The Heuristic Drift Model of the Scrape-off Layer: Physics & Implications

Rob Goldston
Princeton Plasma Physics Laboratory

American Physical Society
Division of Plasma Physics
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Why Do We Care about the Scrape-Off Layer (SOL) Width?

The width of the scrape-off layer, λ_q, determines the parallel heat flux,

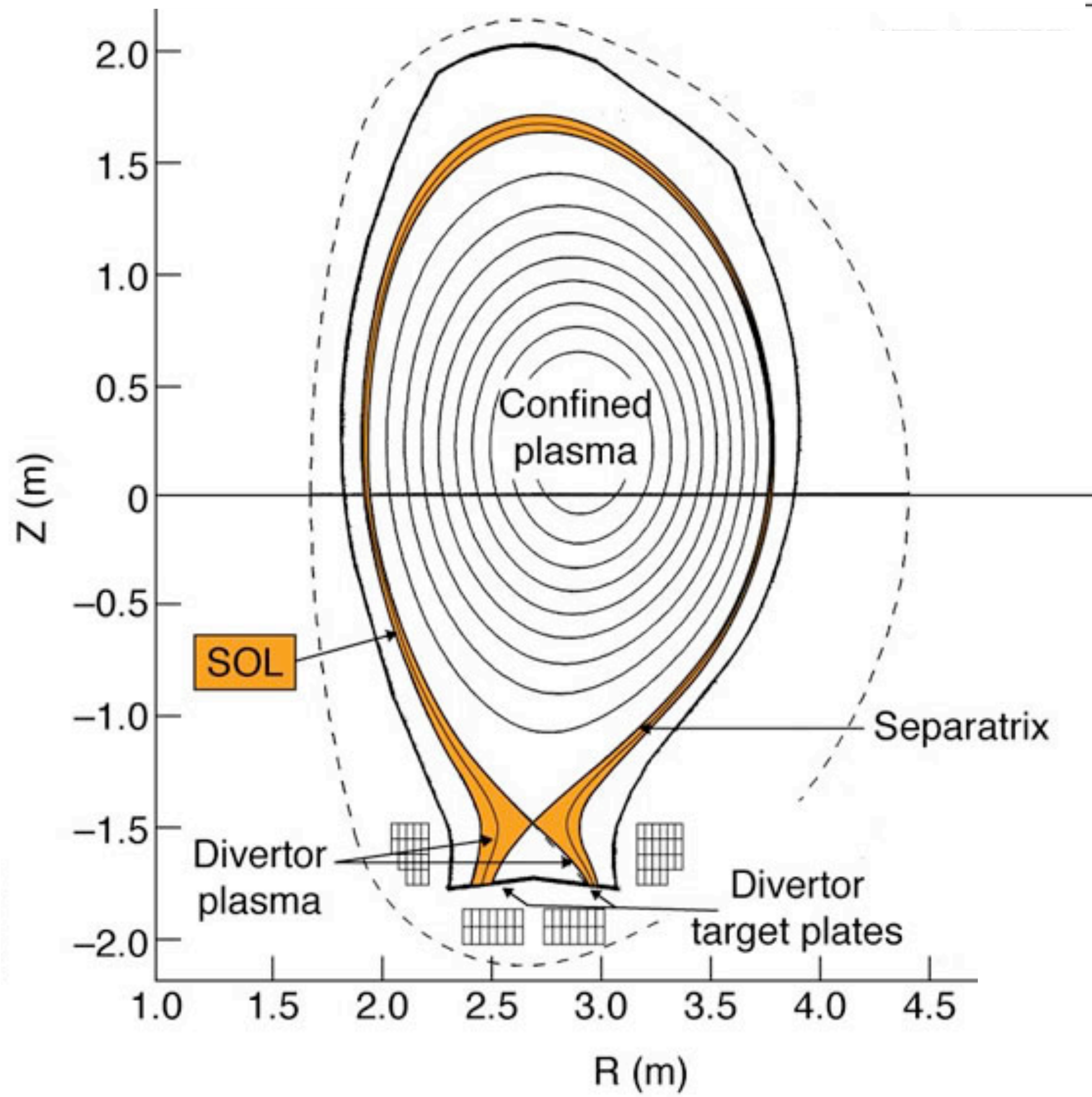
$$q_{\parallel} = \frac{P_{SOL}\left(B/B_p\right)}{4\pi R \lambda_q}$$

which determines the heat flux to the target,

$$q_{\perp,Tar} = q_{\parallel} \sin\alpha$$

and the plasma temperature at the target:

$$q_{\parallel} = \gamma n_{Tar} T_{Tar} c_{s,Tar}$$



Outline

- Heuristic Drift (HD) Model
- Implications for Heat Flux & Impurity Flows
- Near-LCFS Heat flux in Limiter Plasmas
- Possible Connection to Greenwald Limit

What Sets the SOL Width?
Standard Analysis for Turbulence Models

Parallel Confinement:

$$\tau_{\parallel} = (qR)^2 / 2\chi_{\parallel}$$ Conduction

or

$$\tau_{\parallel} = qR/c_s$$ Convection

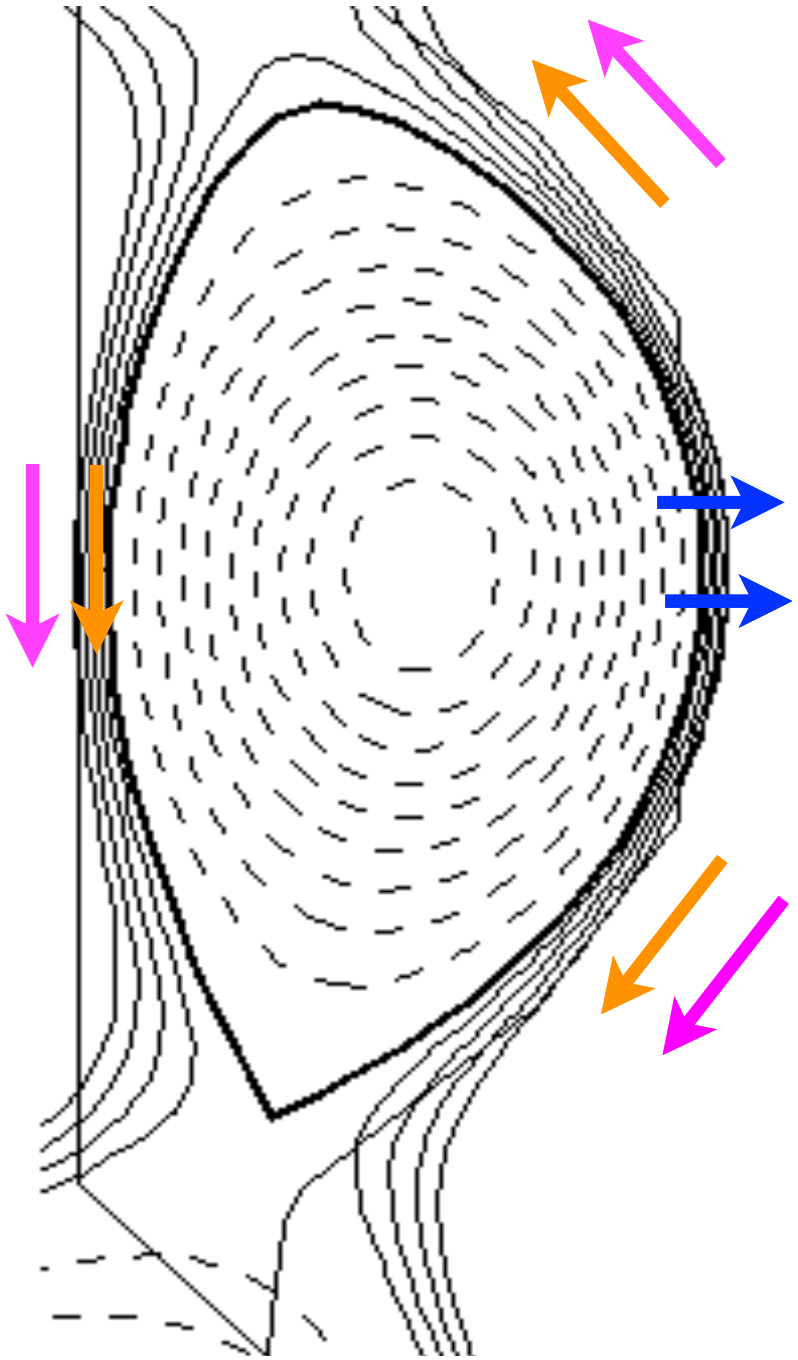
+ Turbulent Cross-Field Diffusion:

$$\lambda = \sqrt{2\chi_{\perp}\tau_{\parallel}}$$

$$= \sqrt{\chi_{\perp}(qR)^2/\chi_{\parallel}}$$

or

$$\lambda = \sqrt{2\chi_{\perp}qR/c_s}$$



HD Model Width Set by Magnetic Drifts

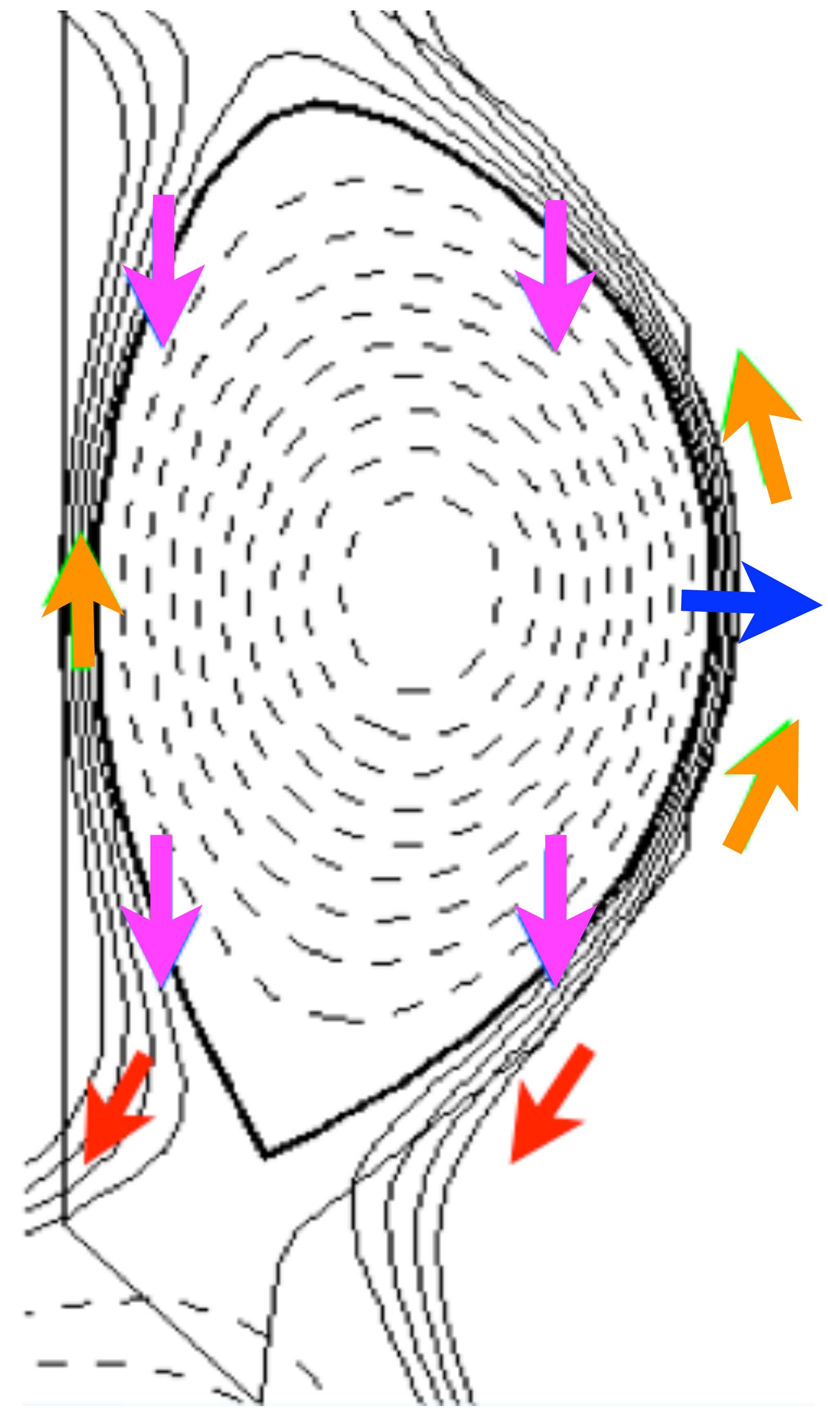
Non-Standard Analysis: $\lambda = v_d \tau_\parallel$

