Heuristic Drift-Based Model of the Power Scrape-Off Width in H-Mode Tokamaks with Low Gas Puff

Rob Goldston Thanks to Thomas Eich, Wojtek Fundamenski, Sergei Krasheninnikov, Brian LaBombard, Bruce Lipschultz, Vladimir Rozhansky, Peter Stangeby, Dennis Whyte and Michael Zarnstorff for helpful discussions

Overview

- **Basic Ideas are Simple**
  - Particles Grad *B* and Curvature *B* drift into the SOL
  - Particles flow out of the SOL at velocity ~ $c_s/2$
  - Electrons carry heat out of SOL per Spitzer
- **Fit to Data is Fairly Good**
  - Gives reasonable predictions of I_{loss}, τ_p.
  - Fits λ_q fairly well in absolute value and scaling
- **Implications for ITER are Complex**
  - Low-gas-puff width is small
  - Heat spreading with gas puff may be very effective
- **Questions and Future Research**

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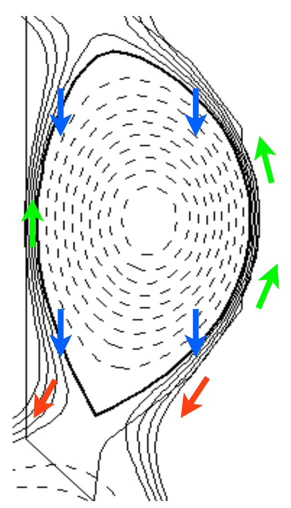
Particles ∇*B* and curv*B* Drift into SOL, Flow out of SOL at ~ $c_s/2$



- **Grad B and curv B drifts cross separatrix**
- **Pfirsch-Schlüter flows connect top and bottom**
- **SOL *also* empties to divertor in $\tau_{||} \sim L_{||}/(c_s/2)$**
- **$\lambda \sim \langle v_d \rangle \tau_{||}$**
- **Corresponds to the limit of P-S theory, including order unity poloidal asymmetries.**

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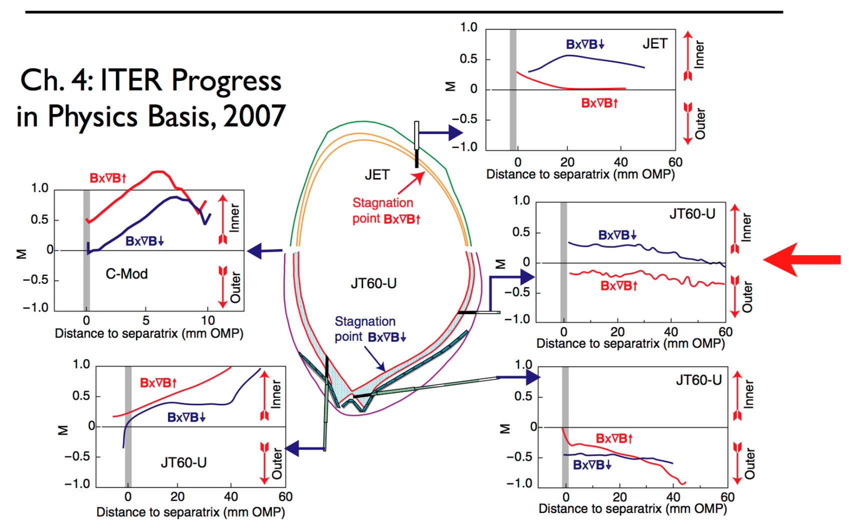
Parallel Flow Picture Supported by Experimental Data

Ch. 4: ITER Progress in Physics Basis, 2007



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(L-Mode data only)

Simple Calculation gives of $\lambda \sim \rho_p$

Re-express $\lambda \sim \langle v_d \rangle \tau_{||}$ as integral of drift across ψ_p from mid-plane (MP) to x-point.

