First-principles theory-based scaling of the SOL width in limited tokamak plasmas, experimental validation, and implications for the ITER start-up

Paolo Ricci,

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1) CRPP, EPFL, Switzerland; 2) CCFE, UK 3) CEA, France 4) Institute of Plasma Physics, Czech Republic 6) ITER Organization, 7) MIT, USA; 8) IPFN, IST, Portugal

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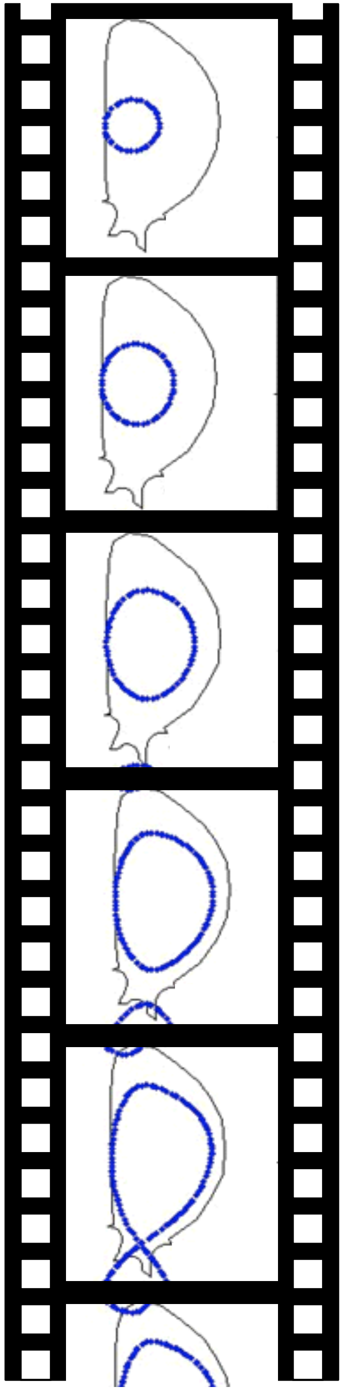
CRPP

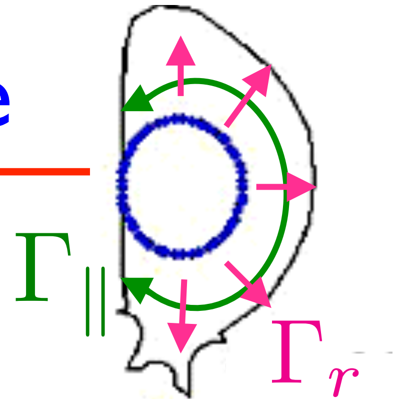


ITER start up and ramp down will be limited

SOL width?

- First-principles analytical scaling of SOL width
- Theory vs experimental observations
- First-principles simulations
- Predictions and implications for ITER

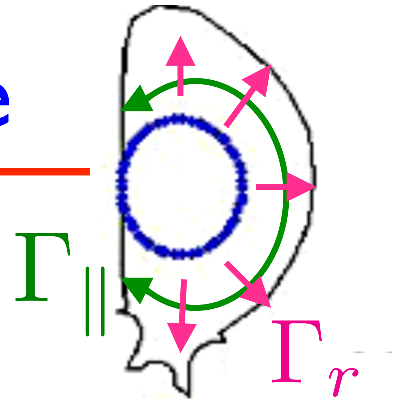
SOL width – first principles estimate



$$\nabla_r \Gamma_r \sim \nabla_{\|} \Gamma_{\|}$$

Ricci et al., PRL 2008; PoP 2013

SOL width – first principles estimate



$\sim c_s p$

Bohm's

$$\nabla_r \Gamma_r \sim \nabla_\parallel \Gamma_\parallel$$

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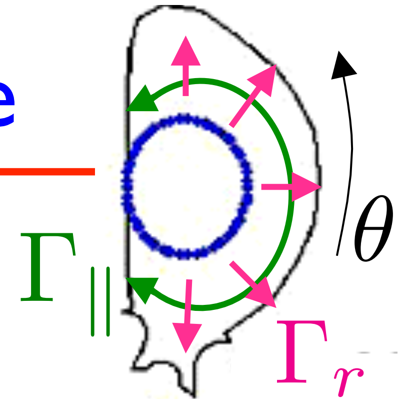

