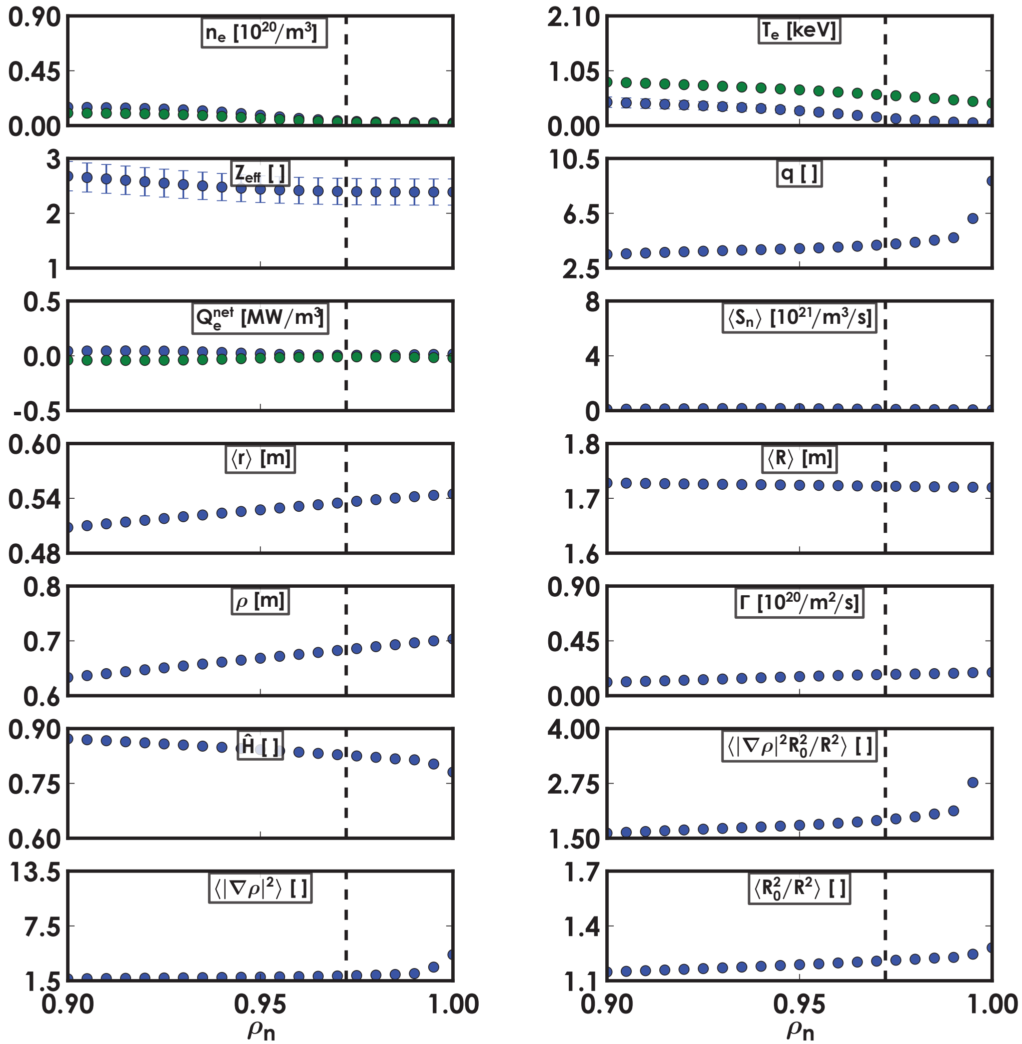
Paleo Predictions: Shot 136186, High ∇T_e^{pc} Low $\hat{s} \rightarrow$ more Anomalous Transport



- Eq. (1) is sensitive to $\bar{a}$ at the edge
- The local source term $\dot{N}_e$ has a larger effect
- Vertical line is ρ_T
- Values at ρ_T:

$$n_e^{exp}|_{\rho_T} = 0.23 \pm 0.013$$
$$n_e^{pc}|_{\rho_T} = 0.47 \pm 0.054$$
$$-\nabla T_e^{exp}|_{\rho_T} = 18 \pm 1.2$$
$$-\nabla T_e^{pc}|_{\rho_T} = 37 \pm 2.9$$

Input Profiles: Shot 136068, Low n_e, B_{T0}; $T_i > T_e$ Low Edge Energy Flows



- **Ion quantities shown in green**
- **Vertical line is ρ_T**
- **Scalar inputs:**

  Bt0= -1 T
  R0=1.7 m
  edge_elec_cond_energy_flow = 0.56 MW
  edge_ion_cond_energy_flow = 0.43 MW
  edge_part_flow = 0.95 x 10^{21}/s