$$\Delta\psi_p = \int_{MP}^{X-pt} \left(\vec{v}_{gc}\cdot\vec{\nabla}\psi_p\right)\frac{dl_{||}}{c_s/2} = \frac{2}{c_s}\int_{MP}^{X-pt}\left(\vec{v}_{gc}\cdot\vec{\nabla}\psi_p\right)\frac{B}{B_p}dl_p;\quad B_p = \frac{\left|\vec{\nabla}\psi_p\right|}{R}$$

$$\Delta\psi_p = \frac{2}{c_s}\int_{MP}^{X-pt}\left(\vec{v}_{gc}\cdot\frac{\vec{\nabla}\psi_p}{\left|\vec{\nabla}\psi_p\right|}\right)RBdl_p = \frac{2}{c_s}\int_{MP}^{X-pt}\frac{2T_{sep}}{\bar{Z}eBR}RB\,\hat{z}\cdot\hat{\varphi}\times d\vec{l}_p = \frac{4T_{sep}}{\bar{Z}ec_s}\int_{MP}^{X-pt}\hat{z}\times\hat{\varphi}\cdot d\vec{l}_p = \frac{4T_{sep}a}{\bar{Z}ec_s}$$

$$\lambda = \frac{\Delta\psi_p}{\left|\nabla\psi_p\right|} = \frac{4T_{sep}a}{\bar{Z}eB_pRc_s};\quad c_s = \left[\frac{\left(1+\bar{Z}\right)T_{sep}}{\bar{A}m_p}\right]^{1/2};\quad \bar{Z} \equiv \frac{n_e}{\sum_i n_i};\quad \bar{A} \equiv \frac{\sum_i n_iA_i}{\sum_i n_i}$$

$$\lambda = \frac{4a}{\bar{Z}eB_pR}\left(\frac{\bar{A}m_pT_{sep}}{\left(1+\bar{Z}\right)}\right)^{1/2} \text{ (ion drift)} \quad or \quad \frac{4a}{eB_pR}\left(\frac{\bar{A}m_pT_{sep}}{\left(1+\bar{Z}\right)}\right)^{1/2} \text{ (electron drift)} \approx \frac{2a}{R}\rho_p$$

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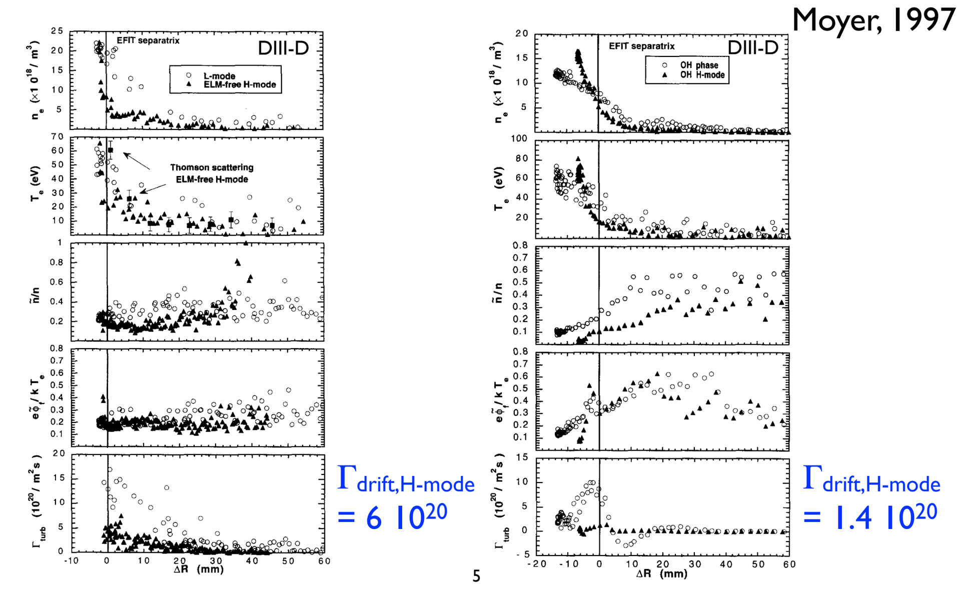
Usual Picture: Turbulence Dominates, but… Turbulent Particle Flux < Magnetic Drift