- Vertical drifts cross separatrix into SOL
- Parallel flows connect SOL to divertor at ~ $c_s/2$, consistent with experiments and a simple flow picture, setting a density channel width:

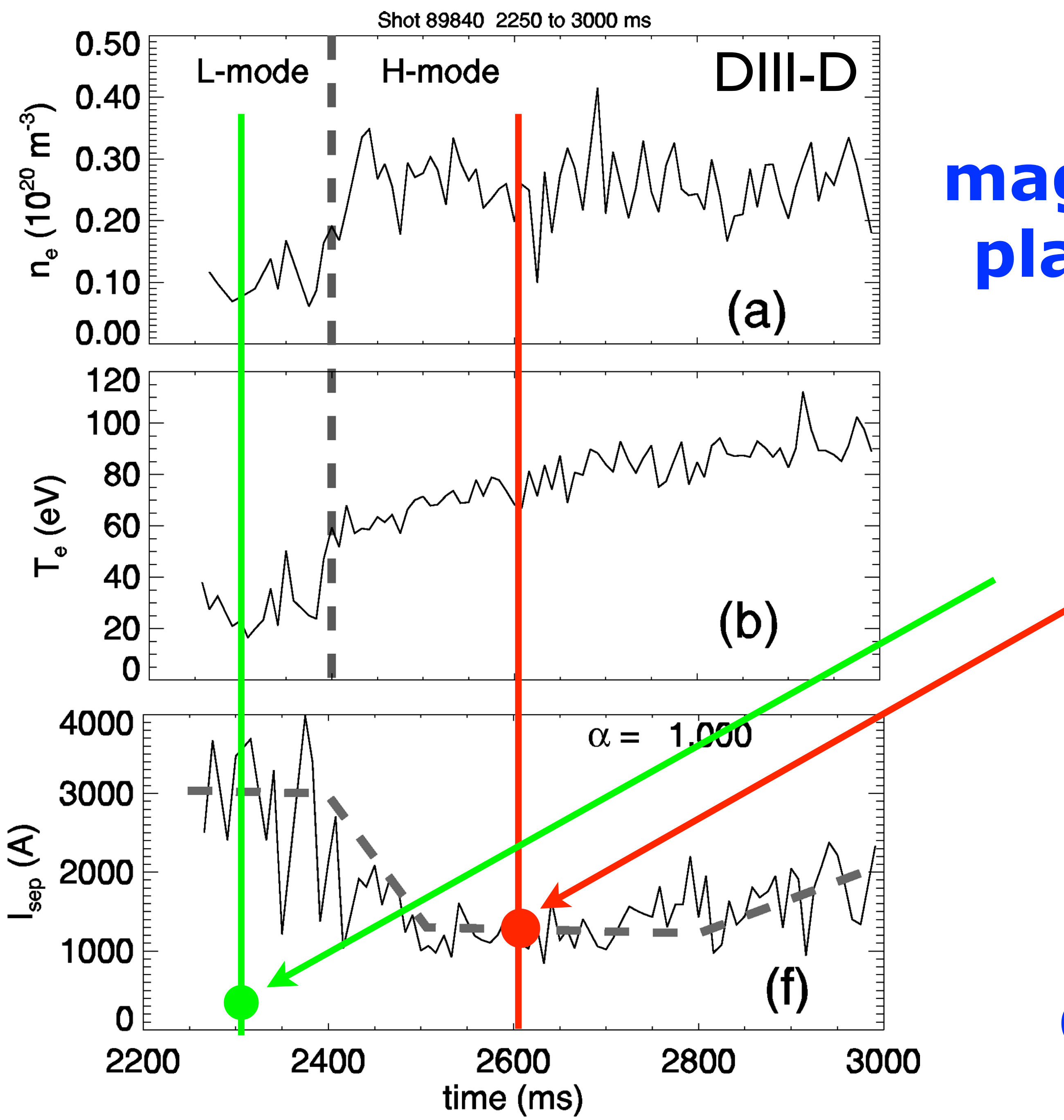
$$\lambda_n \approx v_{\nabla B + curvB} \tau_\parallel \approx 2 v_{\nabla B + curvB} L_\parallel / c_s \approx 2(a/R)\rho_p$$

- Implies Pfirsch-Schlüter flow also ~ $c_s/2$
- Edge T_e (= T_i) is determined by anomalous electron thermal conduction across the separatrix, balanced by Spitzer parallel electron thermal conduction, within λ_n.
- Gives a closed-form, absolute (heuristic) prediction:

$$\lambda_q \simeq 5671 \cdot P_{SOL}^{1/8} \frac{(1+\kappa^2)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left(\frac{2\bar{A}}{1+\bar{Z}}\right)^{7/16} \left(\frac{Z_{eff}+4}{5}\right)^{1/8}$$



Measured Particle Loss in DIII-D H-Mode Equals Drift Loss



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

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

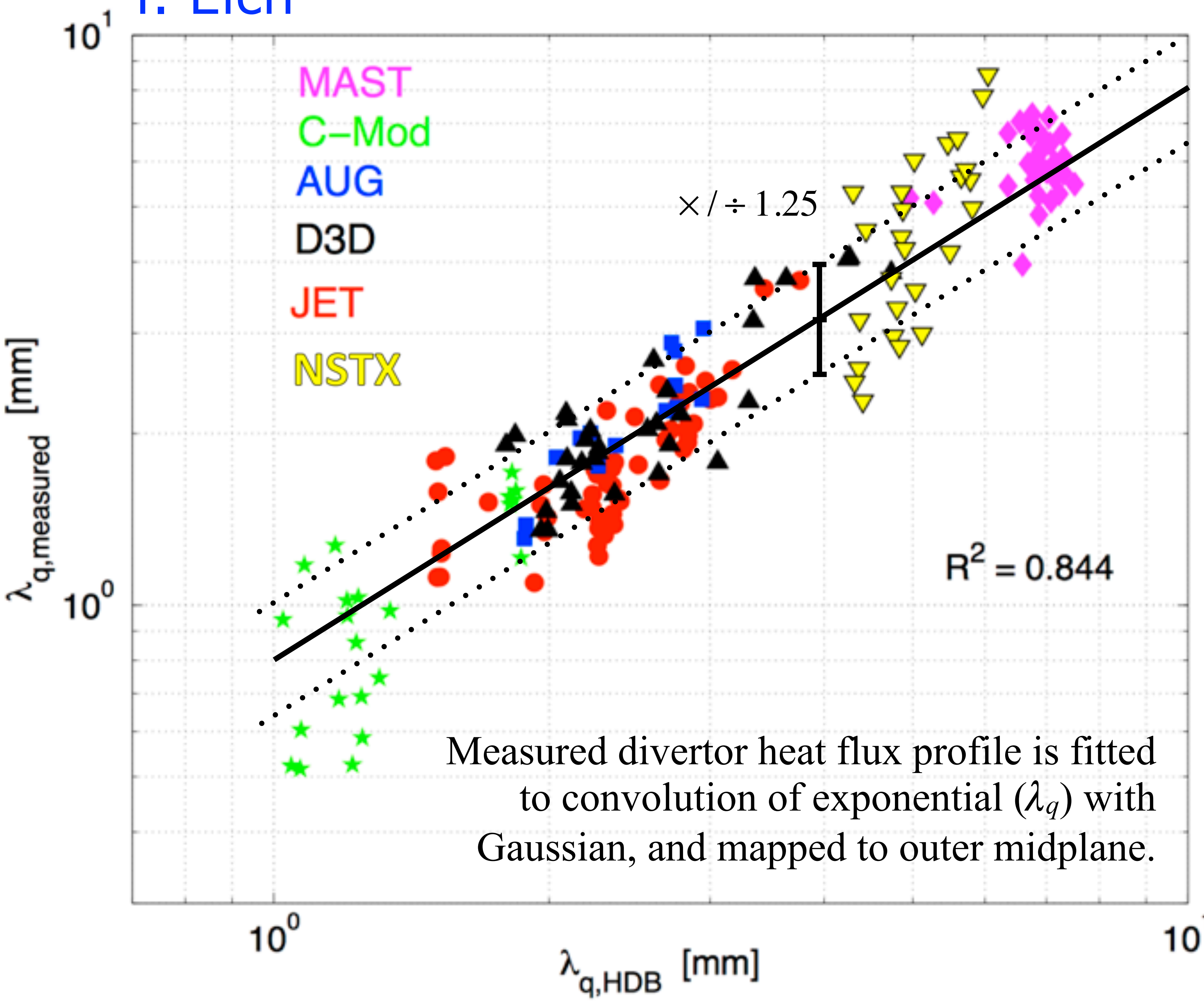
$$\Rightarrow \quad \tau_p = \frac{\pi BRa\kappa n_{core}}{2\left(T_{sep}/e\right)n_{sep}}$$