- **Shot 136097 is similar**

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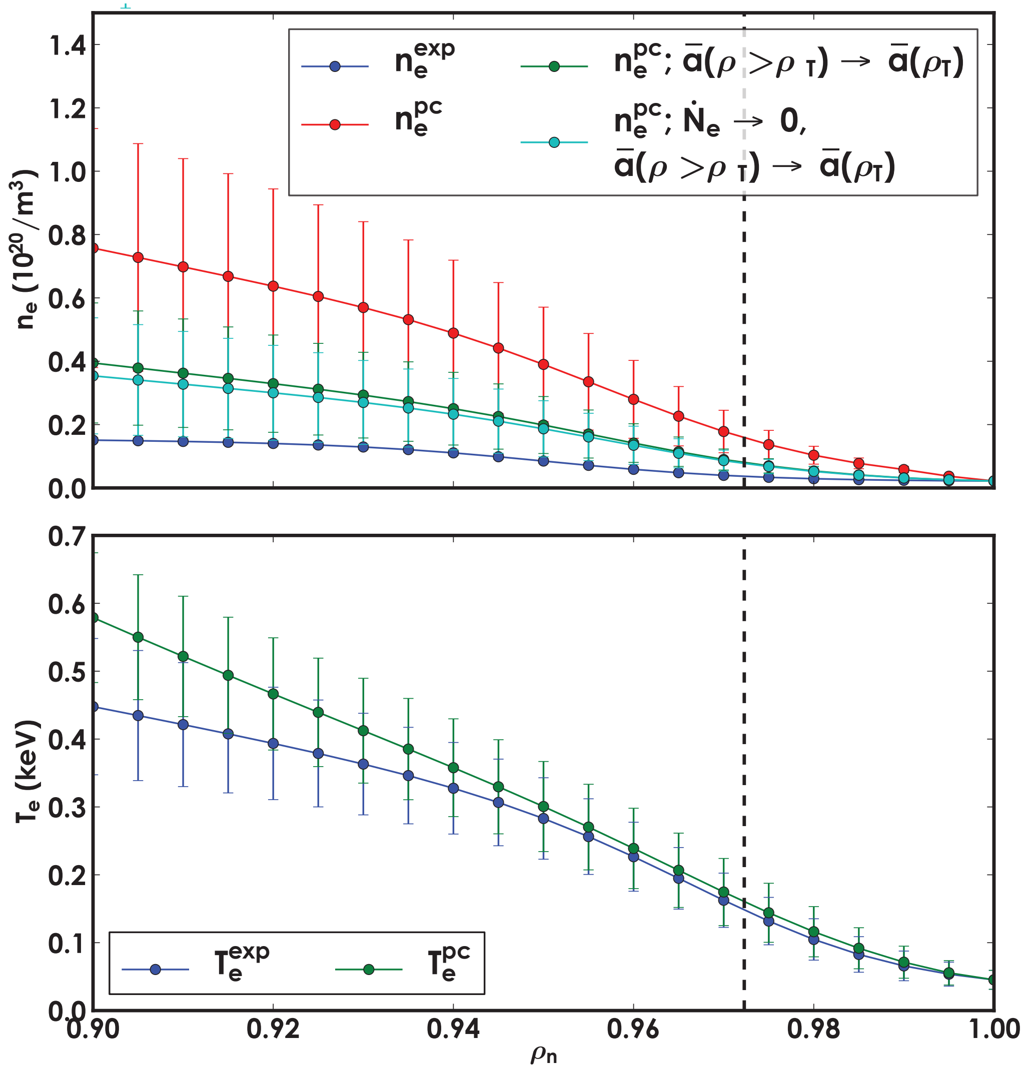
Paleo Predictions: Shot 136068, Low n_e
T_e and ∇T_e Well Matched