$\sim c_s p$

Bohm's

$$\nabla_r \Gamma_r \sim \nabla_{\|} \Gamma_{\|}$$

$$= \langle \tilde{p} \tilde{v}_{E\times B,r} \rangle_t = \frac{1}{B} \left\langle \tilde{p} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t \sim \frac{\gamma \overline{p}}{L_p k_r^2} \sim \frac{\gamma \overline{p}}{k_\theta}$$

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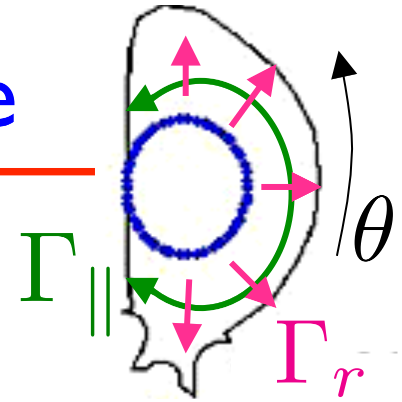


$\sim c_s p$

Bohm's

$$\nabla_r \Gamma_r \sim \nabla_{\|} \Gamma_{\|}$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}_{E\times B}) \simeq 0$$

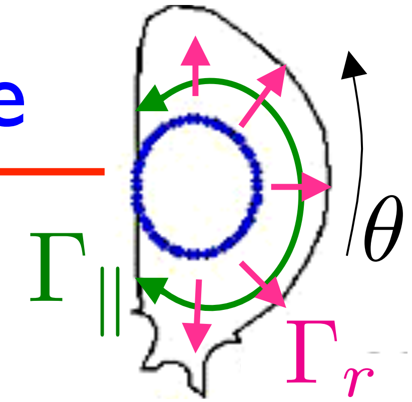
$$= \langle \tilde{p} \tilde{v}_{E\times B,r} \rangle_t = \frac{1}{B} \left\langle \tilde{p} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t \sim \frac{\gamma \overline{p}}{L_p k_r^2} \sim \frac{\gamma \overline{p}}{k_\theta}$$

Removal of driving gradient

$$\frac{\partial \tilde{p}}{\partial r} \sim \frac{\partial \overline{p}}{\partial r} \longrightarrow k_r \tilde{p} \sim \frac{\overline{p}}{L_p}$$

Ricci et al., PRL 2008; PoP 2013

SOL width – first principles estimate



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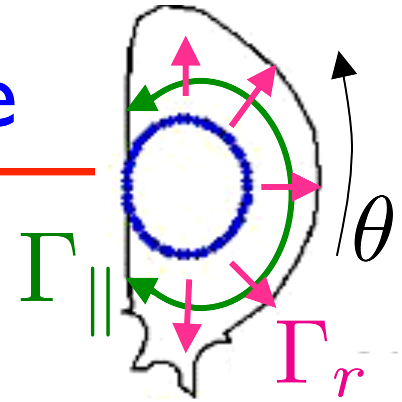

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Nonlocal linear theory, $k_r \sim \sqrt{k_\theta / L_p}$

Ricci et al., PRL 2008; PoP 2013

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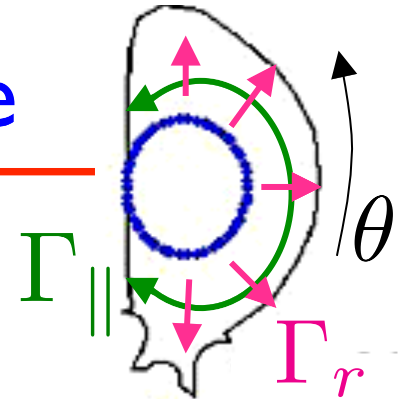