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

G. Porter

HD Model Fits Measured λ_q's Well

T. Eich



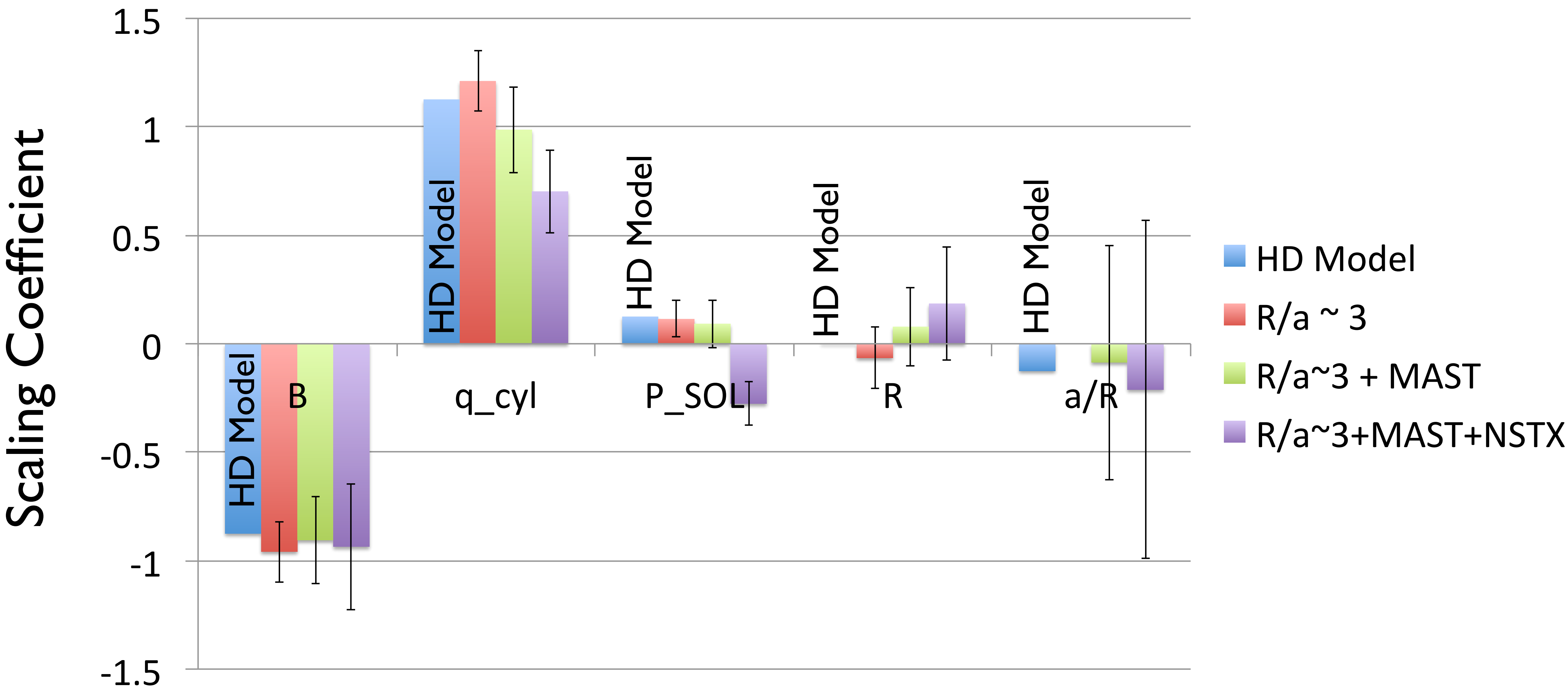
$Data \sim 1.6(a/R)\rho_p$

$\sim HD\ Model / 1.25$

Projection to ITER ~ 1 mm (not counting Gaussian)

Individual Scalings Fit Model

T. Eich



T. Gray

NSTX data set has positively correlated power, current & triangularity.

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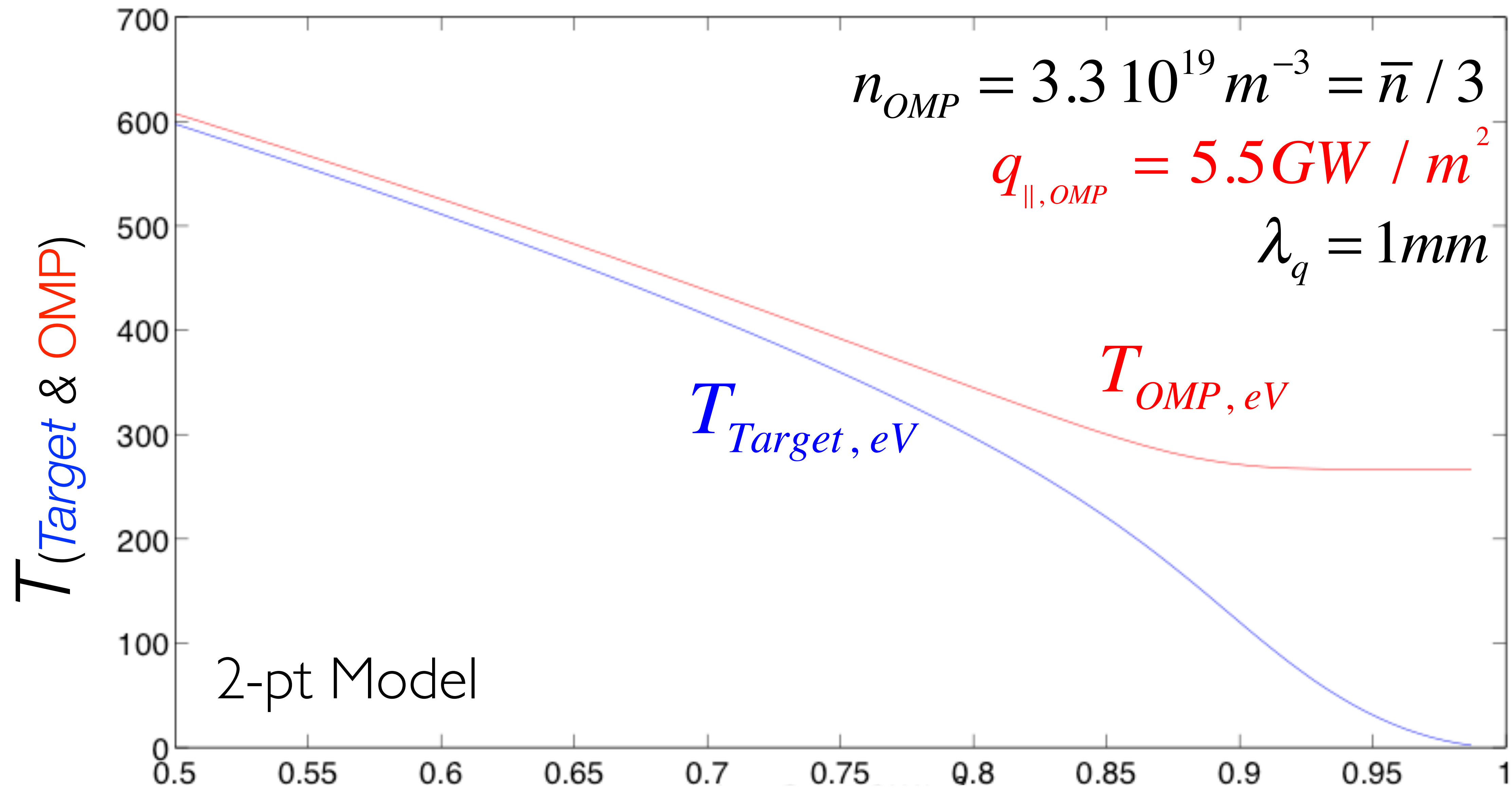
Need High Dissipated Power in ITER

(Transport, Radiation, CX)



$q_{\parallel, Target} = 2.75 GW/m^2$

$q_{\perp, Target} = 100 MW/m^2$

f_{Diss}

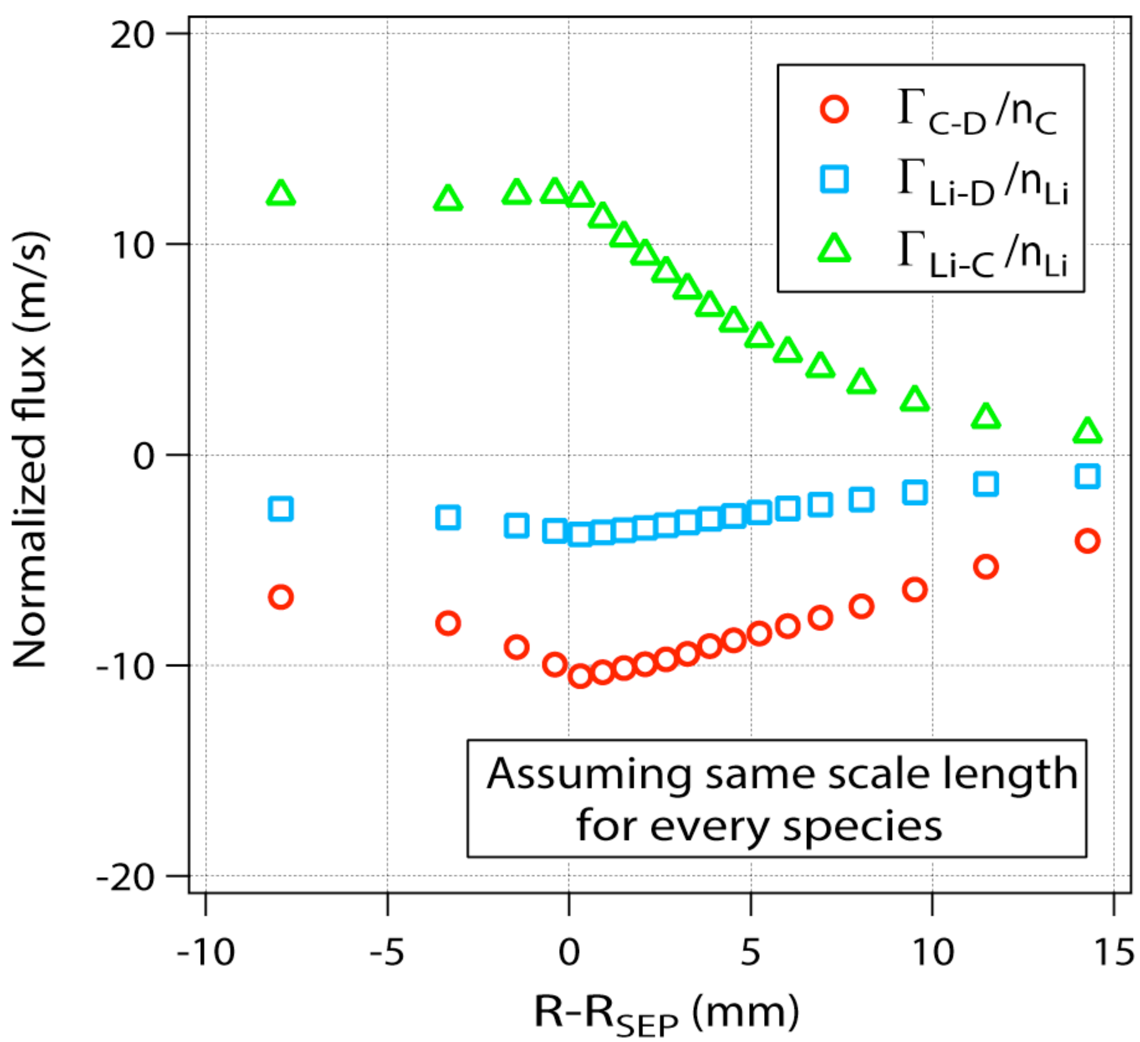
$\equiv 1 - q_{\parallel, Target} / q_{\parallel, OMP}$

