Theory framework for scrape-off layer turbulence in limited tokamaks

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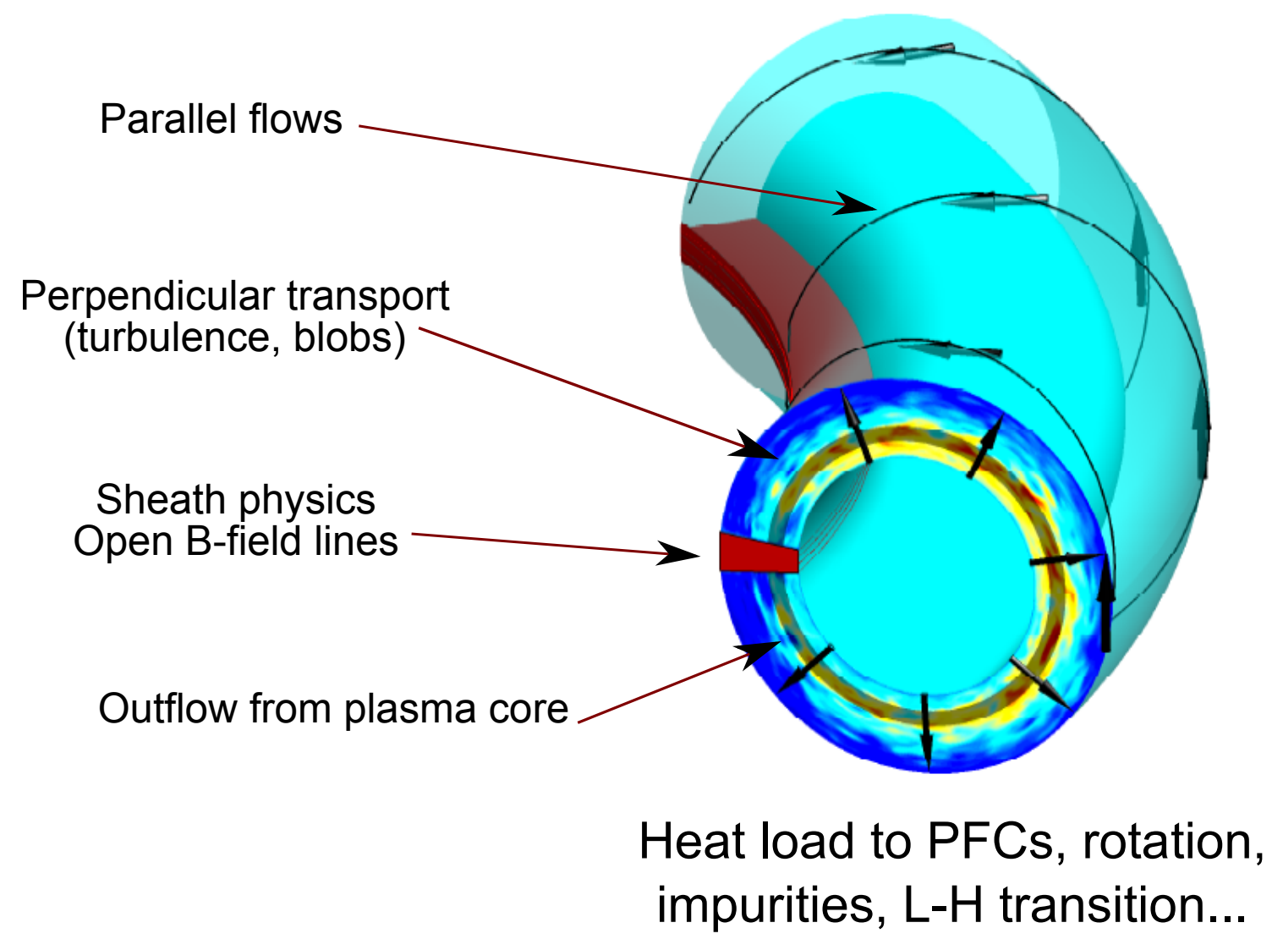
Introduction



We address the following questions regarding the scrape-off layer (SOL) of inner-wall limited tokamak plasmas:

- What is the mechanism determining the turbulence levels in this configuration?
- What instabilities are present and which one dominates?
- What are the effects of finite ion temperature?
- How does the SOL width $L_p = -p/\partial_r p$ change with the plasma parameters?
- Can we explain the presence of a narrow heat flux feature recently observed in near SOL?