Moyer, 1997



$\Gamma_{drift,H-mode} = 6\ 10^{20}$

$\Gamma_{drift,H-mode} = 1.4\ 10^{20}$

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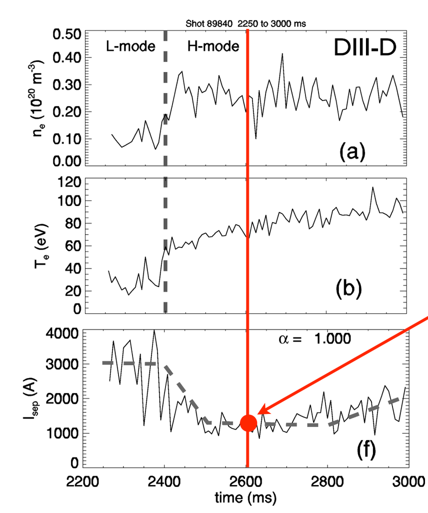
Particle Loss and τ_p Predicted in Low-Gas-Puff H-mode



Porter and DIII-D Team, 1998

Assume **that 1/2 of magnetic drift flux returns to plasma via Pfirsch-Schlüter flow, and 1/2 is lost.**

$$I_{loss} = \frac{2n_{sep}T_{sep}}{RB}\frac{2\pi R2a}{2} = 1.2kA$$

$$\Rightarrow \tau_p = \frac{\pi BRa\kappa n_{core}}{2\left(T_{sep}/e\right)n_{sep}}$$

Gives 375 msec for JET, 70 msec for C-Mod.

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Eliminate T_{sep} with Spitzer

- ***Assume*** **radial electron heat flux fills SOL width defined by flows, and heat is conducted to divertor by Spitzer electron thermal conductivity.**
- **Use 2-point model with Spitzer thermal conductivity to define T_{sep}. Use ellipse for B_p, $L_{||}$.**

$$P_{SOL} = \frac{4\pi R\lambda B_p\chi_{0,S}T_{sep}^{7/2}}{(7/4)BL_{||}}$$

- **Now we have two equations in two unknowns, λ and T_{sep}. Ion- and electron-drift results:**

$$\lambda = 5671\cdot P_{SOL}^{1/8}\frac{\left(1+\kappa^2\right)^{5/8}a^{17/8}B^{1/4}}{I_p^{9/8}R}\left(\frac{2\bar{A}}{\bar{Z}^2\left(1+\bar{Z}\right)}\right)^{7/16}\left(\frac{Z_{eff}+4}{5}\right)^{1/8} \quad \text{all units S.I.}$$

$$\lambda = 5671\cdot P_{SOL}^{1/8}\frac{\left(1+\kappa^2\right)^{5/8}a^{17/8}B^{1/4}}{I_p^{9/8}R}\left(\frac{2\bar{A}}{1+\bar{Z}}\right)^{7/16}\left(\frac{Z_{eff}+4}{5}\right)^{1/8} \quad \text{all units S.I.}$$

- **Only size scaling implicit in weak $P^{1/8}$ term.**

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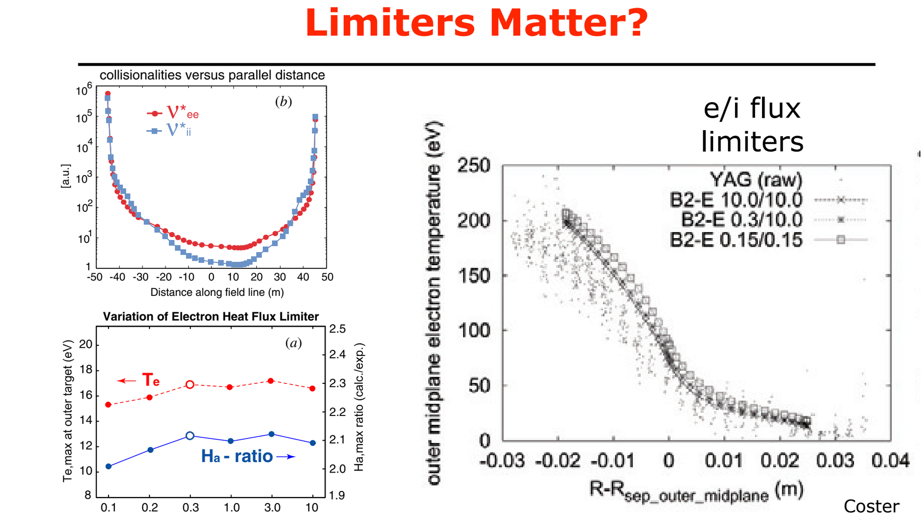
Do Parallel Electron Heat Flux Limiters Matter?