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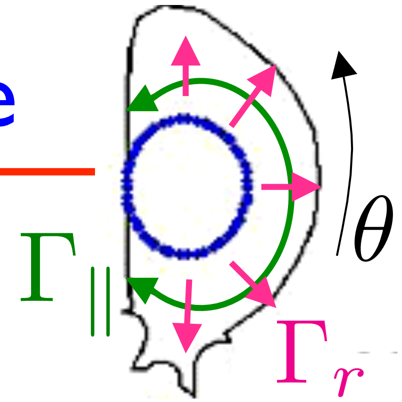

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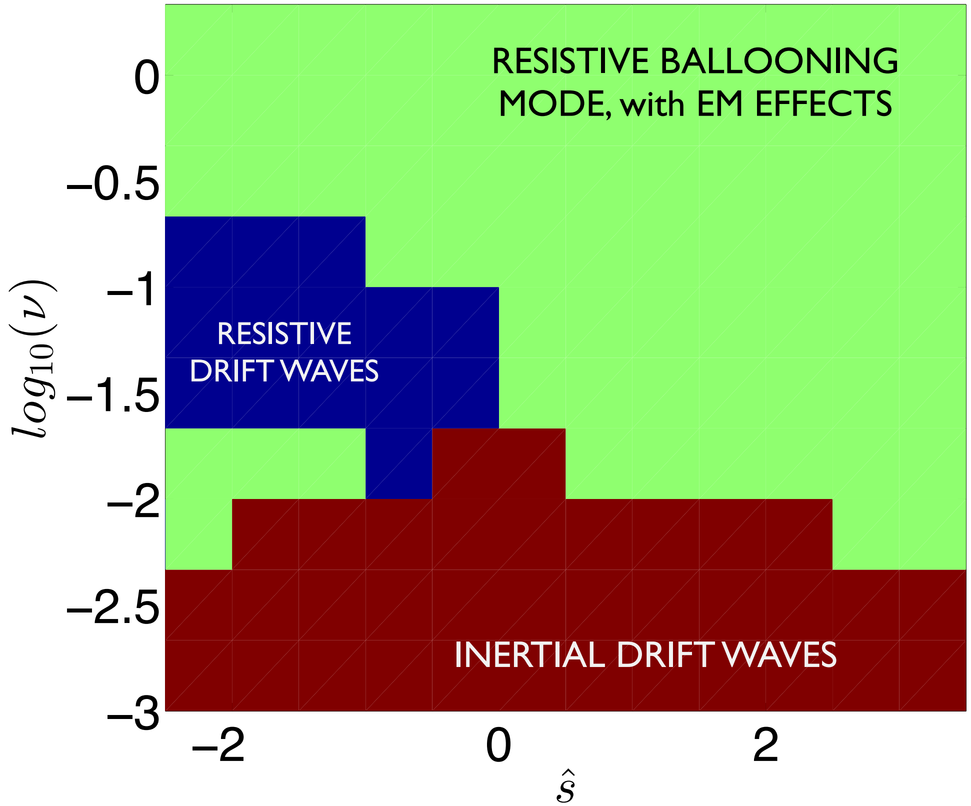
$$L_p \simeq \frac{qR}{c_s}\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

Ricci et al., PRL 2008; PoP 2013

SOL turbulent regimes

Instability driving turbulence depends mainly on q, ν, $\hat{s}$.