We carry out an extensive non-linear simulation scan which is interpreted using analytical theory

Drift-reduced fluid model for SOL turbulence

- Two-fluid Drift-reduced Braginskii equations, $k_\perp^2 \gg k_\parallel^2$, $d/dt \ll \omega_{ci}$ orderings [Mosetto *et al.*]:

$$
\begin{aligned}
\frac{\partial n}{\partial t} &= -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel \cdot (n v_{\parallel e}) + S_n \\
\frac{\partial \omega}{\partial t} &= -\rho_\star^{-1}[\phi, \omega] - v_{\parallel i}\nabla_\parallel \nabla_\perp^2 \phi + \frac{B^2}{n}\nabla_\parallel j_\parallel + \frac{2B}{n}C(p) \\
\frac{\partial \chi}{\partial t} &= -\rho_\star^{-1}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left(\nu\frac{j_\parallel}{n} + \nabla_\parallel \phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e\right) \\
\frac{\partial v_{\parallel i}}{\partial t} &= -\rho_\star^{-1}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p \\
\frac{\partial T_e}{\partial t} &= -\rho_\star^{-1}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4}{3}\frac{T_e}{B}\left[\frac{1}{n}C(p_e) + \frac{5}{2}C(T_e) - C(\phi)\right] + \frac{2}{3}T_e\left[0.71\nabla_\parallel j_\parallel - \nabla_\parallel v_{\parallel e}\right] + S_{T_e} \\
\frac{\partial T_i}{\partial t} &= -\rho_\star^{-1}[\phi, T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4}{3}\frac{T_i}{B}\left[C(T_e) + \frac{T_e}{n}C(n) - C(\phi)\right] \\
&\quad + \frac{2}{3}T_i\left(v_{\parallel i} - v_{\parallel e}\right)\frac{\nabla_\parallel n}{n} - \frac{2}{3}T_i\nabla_\parallel v_{\parallel e} - \frac{10}{3}\frac{T_i}{B}C(T_i) \\
\nabla_\perp^2 \psi &= n(v_{\parallel i} - v_{\parallel e}) = j_\parallel,\ \chi = v_{\parallel e} + \frac{m_i}{m_e}\frac{\beta}{2}\psi,\ \rho_\star = \rho_s/R \\
\omega &= \nabla_\perp^2 \phi - \nabla_\perp^2 p_i,\ \nabla_\parallel f = \mathbf{b}_0 \cdot \nabla f + \rho_\star^{-1}\frac{\beta}{2}[\psi, f]
\end{aligned}
$$

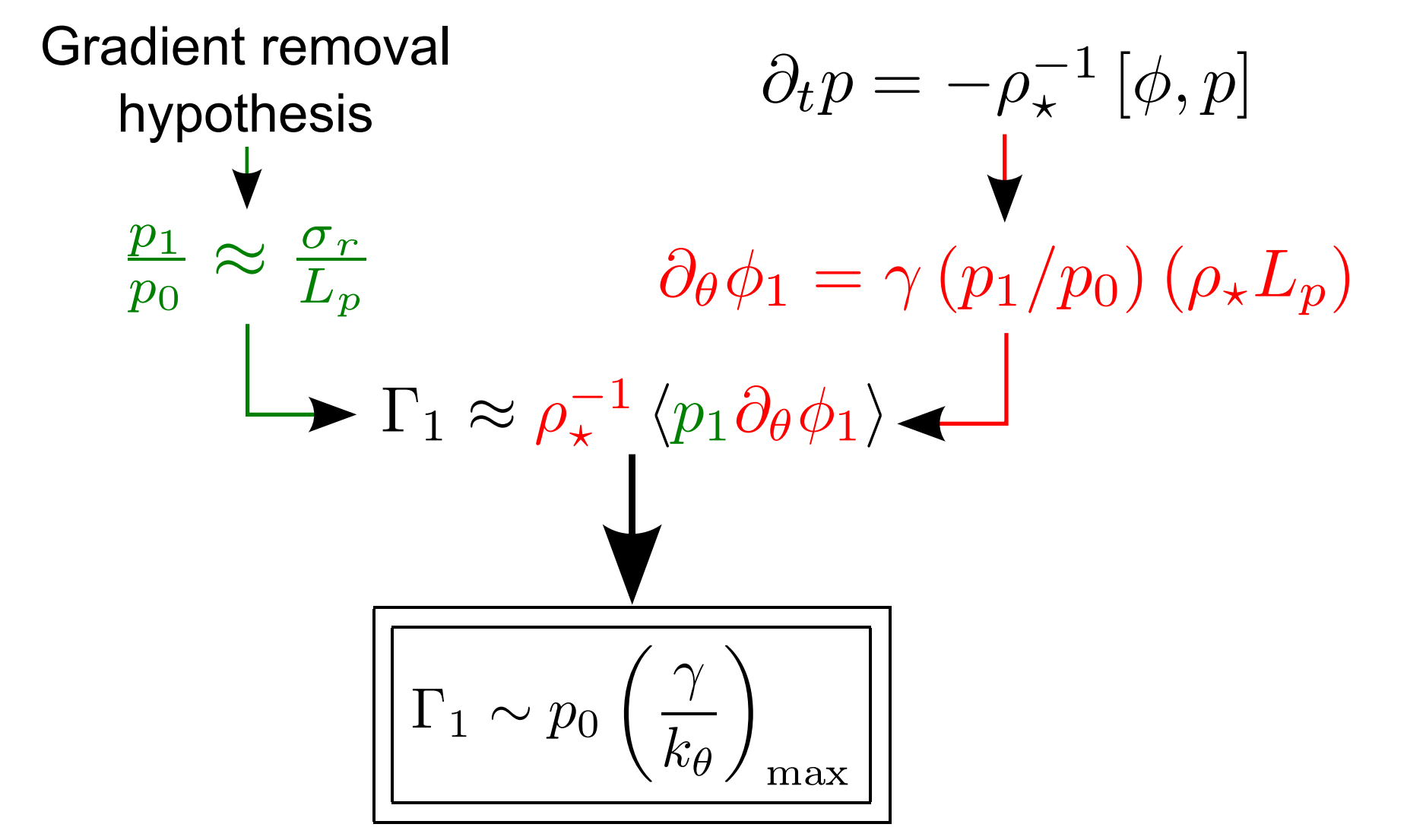
- These equations are implemented in GBS, a 3D, flux-driven, global turbulence code with circular geometry including electromagnetic effects
- System is closed with set of first-principles boundary conditions applicable at the magnetic pre-sheath entrance where the magnetic field lines intersect the limiter [Loizu *et al.*, PoP 2012]
- Note: normalized units used throughout: $L_\perp \to \rho_s$, $L_\parallel \to R$, $t \to R/c_s$, $\nu = ne^2 c_s/(m_i \sigma_\parallel R)$