$q_{\parallel, Target} = 275 MW/m^2$

$q_{\perp, Target} = 10 MW/m^2$

Narrow SOL Gives Strong Classical Impurity Flows

- **Gradient scale lengths are short, so friction between ion diamagnetic currents is large, causing radial ion exchange.**
  - **High-Z impurities (e.g, C, W) driven strongly inwards for $\lambda_z = \lambda_D$**
  - **Low-Z impurities (e.g., Li) driven weakly inwards by friction with D^+, outwards by friction with higher-Z for equal λ's.**



Calculations for NSTX
Outer Midplane Conditions
(no ∇T_i contribution)

F. Scotti

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- Heuristic Drift (HD) Model
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- Near-LCFS Heat-flux on Inner-Wall Limiters
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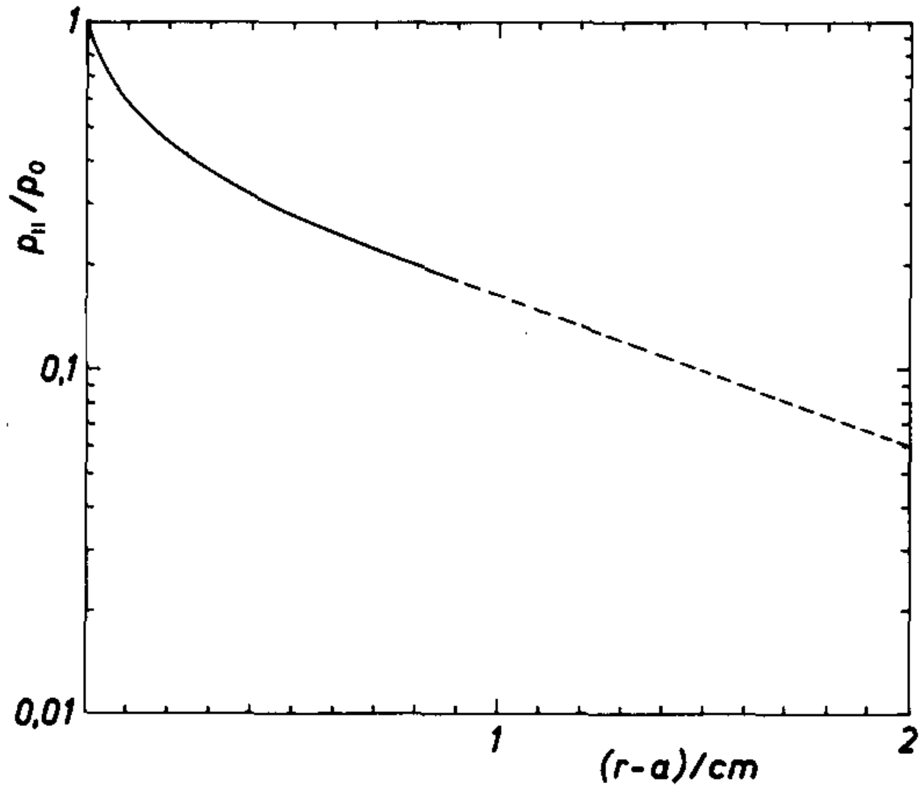
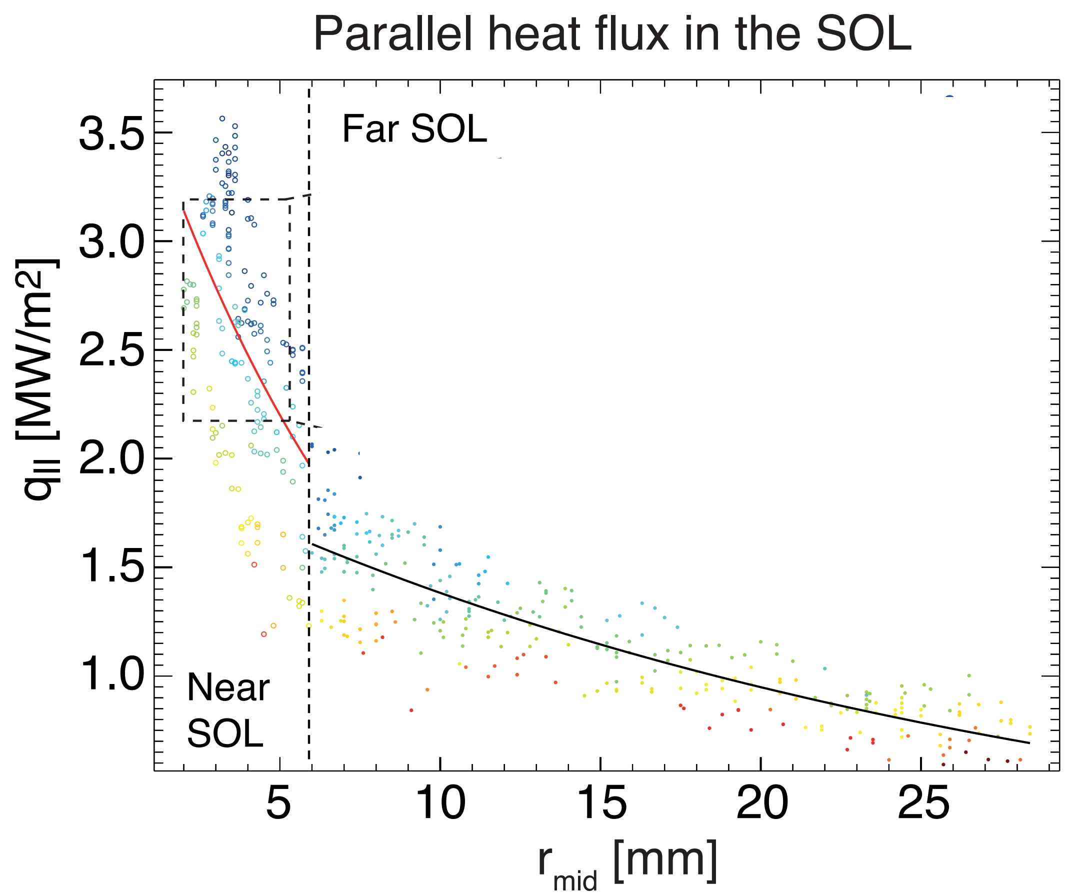
T-10, TEXTOR and JET Limiter Plasmas Show Narrow Heat Flux Feature near LCFS



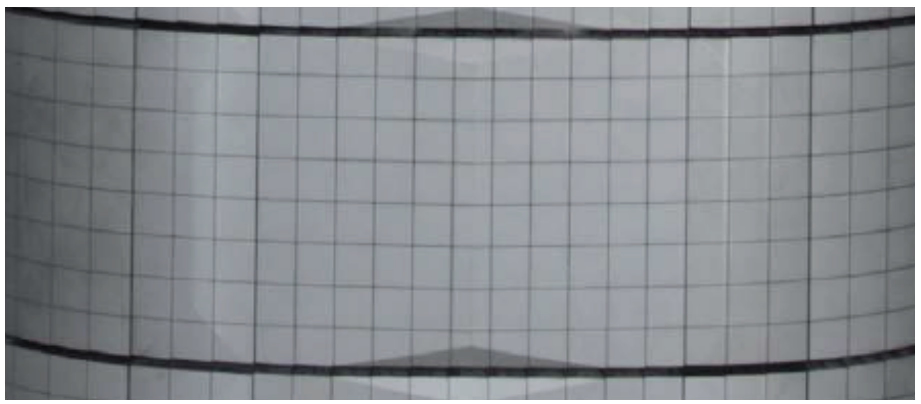
T-10 Pumped Limiter
Chankin, 1987

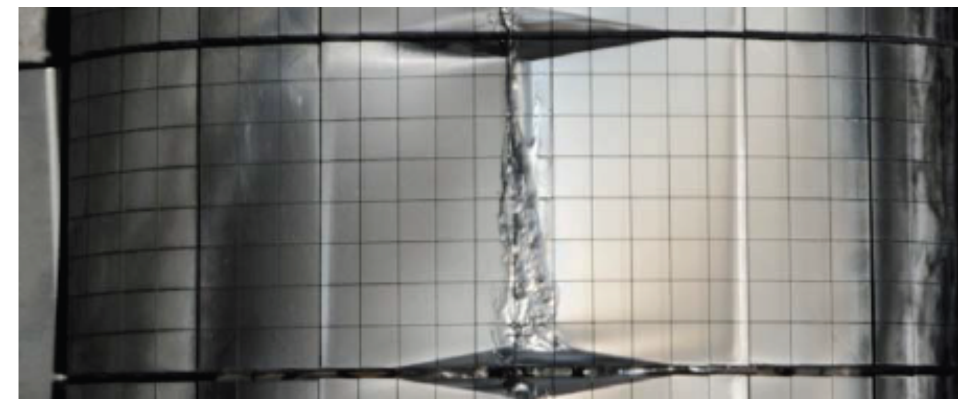


JET Inner-Wall Limiter
Arnoux, 2013

Careful ~ logarithmic shaping to match expected heat flux reveals narrow near-LCFS feature
(Not so visible on "unoptimized" rounded limiters!)

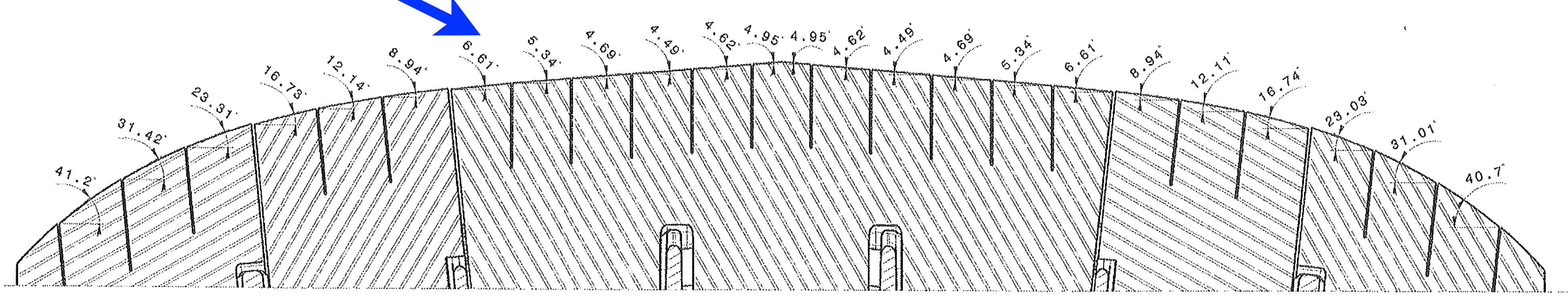
The Narrow Feature Resulted in Melting





JET Inner Wall Limiter was carefully designed for 1cm λ_q

Shows melting near the crown



COMPASS Installed a Dedicated Test Limiter

Tiltable between Shots!