Mosetto et al., PoP 2013

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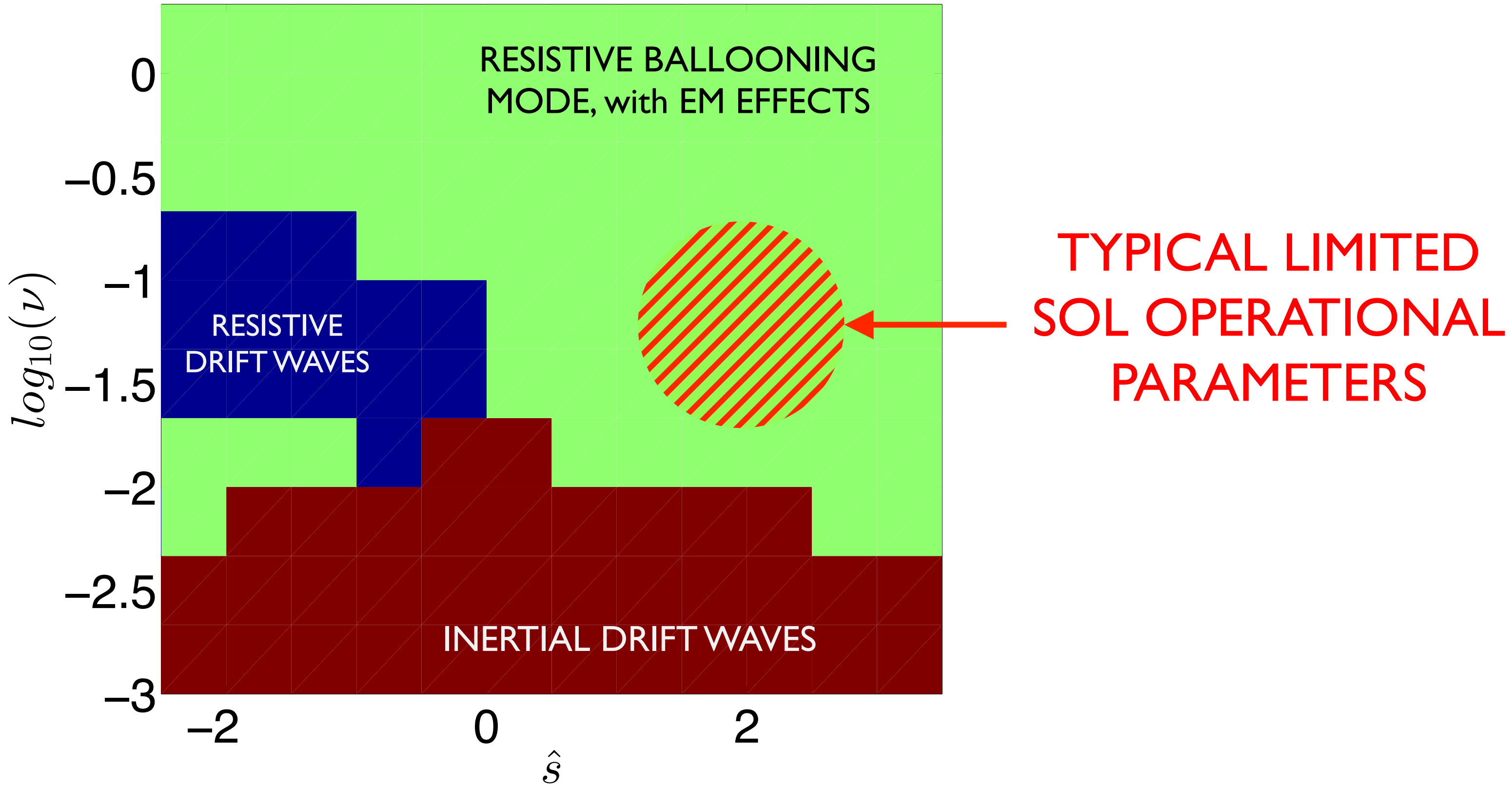