Chankin et al. 2006

Coster et al. 2004

Since we care about $T^{1/2}$ for given P_{SOL}, this seems to be a small effect.

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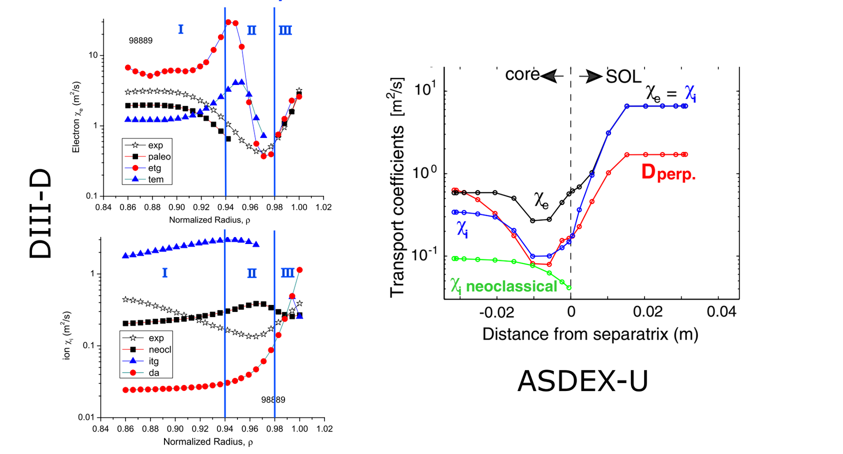
How Does Electron Heat Fill the SOL? (1)

- **Ion thermal transport is ~ neoclassical in the pedestal, electrons > ions, and far above electron neoclassical.**



- **Electron heat likely moves across separatrix faster than V_d.**

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How Does Electron Heat Fill the SOL? (2)

- **Drift heat flux is $q = 5nT^2/(ZeRB) = (5/2)nTV_d$**
- ***Assume* 50% of drift heat flux across separatrix goes to divertor, 50% returns to plasma by P-S flow.**
- **In JET at T_{sep} = 100 eV, n_{sep} = 2 $10^{19}/m^3$, B = 2T, net one-species drift heat flow is ~ 0.5 MW. Too low.**
- **For $\chi_{e,an}$ = 1 m^2/sec, λ = 4mm, $T_{e,sep}$ = 100 eV, anomalous electron heat flow is 12.5 MW. About right.**
- **Diffusive thermal fill time for 4mm SOL is 8 μsec. Parallel loss time at 100 eV is 10 μsec. Drift time is 260 μsec.**
- **Consistent with electrons thermally filling 4mm SOL region by anomalous transport, *but not by drifts.***
- **Electron heat flow past density channel limited by $q_\perp = \langle\tilde{p},\tilde{v}\rangle$ and by low parallel heat flux in sheath-limited regime.**

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How do Poloidal and Radial ExB Drifts Affect the Heuristic Picture?

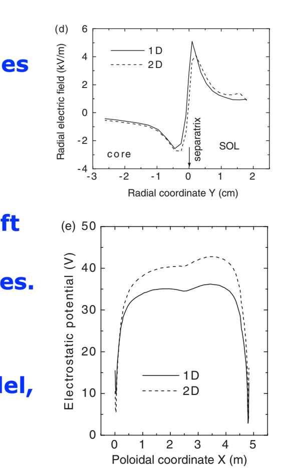
- **If the electric potential in the SOL varies radially with $e\nabla\phi \sim T/\lambda$, the poloidal *ExB* drift is ~ R/a times the poloidal projection of the ion thermal speed.**

$$\frac{E_r}{B_T} \sim \frac{T}{eB_T\lambda} = \frac{T}{eB_T}\frac{ZeR\langle B_p\rangle}{a(mT)^{1/2}} = v_{t,i}\frac{R}{a}\frac{\langle B_p\rangle}{B_T}$$