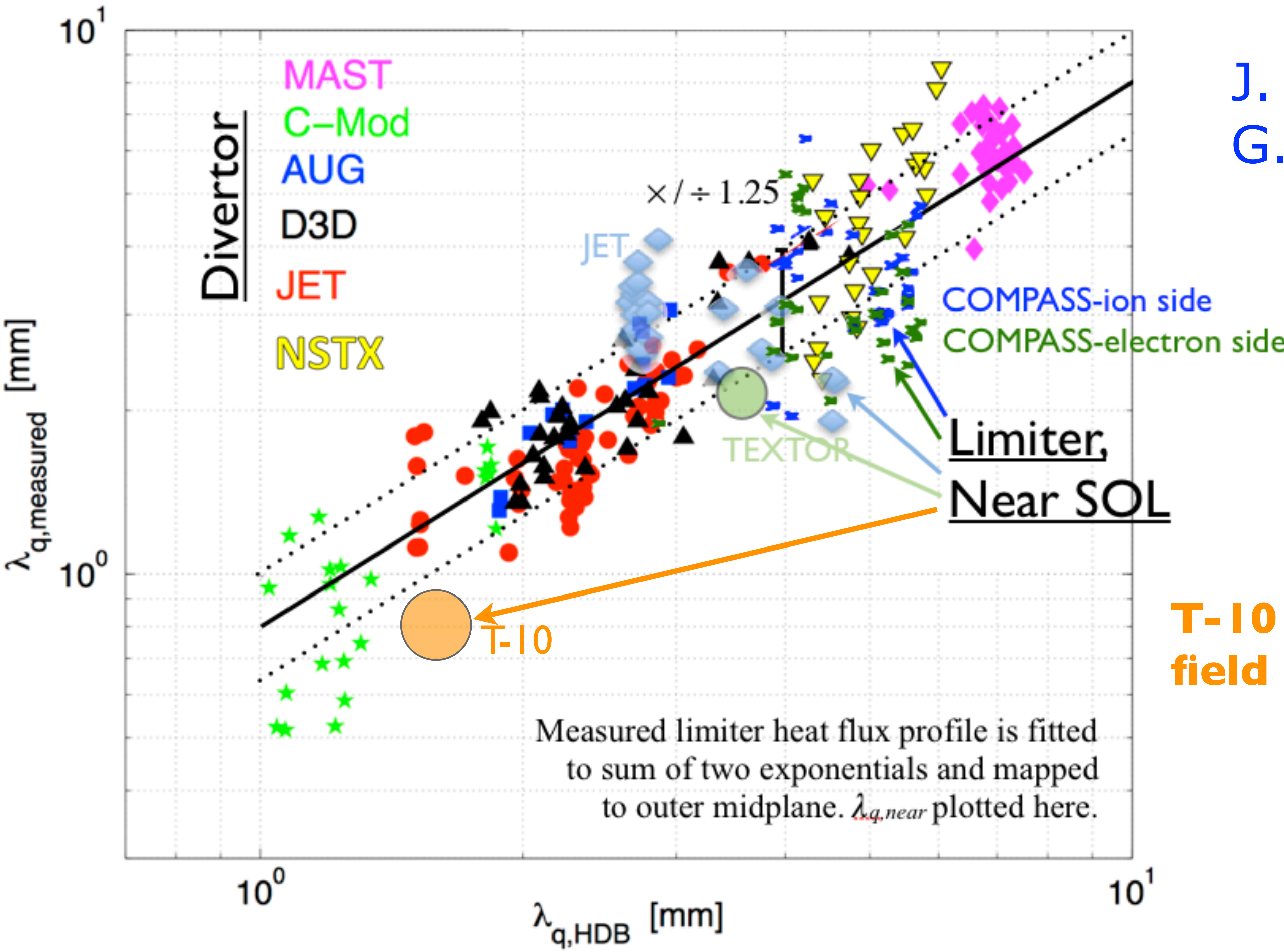
Demonstrated that the narrow feature responds to limiter angle $\propto \sin\alpha$

⇒ Not cross-field transport to the limiter surface

Caveats:
- **Feature not seen on OWL.**
- **Seen sometimes on probes.**
- **Non-ambipolar currents?**

R. Dejarnac, J. Horaçek,
M. Komm, R. Panek,
P.C. Stangeby, P. Vondraçek

Narrow Limiter Feature ~ HD Model



J. Horaçek
G. Arnoux

T-10 data had high field and low q = 2.

- Limiters have slightly higher $T_e^{1/2}$ due to sheath-limited ⇒ wider than HD
- But also faster flow due to low local re-ionization ⇒ narrower than HD

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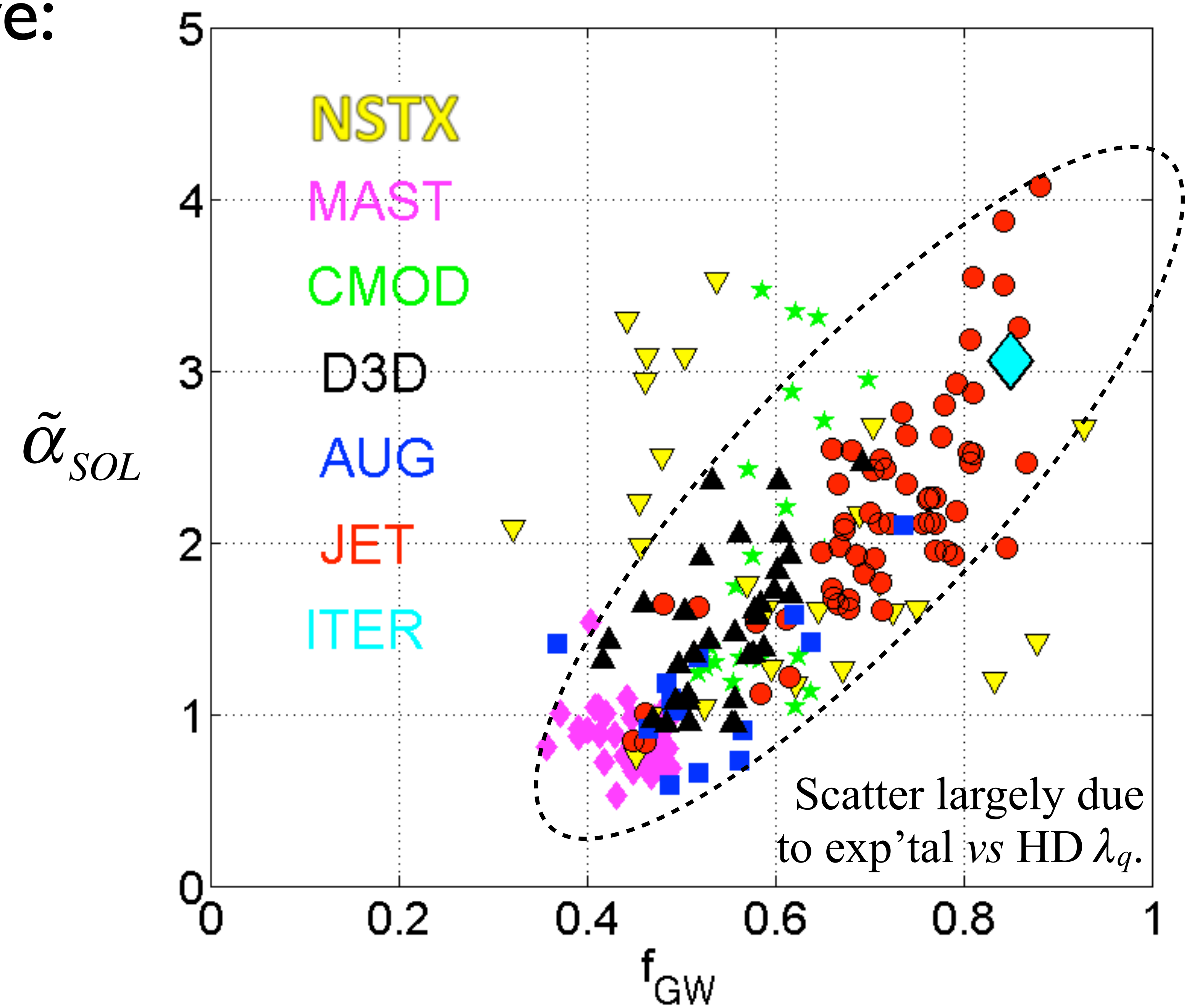
Measured λ_q + Spitzer T_e + $n_{sep} \approx \bar{n}/3$ ⇒ MHD Ballooning Drive Rises with n/n_{GW}

MHD ballooning drive:

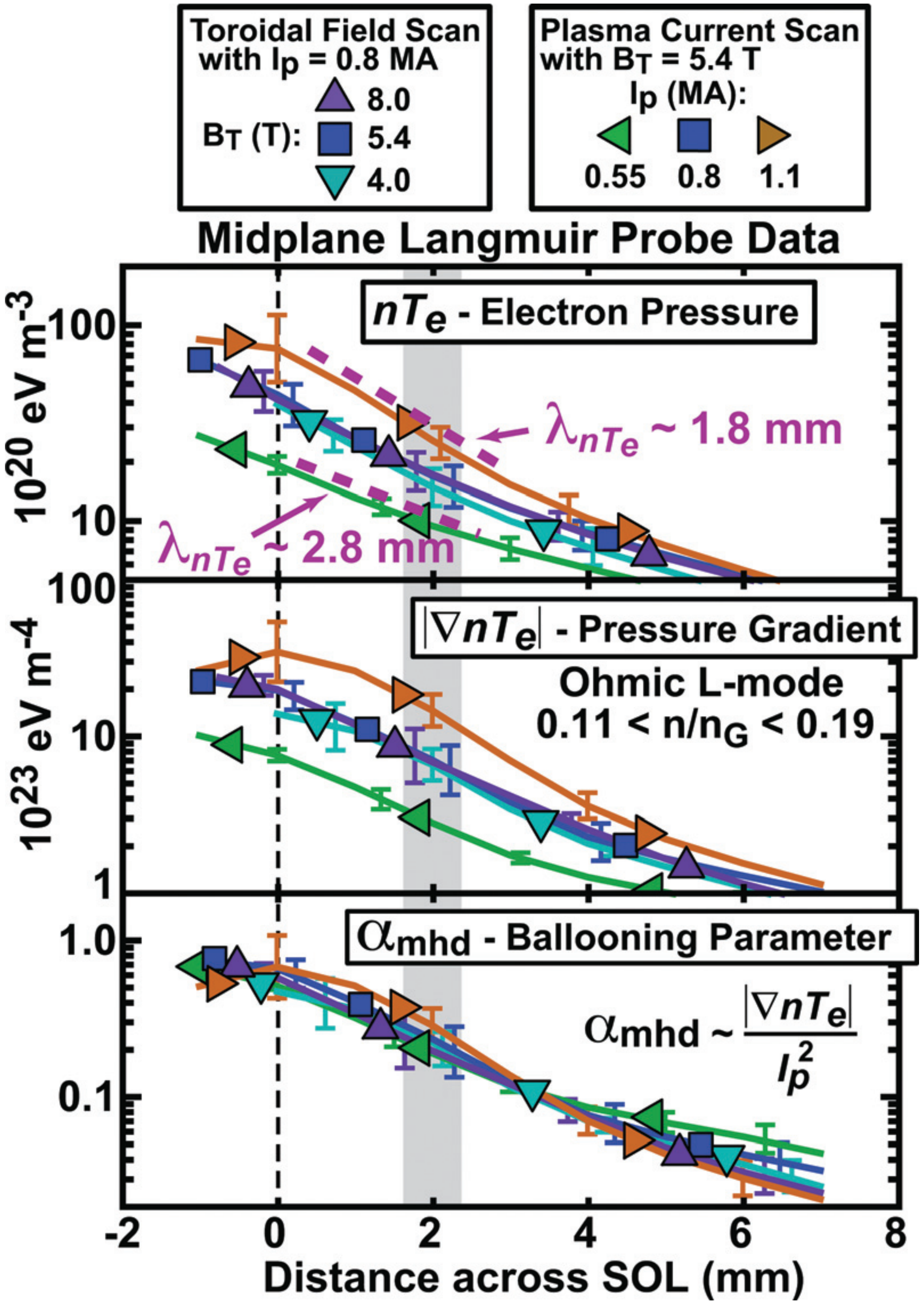
$$\tilde{\alpha}_{SOL} \equiv \frac{Rq_{cyl}^2 2\left(\bar{n}/3\right)T_{Spitzer}}{\left\langle \lambda_{q,exp} \right\rangle_{pol}\left(B_t^2/2\mu_0\right)}$$

- Data (and model) give α depending almost exclusively on f_{GW}, *without invoking ballooning physics.*
- Does the ballooning drive in the SOL kick in at high f_{GW} causing the density limit?



C-MOD Data Show Little Variation in α *at Fixed f_{GW}*, as Predicted by HD Model

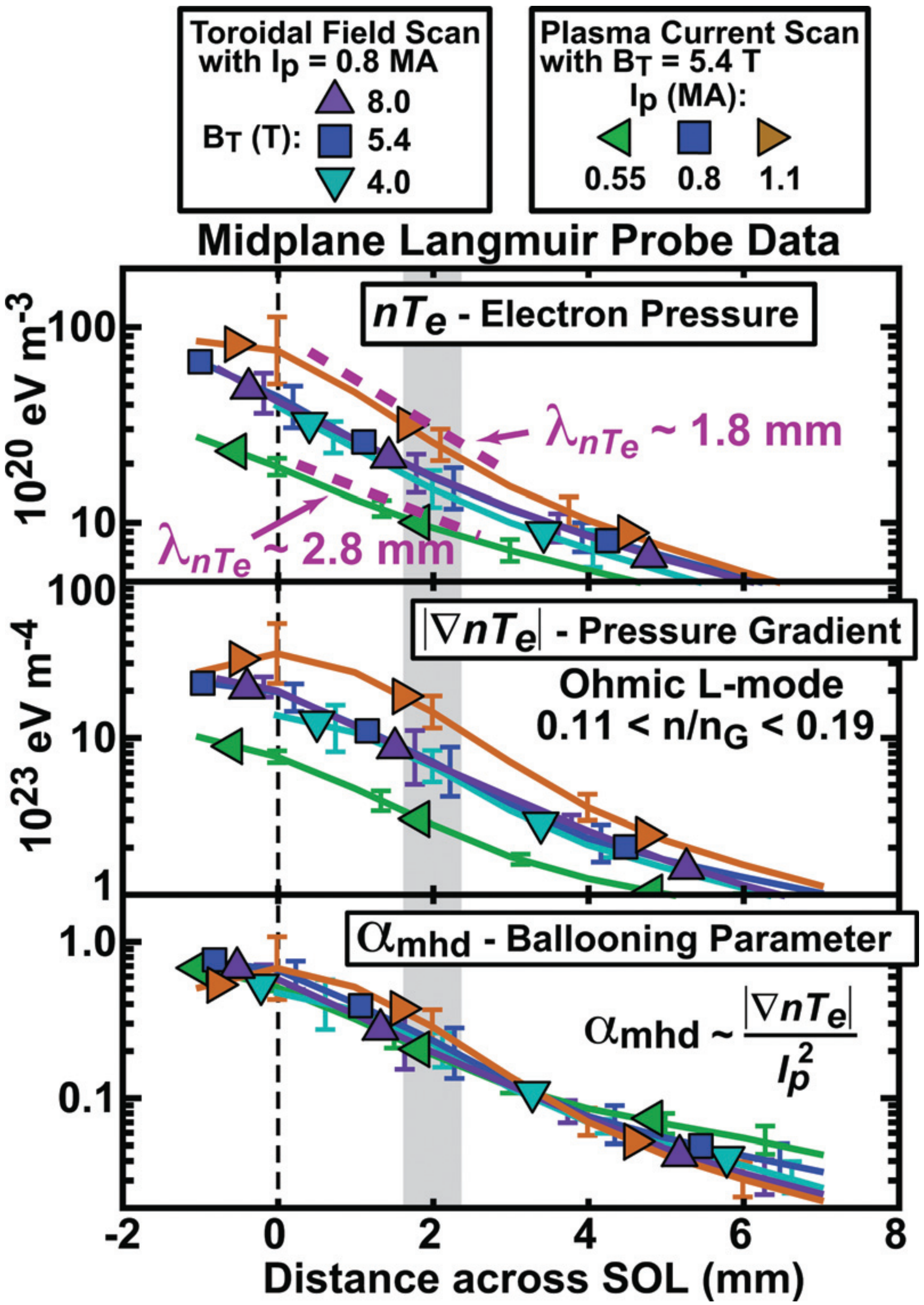
B. LaBombard



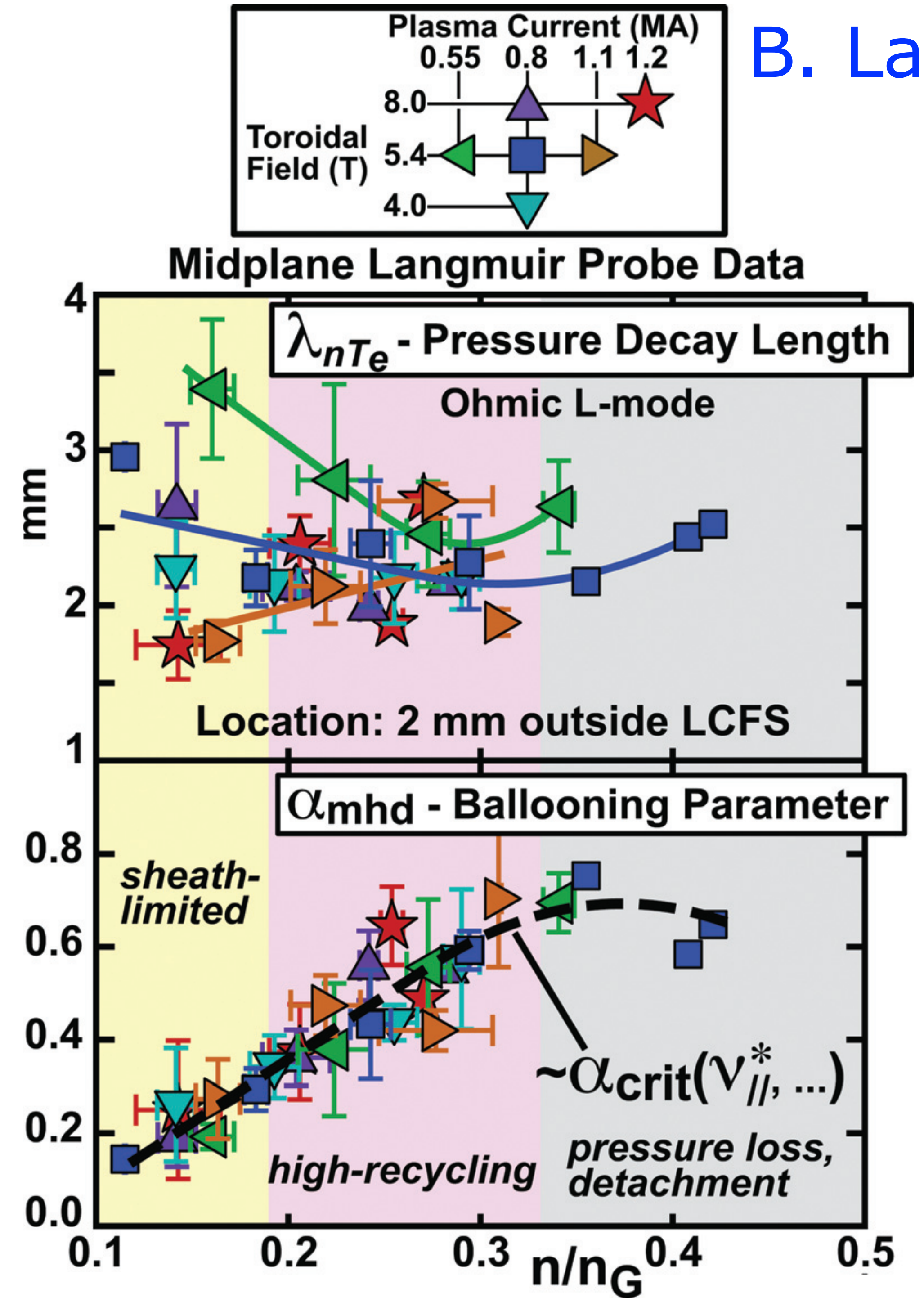
Nearly constant f_{GW}

These Same Data Show α Rises Strongly with f_{GW} – as Predicted by HD Model

B. LaBombard



Nearly constant f_{GW}



f_{GW} Scan

HD Model + MHD Limit
⇒ f_{GW} ~ 1 Limit

- **Assume $p/p' = \lambda_{q,HD}$, get T from Spitzer**
- **Assume $n_{sep} = \bar{n}/3$**
- **Assume** $\tilde{\alpha} \equiv \dfrac{R q_{cyl}^2 \left(2\bar{n}/3\right) T_{Spitzer}}{\lambda_{q,HD}\left(B_t^2/2\mu_0\right)} = \alpha_{crit} = C_\alpha \left(1+\kappa^2\right)^\nu$
- **Solve for $f_{GW,crit} \equiv (\bar{n}/\bar{n}_{GW})_{crit}$**

$$f_{GW,crit} = 24.4\left[\left(\frac{a}{P_{SOL} B_t q_{cyl} R}\right)\left(\frac{5}{Z_{eff}+4}\right)\right]^{1/8}\left[\frac{2\bar{A}}{\left(1+\bar{Z}\right)}\right]^{9/16} C_\alpha \left(1+\kappa^2\right)^{\nu-3/2}$$