Turbulent saturation mechanism

- In GBS non-linear simulations, sheared flows do not contribute significantly to saturation
- We extract the following observations regarding turbulent transport [Ricci and Rogers, PoP 2013]:

(1) Mode saturation caused by local pressure profile flattening	*(2) Radial extension of the mode given by non-local linear theory*	*(3) Perpendicular turbulent transport driven by* **E** × **B** *convection*
$\partial_r p_0 \sim \partial_r p_1 \to p_1/p_0 \sim \sigma_r/L_p$	$\sigma_r = \sqrt{L_p/k_\theta}$	$\Gamma_1 = -\rho_\star^{-1}[\phi, p]$

From these observations, we obtain an estimate of Γ_1:



$$\partial_t p = -\rho_\star^{-1}[\phi, p]$$

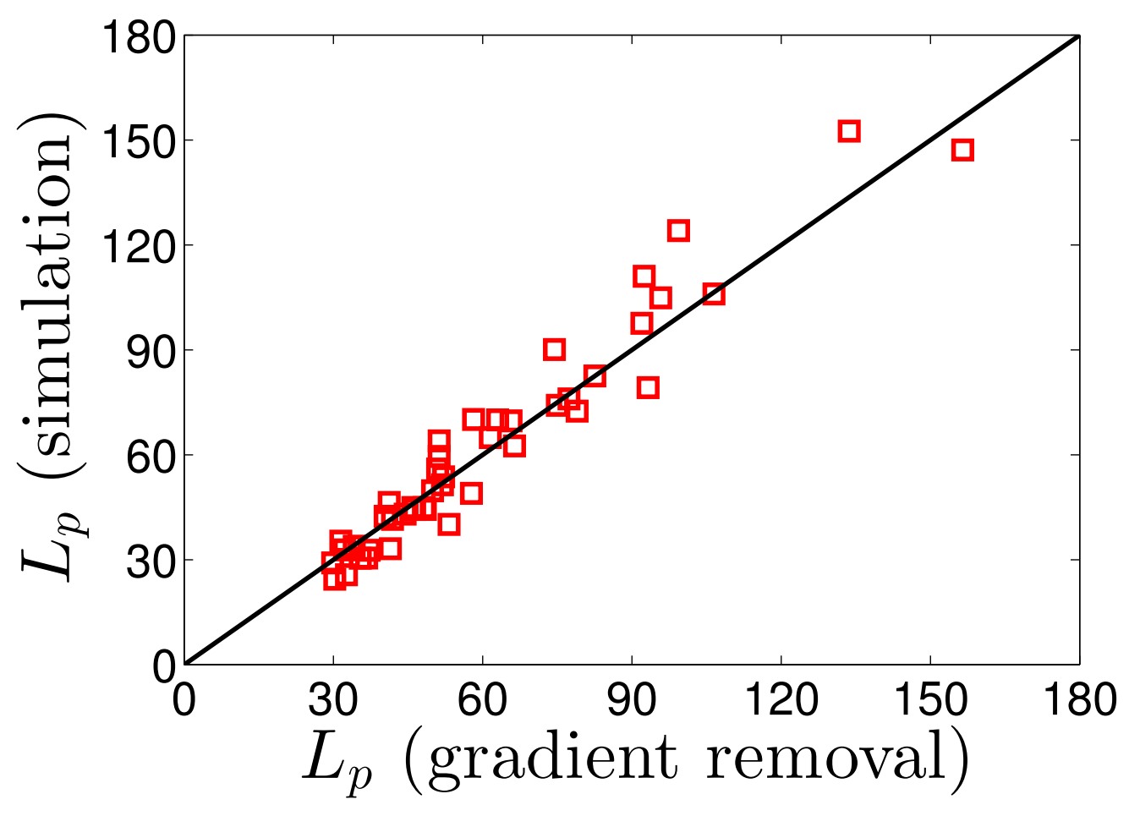
$$\frac{p_1}{p_0} \approx \frac{\sigma_r}{L_p} \qquad \partial_\theta \phi_1 = \gamma\,(p_1/p_0)\,(\rho_\star L_p)$$