- **If the electric potential in the SOL varies poloidally with, $e\nabla\phi \sim T/a$, then the radial *ExB* drift is comparable to the ∇*B* and curv*B* drifts. This effect is normally greatest near divertor plates.**

$$\frac{E_p}{B_T} \sim \frac{T}{eBa\sqrt{\left(1+\kappa^2\right)/2}}$$

- **Since these scale like the drifts in the simple model, they should not change the basic dimensional scaling, but could trade *a vs. R*.**
- **Does this mechanism give strong ExB shear ⇒ H-mode?**



Rozhanski et al. 2003

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JET/AUG Comparison with Model "Eery"

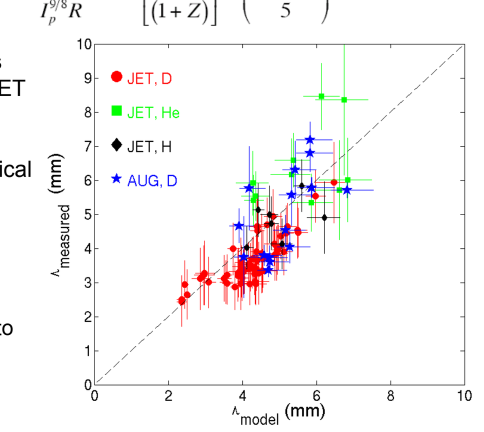
Comparison to Goldston model

$$\Delta_{Drift} = 5671\ P_{SOL}^{1/8}\frac{\left(1+\kappa^2\right)^{5/8}a^{17/8}B^{1/4}}{I_p^{9/8}R}\left[\frac{2A}{(1+Z)}\right]^{7/16}\left(\frac{Z_{eff}+4}{5}\right)^{1/8}$$

The Goldston model works remarkably well for both, JET and ASDEX Upgrade

Estimation of lam_int identical for JET and AUG.

Goldston model eerily close to the AUG/JET results



17.05.2011 ITPA, Helsinki T.Eich 18/16

Thomas Eich, ITPA Div-SOL 2011

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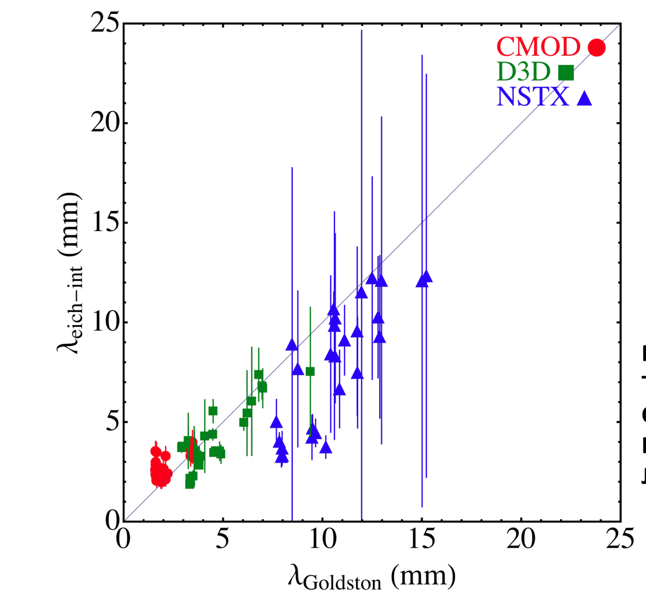
US Data Fit Reasonably Well Too



M.A. Makowski, D. Elder, T.K. Gray, B.LaBombard, C.J. Lasnier, A.W. Leonard, R.Maingi, P.C. Stangeby, J.L.Terry, J. Watkins

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Eich Used a q(x) Model from Wagner to Extract More Information

- **How should you fit the heat flux profile?**
- **For fast ions, Wagner (1982) posited convective transport along B, plus simple diffusive transport across B.**
- **He assumed an exponential flux profile upstream.**
- **He convolved the upstream profile with simple diffusion (Gaussian) as the particles travel along the divertor leg.**

$$q(x) = \frac{q_0}{2}\exp\left[\left(\frac{S}{2\lambda_qf_x}\right)^2 - \frac{x}{\lambda_qf_x}\right]erfc\left(\frac{S}{2\lambda_qf_x} - \frac{x}{S}\right)$$

- **S = Gaussian width due to diffusion**
  λ_q = X-point exponential width mapped to OMP,
  f_x = flux expansion from OMP
- **This model is incorrect for parallel heat diffusion, for example Spitzer, coupled with a temperature dependent perpendicular diffusion, for example Bohm.**
  ⇒ It should not work for electron heat flux in divertor.