- **Numerical value is of order unity**
- **Weak dependence on everything but A and κ**
- **Myra *et al.* (PP8.38) find ν ~ 0.4 for n = ∞ ballooning mode at separatrix, at small <δ>. We know δ plays a big role.**
- **See also Makowski *et al.* (UP8.36). Need ∇p_i data.**

Conclusions

- **A very simple "Heuristic Drift" model is consistent with divertor heat-flux data.**
  - Need to test model in 2-D edge codes, include high flow, determine role of radial, poloidal electric fields.
  - Classical radial impurity flows to be added to 2-D edge codes?
- **Implies need for highly dissipative ITER divertor.**
  - Transport, radiation, charge-exchange.
- **Narrow, high-heat-flux layer on Inner-Wall Limiters ~ consistent with HD model prediction.**
- **Greenwald (and/or H-mode) density limit may be caused by MHD ballooning drive in the SOL.**
  - Need more detailed SOL measurements, especially ∇p_i.
- **Tokamak plasmas seem to be surrounded by λ_q ~ magnetic drift speed • poloidal sound transit time. The consequences can be significant.**

Back-up Slides

Field Line Integral gives λ = (2a/R)ρ_p

Express $\lambda \sim \langle v_d \rangle \tau_{||}$ as the time integral of $\vec{v}_{curv+\nabla B} \cdot \vec{\nabla}\psi_p$ from mid-plane (MP) to x-point.

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

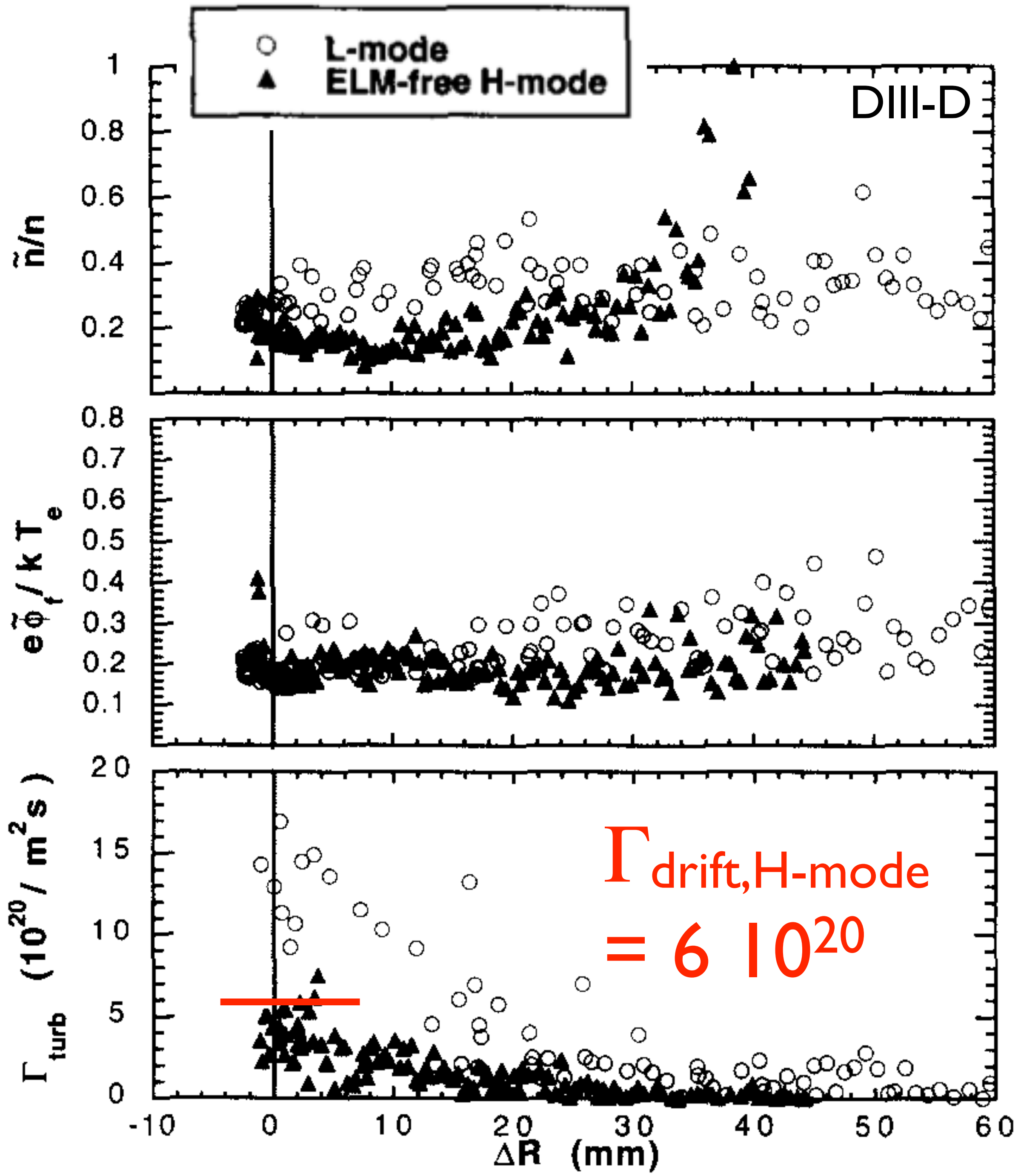
$$\Delta\psi_p = \frac{2}{c_s} \int_{MP}^{X-pt} \left(\vec{v}_{curv+\nabla B} \cdot \frac{\vec{\nabla}\psi_p}{\left|\vec{\nabla}\psi_p\right|}\right) RBdl_p = \frac{2}{c_s} \int_{MP}^{X-pt} \frac{2T_{sep}}{\bar{Z}eBR} RB\ \hat{z} \cdot \hat{\varphi} \times d\vec{l}_p = \frac{4T_{sep}}{\bar{Z}ec_s} \int_{MP}^{X-pt}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

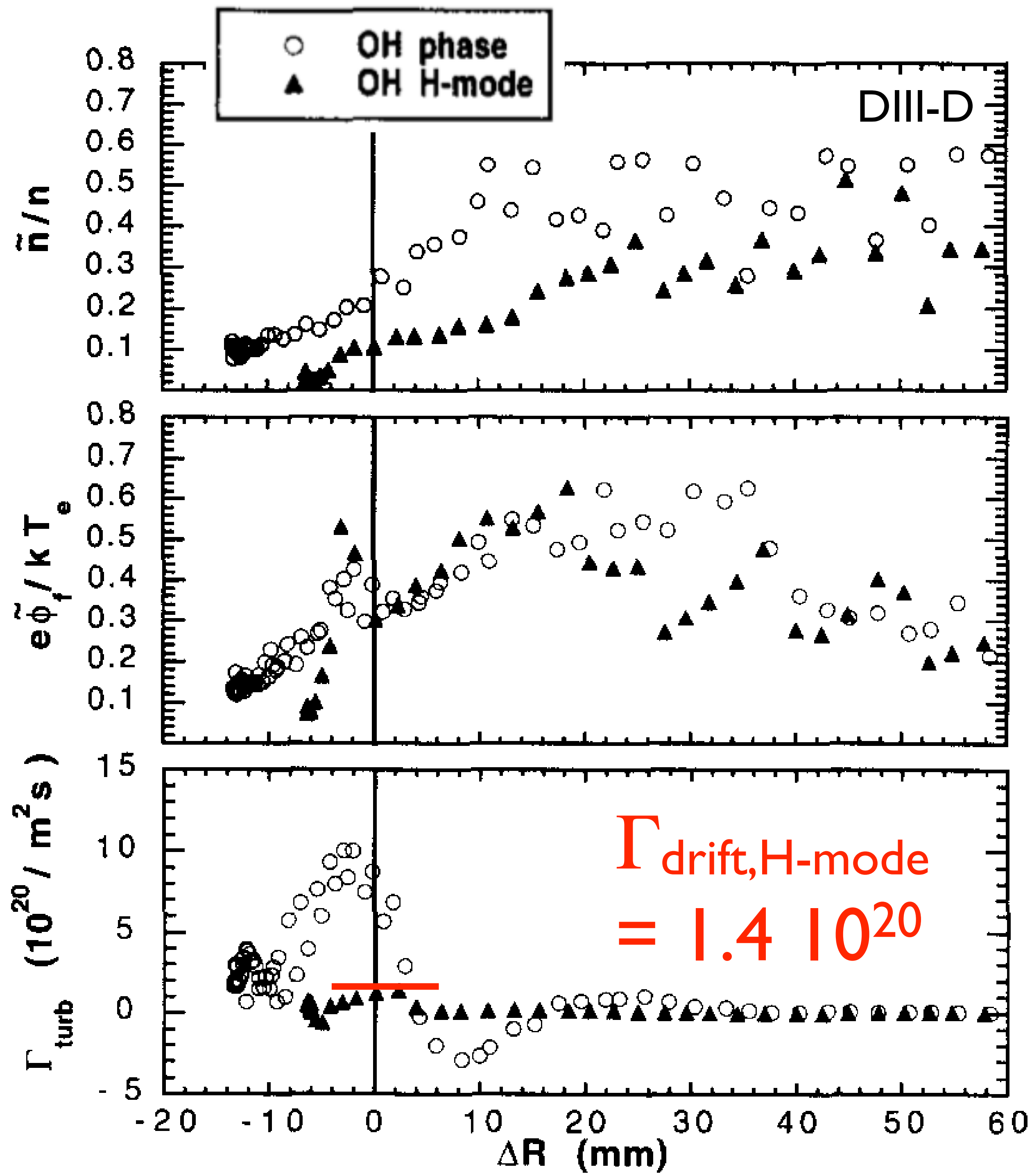
$$\lambda = \frac{\Delta\psi_p}{\left|\nabla\psi_p\right|} = \frac{4T_{sep}a}{\bar{Z}eB_pRc_s}; \qquad c_s = \left[\frac{\left(1+\bar{Z}\right)T_{sep}}{\bar{A}m_p}\right]^{1/2}; \qquad \bar{Z} \equiv \frac{n_e}{\sum_i n_i}; \qquad \bar{A} \equiv \frac{\sum_i n_i A_i}{\sum_i n_i}$$