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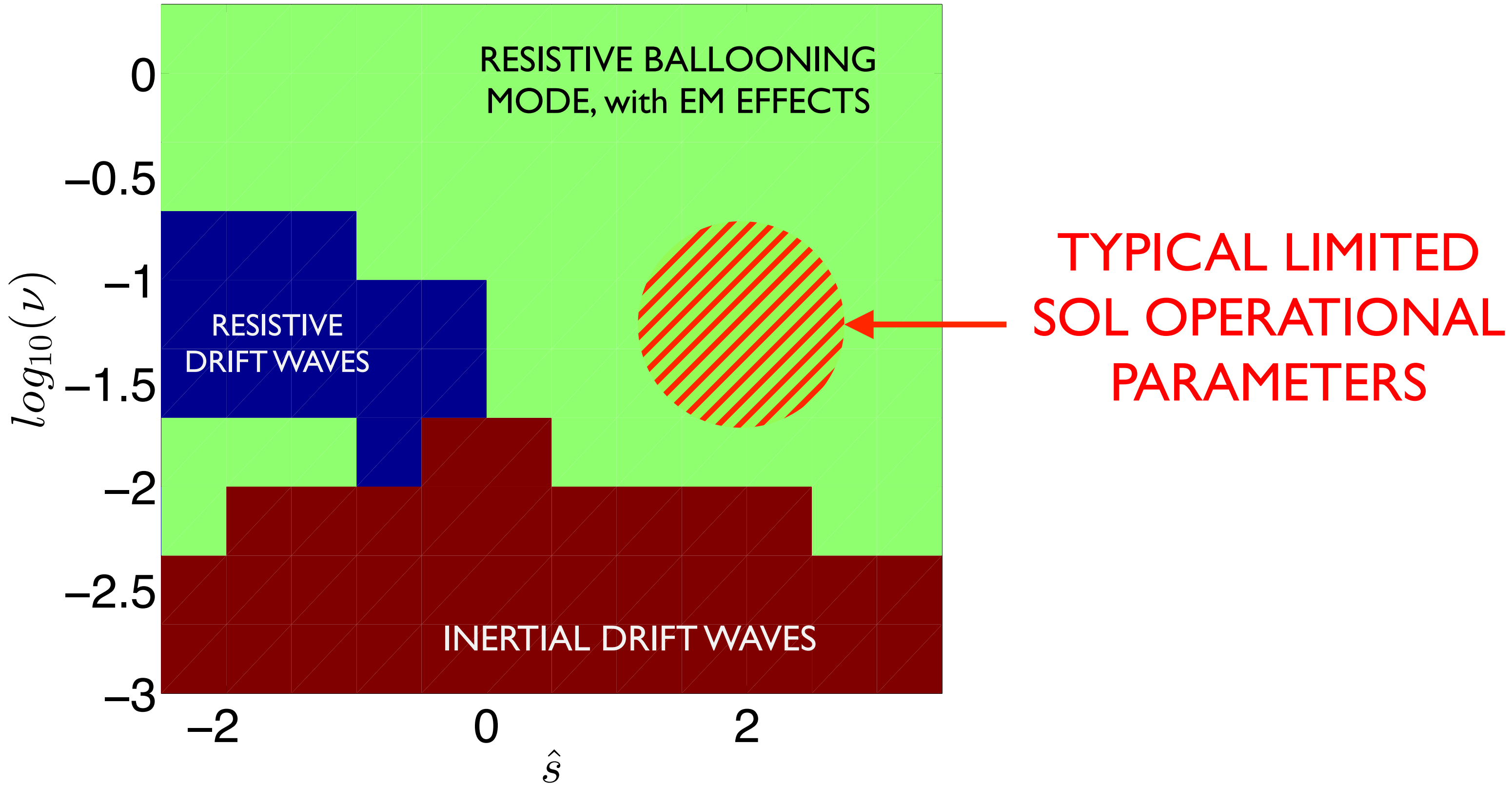