$$\Gamma_1 \approx \rho_\star^{-1}\langle p_1 \partial_\theta \phi_1 \rangle$$

$$\boxed{\Gamma_1 \sim p_0\left(\frac{\gamma}{k_\theta}\right)_{\max}}$$

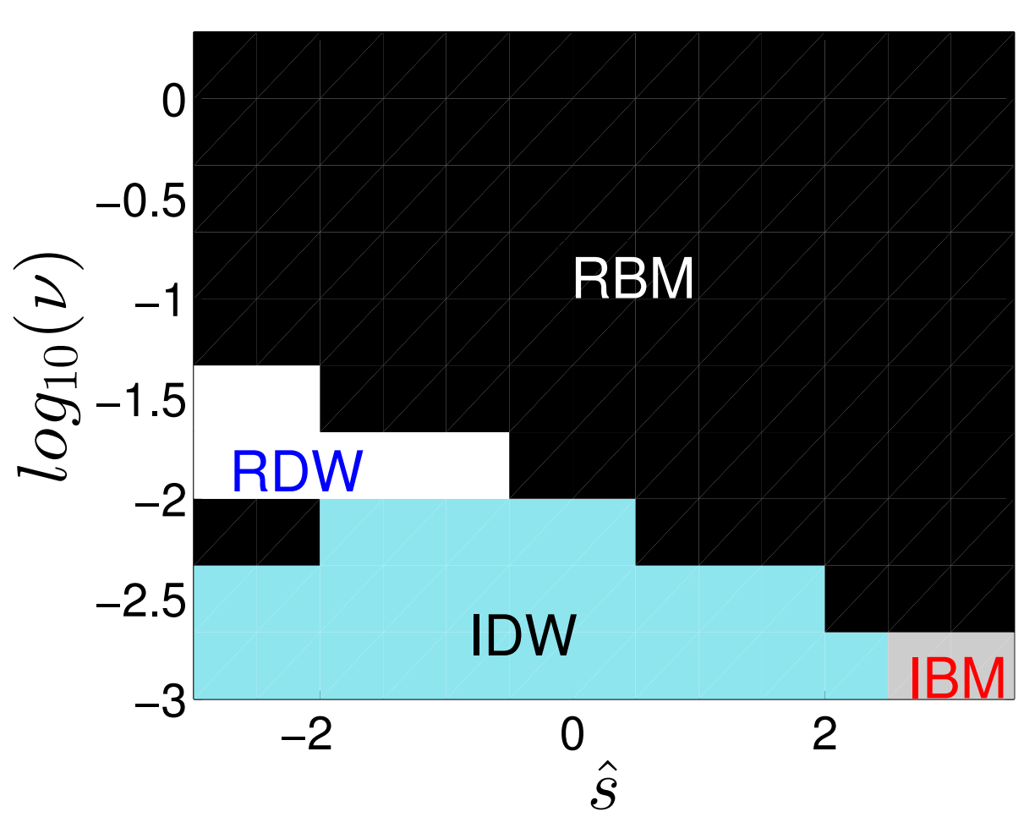
Which results in an estimate of the SOL width:

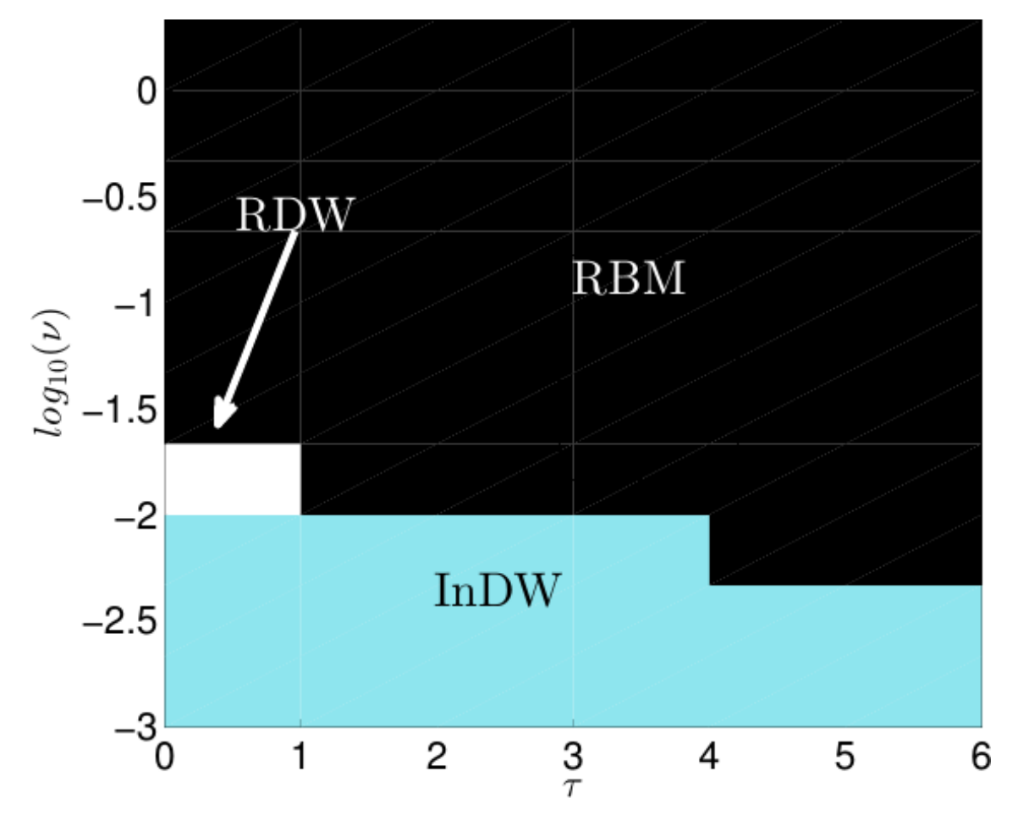
$$\boxed{L_p = q\left(\frac{\gamma}{k_\theta}\right)_{\max}}$$