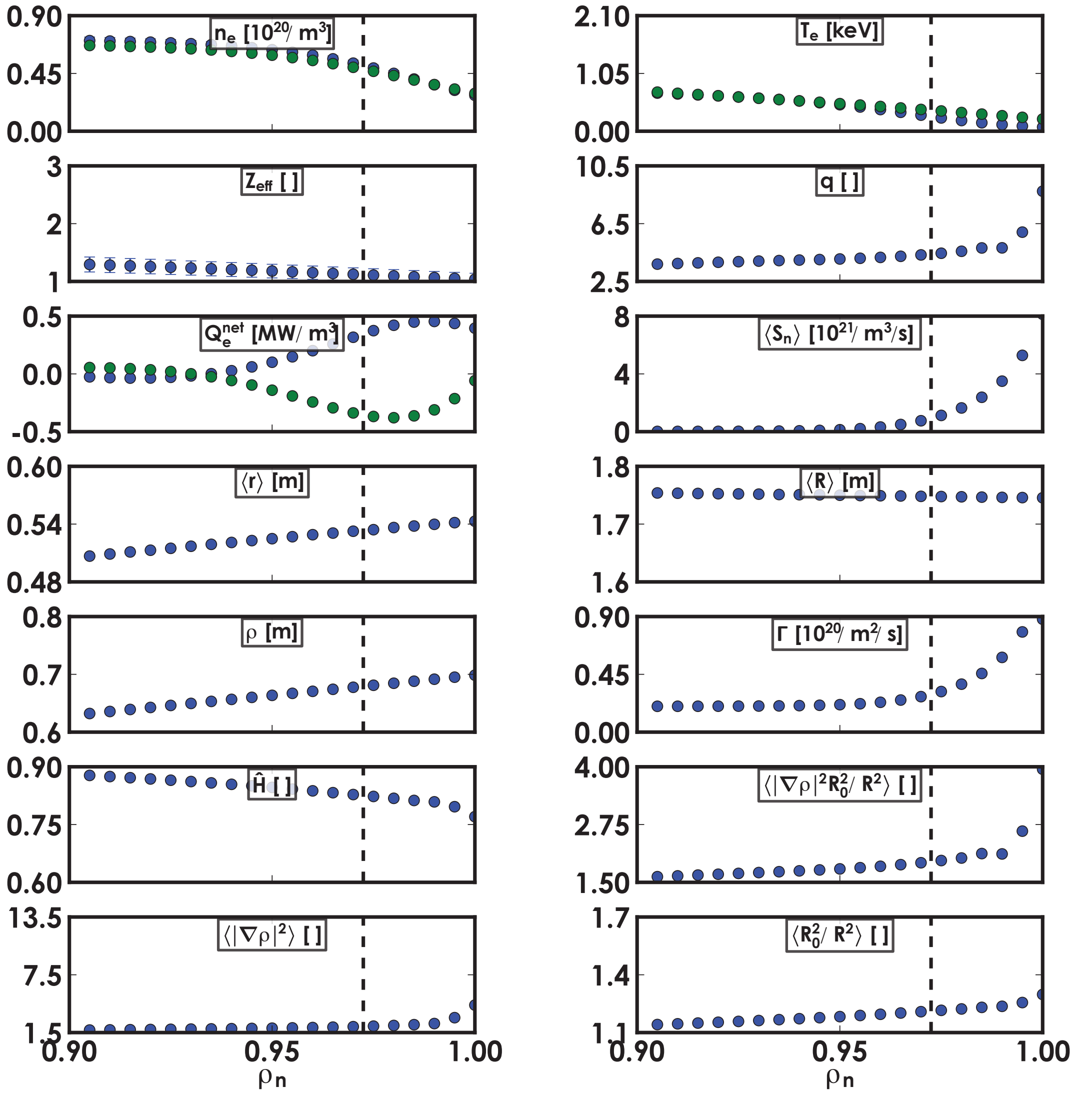


- Eq. (1) is sensitive to $\bar{a}$ at the edge
- The local source term $\dot{N}_e$ is not a large contributor
- Vertical line is ρ_T
- Values at ρ_T:

$$n_e^{exp}|_{\rho_T} = 0.37 \pm 0.023$$
$$n_e^{pc}|_{\rho_T} = 0.66 \pm 0.15$$

  - $\nabla T_e^{exp}|_{\rho_T} = 22 \pm 2.4$
  - $\nabla T_e^{pc}|_{\rho_T} = -2.5 \pm 0.55$