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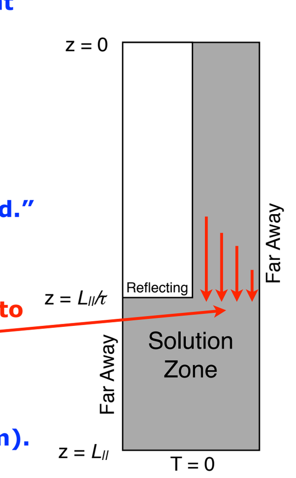
The Incorrect Model Works Well - I

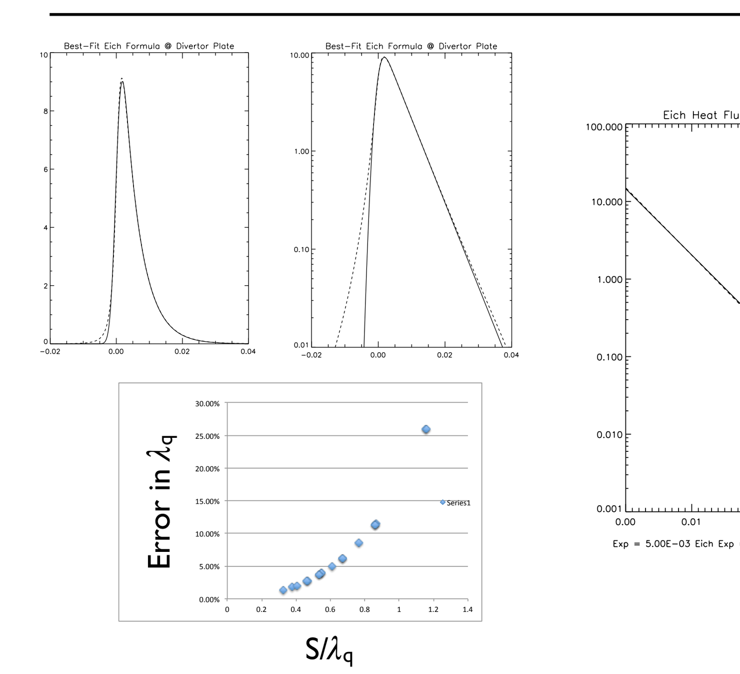
- **Model the problem by solving the nonlinear heat equation in "straightened out" geometry.**
- **Nonlinear code previously used to address a number of scrape-off layer problems, such as relation of upstream T_e profile to divertor heat flux profile, including cross-field transport.**
- **Relationship to 2-point model: "It's Complicated."**

For this case:

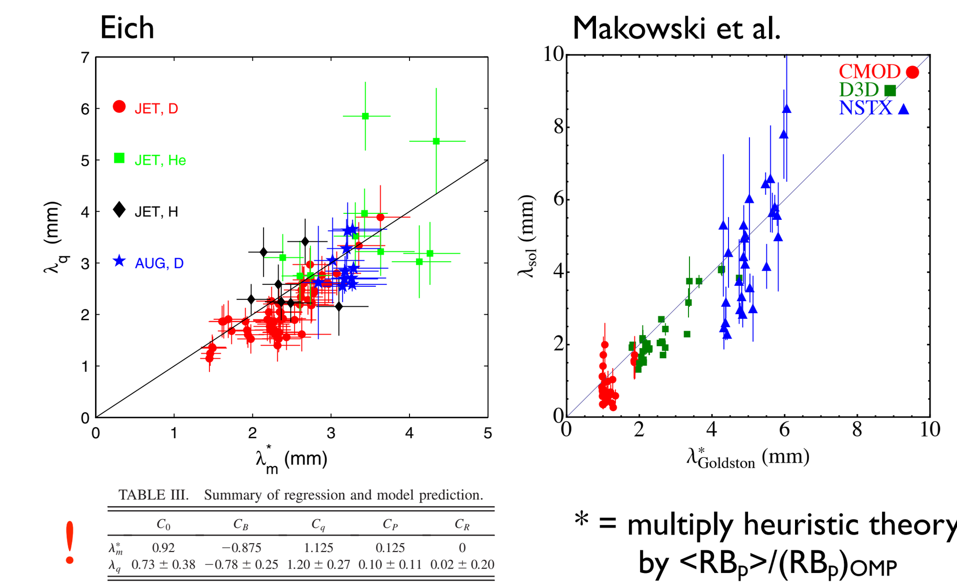
- **Parallel heat flux across from X-point is forced to have an exponential profile with width λ_q.**
- **Parallel heat diffusivity goes like $T^{5/2}$ (Spitzer).**
- **Perpendicular heat diffusivity goes like T (Bohm). Fit profile of heat flux at the divertor plate with Wagner/Eich function. Extract λ_q.**