Identifying the dominant instabilities with finite T_i effects

- Reduced linear models combined with saturation theory identify dominant mode [Mosetto *et al.*, PoP 2013]
- Relevant parameters for inner-wall limited SOL: $q = 3$–10, $\nu \sim 0.01$, $\hat{s} \approx 2$
- In circular, limited plasmas, resistive ballooning modes (RBMs) are dominant in the SOL (also, no ITGs)

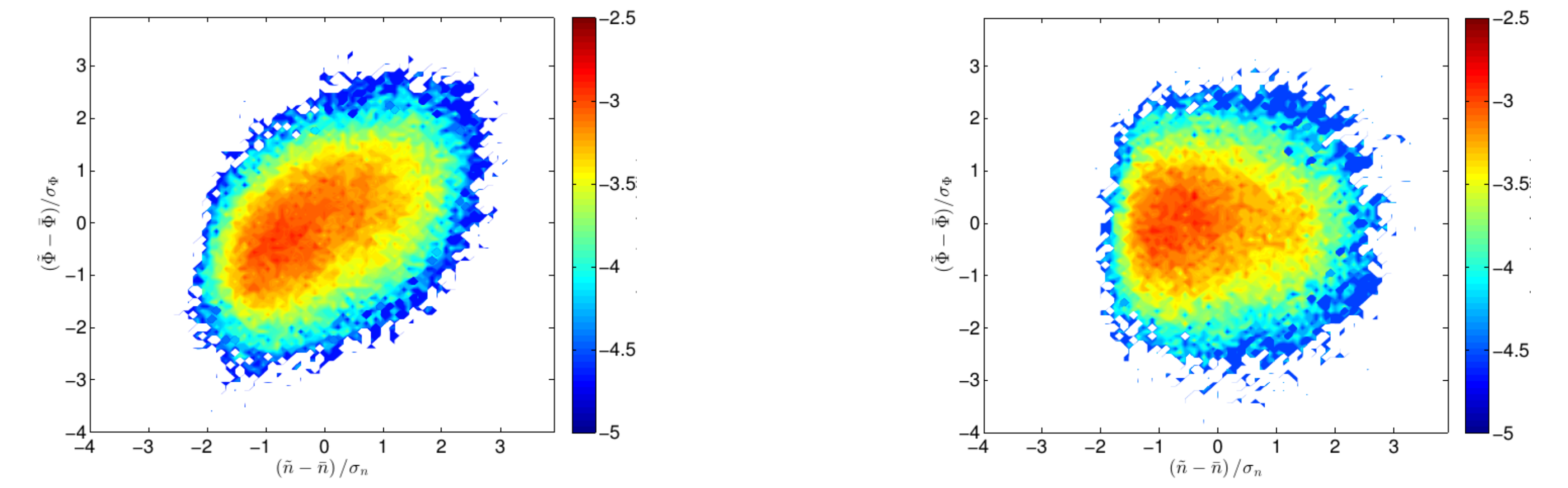




- Presence of RBMs confirmed in simulations of TCV SOL at realistic parameters [Halpern *et al.*, NF 2014]
- Adding ion temperature effects alters RBM / IDW transition → lower ν needed for IDW [Mosetto, 2014]

Enhancement of RBMs with finite ion temperature effects

- GBS simulations ($\rho_\star^{-1} = 500$, $\nu = 0.1$) with T_i show enhancement of RBM component [Mosetto, 2014]
- Joint PDF of density and potential fluctuations at $T_i/T_e = 1$ (left) and at $T_i/T_e = 4$ (right)



- As ion temperature is increased, adiabatic coupling is decreased, phase between n and ϕ increases