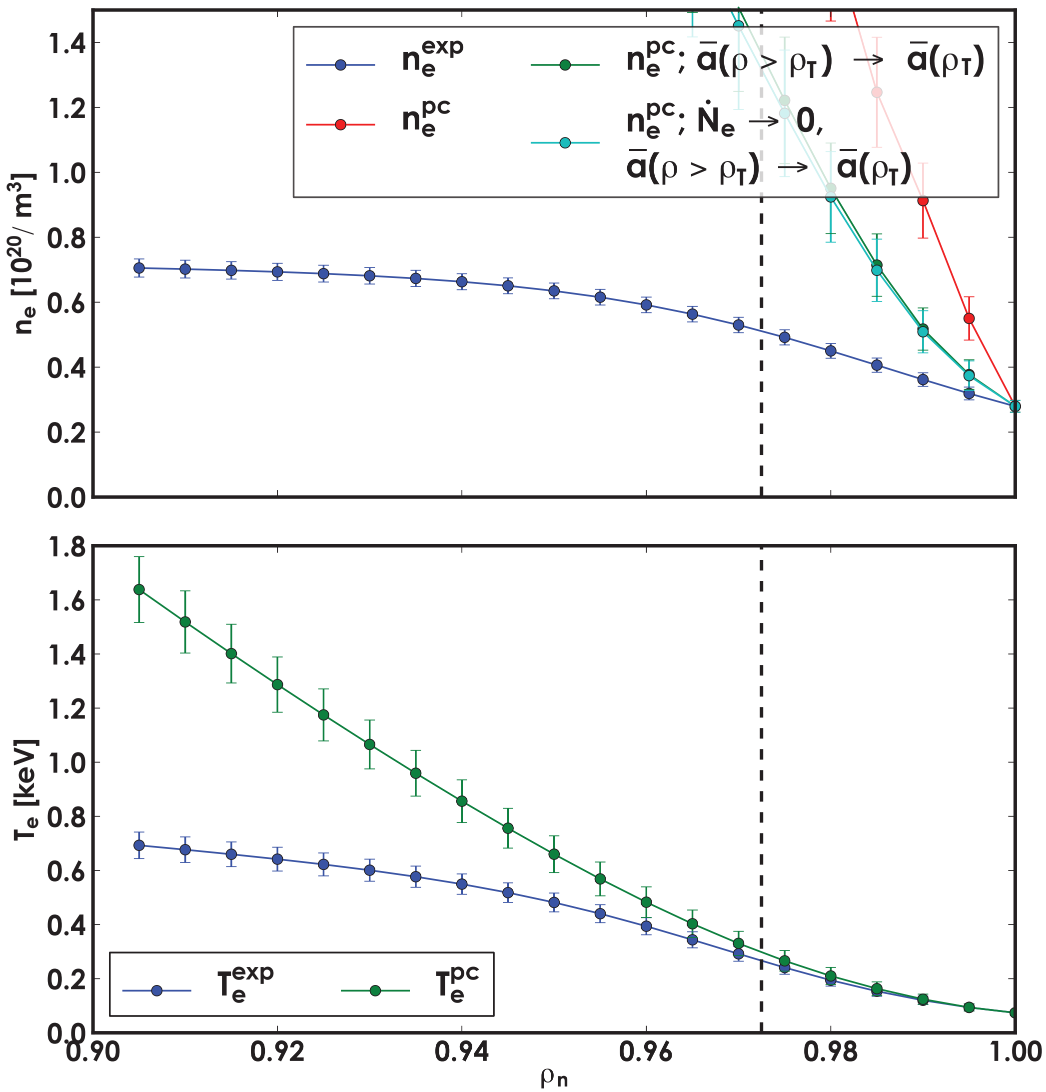
Input Profiles: Shot 138431, High n_e Low Z_{eff}



- **Ion quantities shown in green**
- **Vertical line is ρ_T**
- **Scalar inputs:**

Bt0= -2.1 T
R0=1.7 m
edge_elec_cond_energy_flow = 3.1 MW
edge_ion_cond_energy_flow = 2.8 MW
edge_part_flow = 4.4 x 10^{21}/s

Paleo Predictions: Shot 138431, High n_e T_e and ∇T_e well Matched



- Eq. (1) is sensitive to $\bar{a}$ at the edge
- The local source term $\dot{N}_e$ is not a large contributor
- Vertical line is ρ_T
- Values at ρ_T:

$$n_e^{exp}|_{\rho_T} = 0.53 \pm 0.024$$
$$n_e^{pc}|_{\rho_T} = 1.5 \pm 0.26$$

- $\nabla T_e^{exp}|_{\rho_T} = 15 \pm 1.3$
- $\nabla T_e^{pc}|_{\rho_T} = 20 \pm 2.3$

Summary

- DIII-D pedestal group has collected a database of profiles
- Paleoclassical predictions for n_e and ∇T_e have been compared to the database of profiles evaluated at the T_e symmetry point ρ_T
- The ratio of paleoclassical prediction to experimental measurement is closer for ∇T_e than n_e
- n_e^{pc} correlates well with n_e^{exp}
- n_e^{pc} depends heavily on the edge parameters $\bar{a}$, D_η; not so much on $\dot{N}_e$
- ∇T_e^{pc} depends heavily on the edge electron conductive power flow
- Future: Couple paleoclassical with TGLF to obtain anomolous transport at top of pedestal