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

ion drift — *electron drift*

In H-Mode: Magnetic Drift Flux ≥ Turbulent Flux



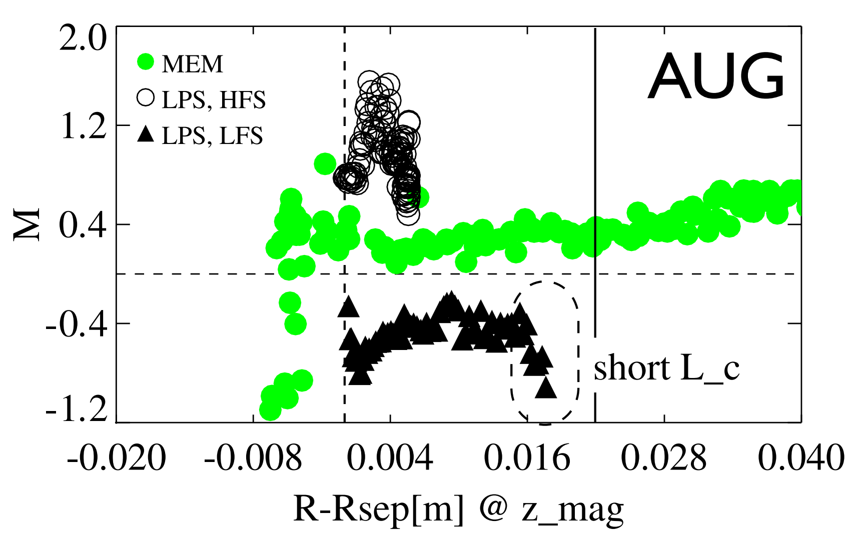


R. Moyer

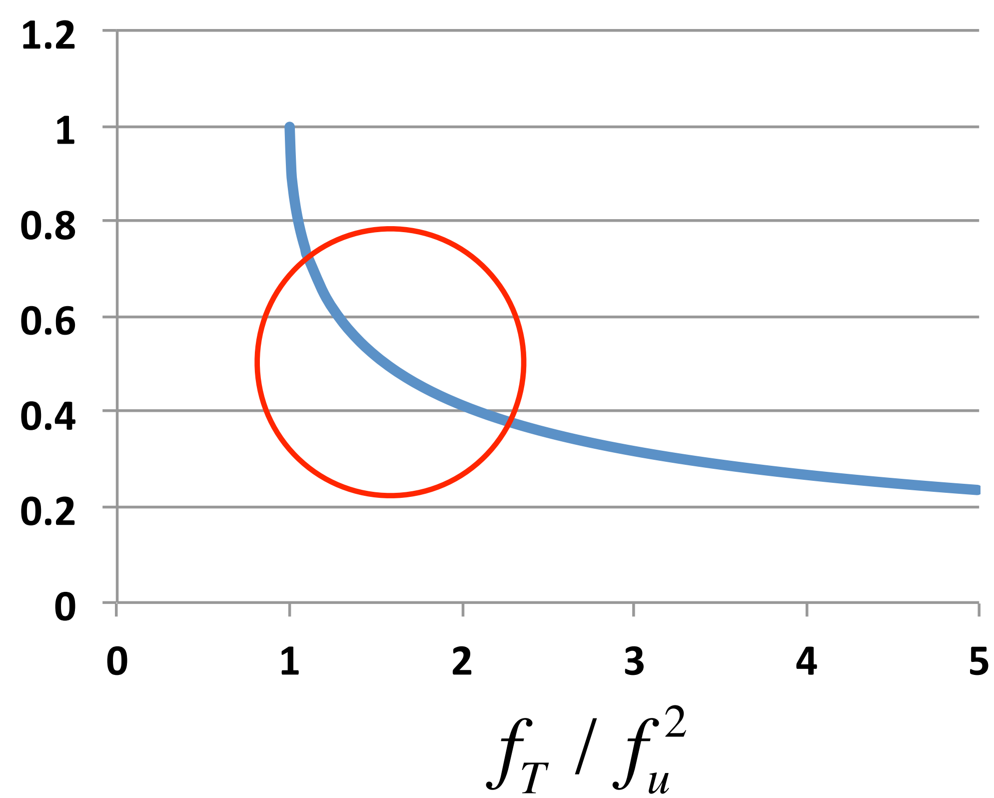
$C_s/2$ Flow ~ Consistent with 3pt Model

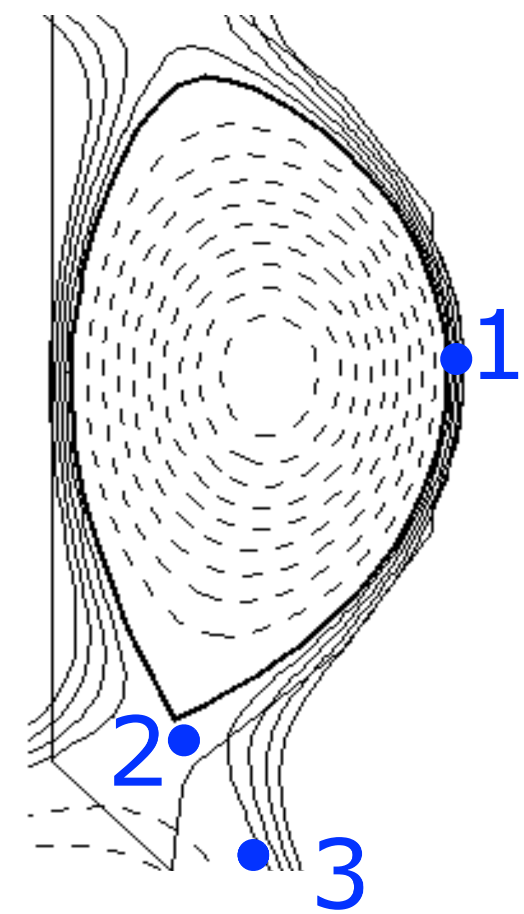
- $f_u \equiv$ upstream source to SOL / total source to SOL ~ 1/4
- $f_T \equiv$ $T_{target}/T_{upstream}$ ~ 1/10
- M_X = *Mach number at X-point*

$$M_x = \left(\frac{f_T}{f_u^2}\right)^{1/2} - \left(\frac{f_T}{f_u^2} - 1\right)^{1/2}$$



H. Muller



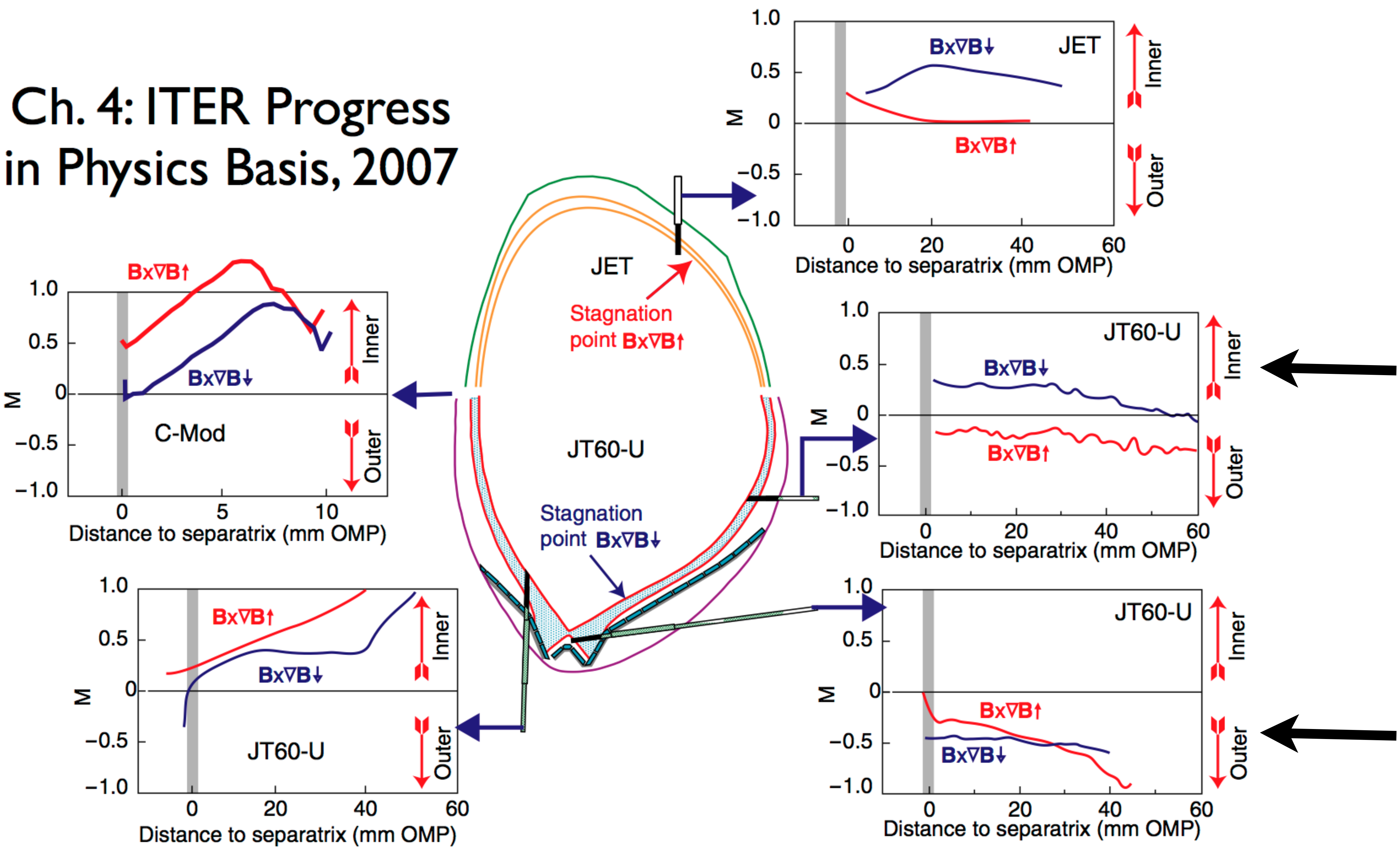


- Lower f_u (better plugging) tends to be tied to lower f_T (colder divertor target) ⇒ M_X ~ self-regulating

P. Stangeby

Parallel Flow Picture Supported by Experimental Data

Ch. 4: ITER Progress in Physics Basis, 2007



L-Mode data only

(Also strong flows in AUG H-mode near x-point.)