Scrape-off layer width

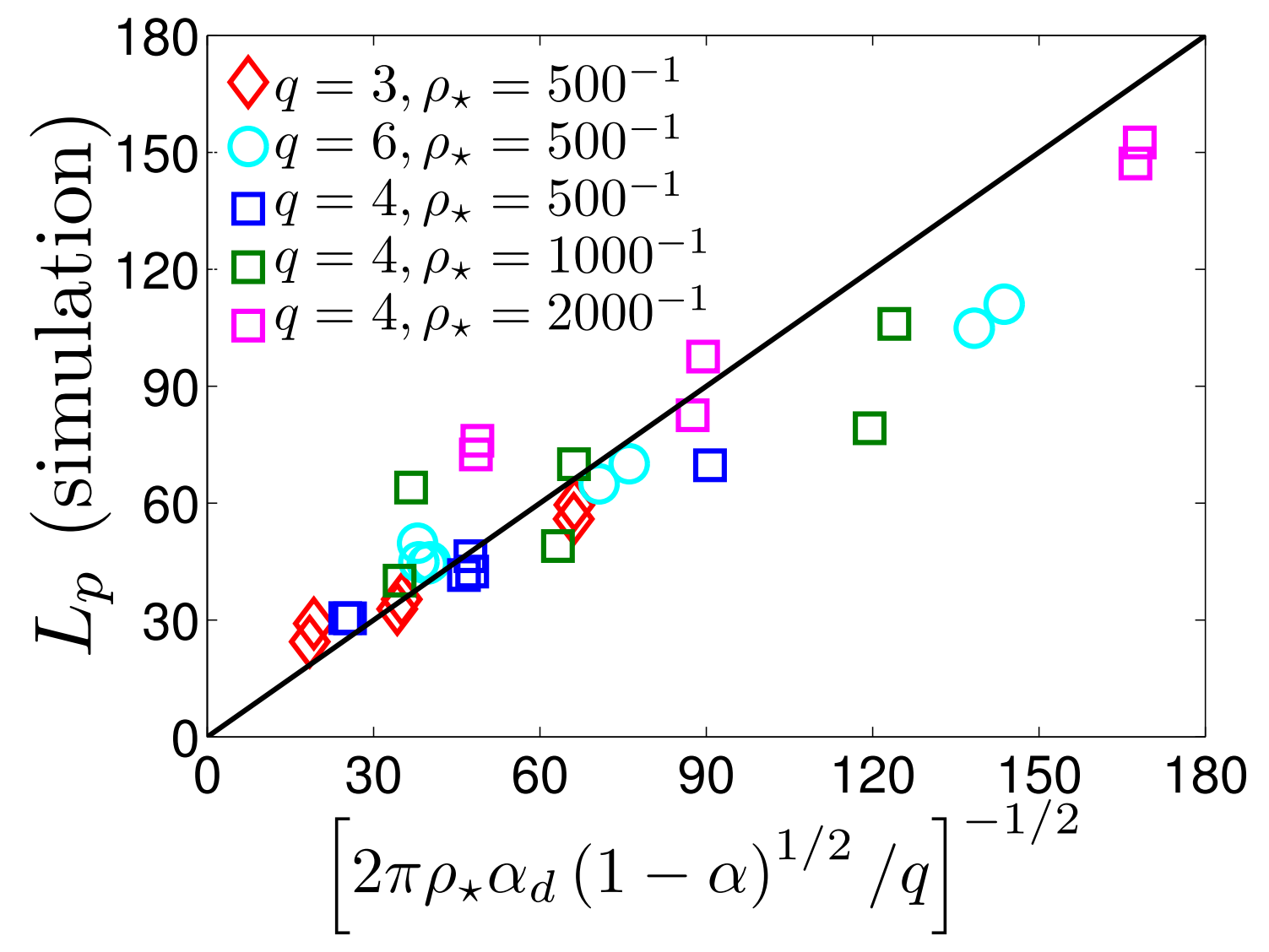
- The SOL width can be obtained analytically by considering *gradient removal saturated RBMs*:

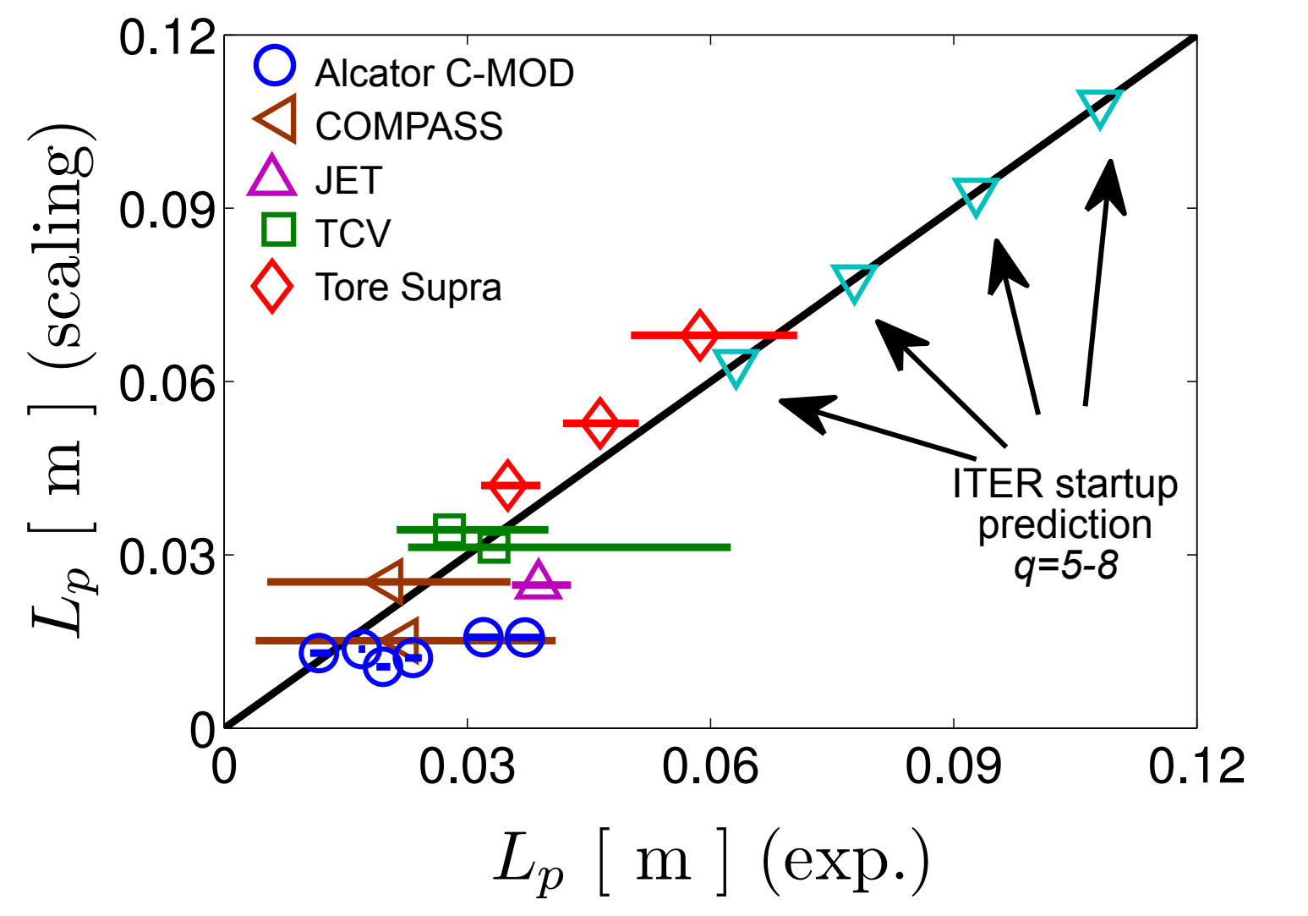
$$L_p = q\left(\frac{\gamma}{k_\theta}\right)_{\max} \qquad \gamma_b = \sqrt{2/(\rho_\star L_p)} \qquad k_b = \sqrt{(1-\alpha)/(\nu\gamma_b)}/q$$

$$
\begin{aligned}
\alpha_d^{-1} &= 2^{7/4}\nu^{1/2}\left(\rho_\star L_p\right)^{1/4}\pi q) \\
\alpha &= \frac{q^2\beta}{\rho_\star L_p}
\end{aligned}
$$

- Dimensionless and engineering parameter scalings of the SOL width follow [Halpern *et al.*, NF 2013]:

$$\boxed{L_p = \left[2\pi\rho_\star\alpha_d\,(1-\alpha)^{1/2}/q\right]^{-1/2}} \qquad \boxed{L_p \approx 7.2 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e0}^{-2/7} n_{e0}^{2/7} (1 + T_i/T_e)^{1/7}\ [\,\mathrm{m}\,]}$$