The Incorrect Model Works Well - II



The Resulting Fits are Good



* = multiply heuristic theory by $\langle RB_p\rangle/(RB_p)_{OMP}$

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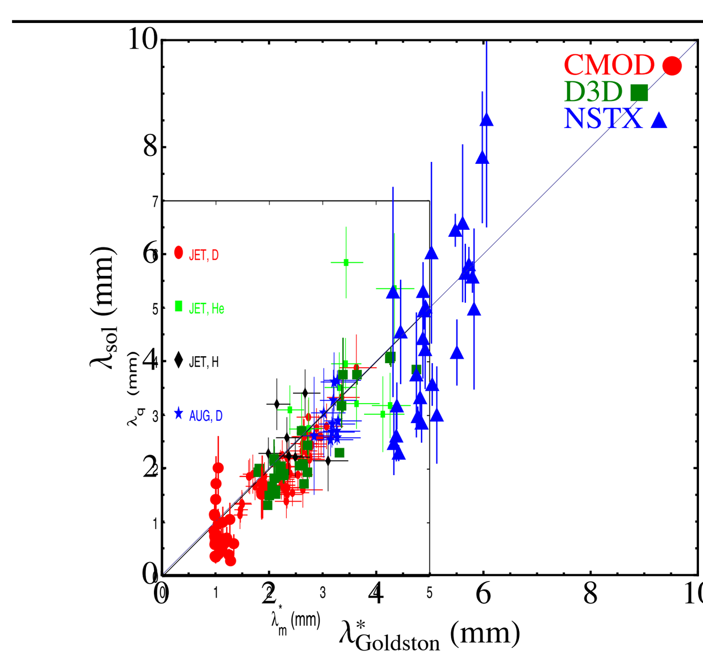
And They Fit Together Pretty Well



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Future Research

- **Numerical simulation corresponding to heuristic model is needed. Heuristic analysis is not accurate to terms of order unity.**
  - Need high resolution, low dissipation solutions
  - Need realistic, validated results on electric fields
  - Resolve ion *vs.* electron drifts (Z and A dependence)
- **More extensive species scaling studies**
- **More comparisons with total loss current, τ_p**
- **Low-field / high-field DND widths vs. δ**
- **Effects of Snowflake, Super-X geometries.**
- **Gas puffing to spread heat load with shielding SOL.**

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Conclusions

- **Heuristic model balances magnetic drifts with $c_s/2$ losses giving SOL width = (2a/R) ρ_p ~ high-speed limit of P-S flow. Edge temperature set by Spitzer parallel thermal conduction.**
- **Size scaling only implicit through $P^{1/8}$**
- **Model consistent with recent experimental results from JET, ASDEX, C-Mod, DIII-D, NSTX.**
- **Size comes in only implicitly through P_{SOL}. Good match to JET and ASDEX suggests weak size scaling ~ correct.**
- **Eich/Wagner model gives good fit. ASDEX/JET fit coefficients very close to model predictions.**
- **Will ITER SOL shield pedestal from neutrals, so SOL density profile can be widened via strong gas puff?**
  - **Heuristic model would predict effective heat spreading. At high gas puff rate density channel would be much wider, since flow rate would drop below $c_s/2$.**

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