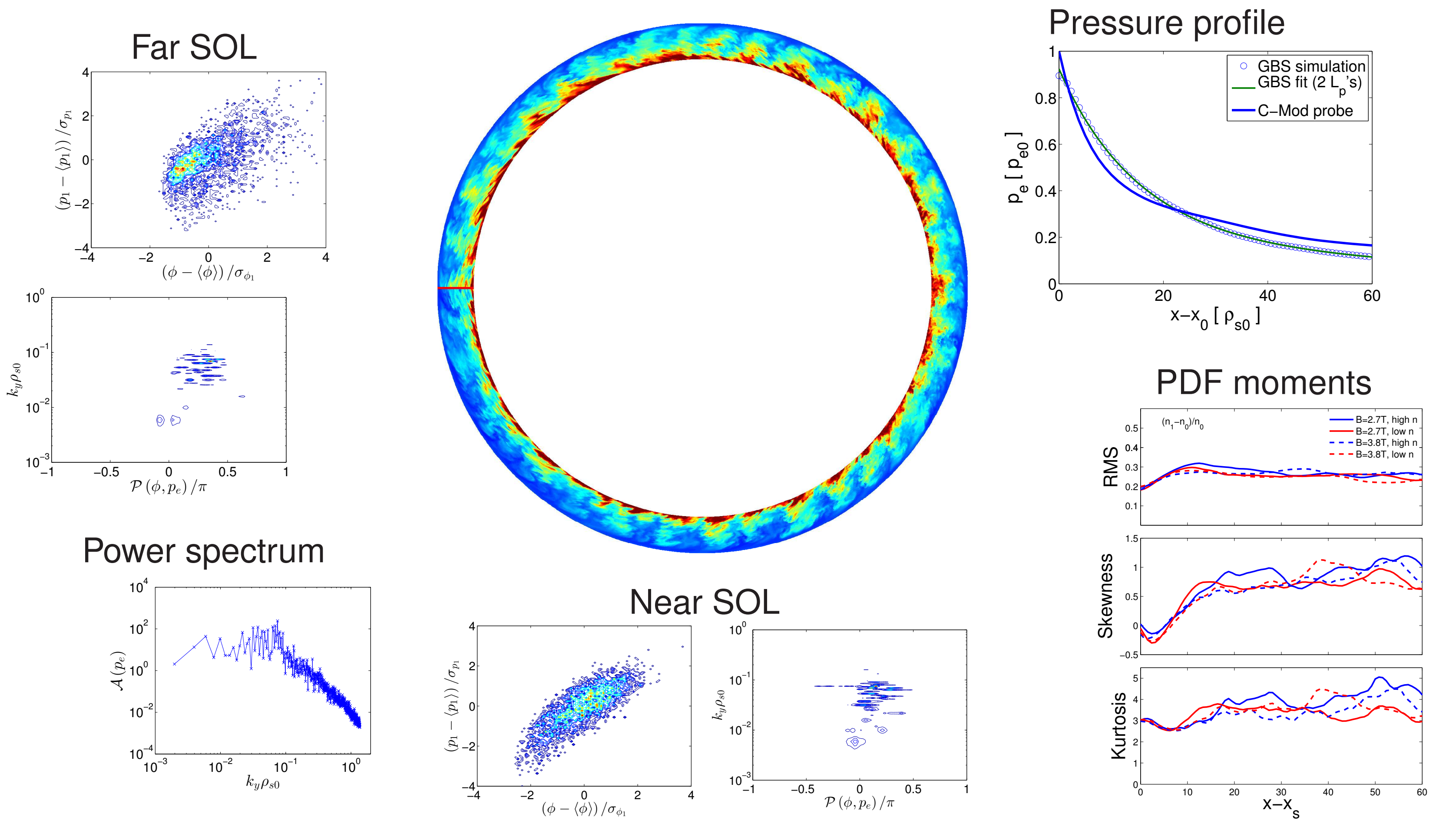


- Scalings obtained from least-squares-fitting of all simulation data verify our theory:

$$
\begin{aligned}
L_p &= q^{0.98}\rho_\star^{-0.46}\nu^{0.17}\beta_{e0}^{0} \\
L_p &\sim q^{0.98} R^{0.63} B^{-0.56} [\mathrm{m}]
\end{aligned}
\tag{1}
$$

Simulations of C-Mod limited discharges

- Attempt to understand mismatch between scalings and C-Mod data from [Zweben *et al.* PoP 2009]
- Simulation parameters: $R = 0.67$m, $B = 2.7, 3.8$T, $q = 2.7$, $T_e = 22$–36eV, $n_e = 1$–$4 \times 10^{19}\mathrm{m}^{-3}$
  - $L_y \approx 4000$, $\rho_\star^{-1} \approx 2000$ → use 1024 cores × 20 days runtime, $\sim 10^6$ core hours in Helios



- GBS simulations reproduce many features observed in discharges
  - Pressure profile is a decaying exponential with 2 decay lengths
  - Large fluctuations $\sim 30\%$, skewed PDF indicates presence of blobs
  - Two distinct regions: drift dominated vs. interchange dominated
- Detailed validation work between code and experimental measurements in progress
  - Dedicated experiments at C-Mod using GPI, mirror Langmuir probe, Mach probes, etc

Conclusions

- Developed predictive theory for SOL width of inner-wall limited tokamak plasmas
- Assessed effect of ion temperature effects on turbulence → enhancement of RBMs
- Obtained SOL width scaling as a function of dimensionless / engineering plasma parameters
- Started detailed validation work to assess correctness of theory
- Found two SOL decay lengths in simulations of C-Mod limited plasmas
  - Near SOL: drift-wave dominated, steeper profile
  - Far SOL: interchange dominated (blobs), flatter profile

Thanks to B Labit, I Furno, G Arnoux, J Gunn, J Horacek, M Kočan, B LaBombard, and C Silva for kindly providing their SOL profile measurements

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41st EPS Conference on Plasma Physics, Berlin 2014 - Jun 23-27th 2014