$$L_p = \frac{qR}{c_s}\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

Mosetto et al., PoP 2013

SOL turbulent regimes

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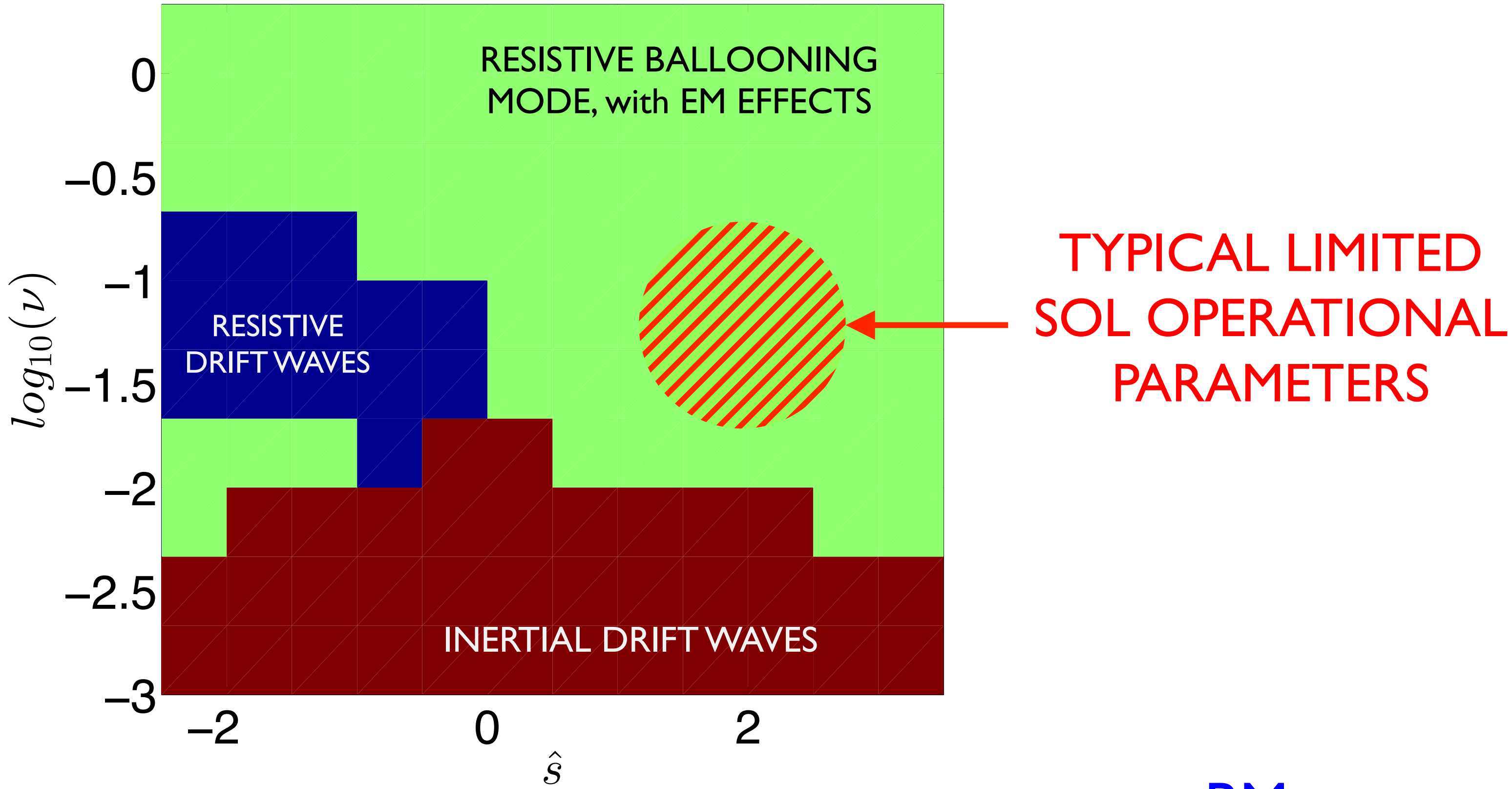

$$L_p = \frac{qR}{c_s}\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

BM: $\gamma \sim \gamma_b = c_s\sqrt{\frac{2}{RL_p}}$

BM: $k_\theta \sim \sqrt{\frac{\mu_0 \sigma_\parallel c_A^2}{q^2 R^2 \gamma_b}}$

Mosetto et al., PoP 2013

Ballooning scaling, good agreement with experiments

In SI units:

$$L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e,\mathrm{LCFS}}^{-2/7} n_{e,\mathrm{LCFS}}^{2/7} \left(1 + \frac{T_{i,\mathrm{LCFS}}}{T_{e,\mathrm{LCFS}}}\right)^{1/7}$$

Halpern et al., NF 2013, NF 2014

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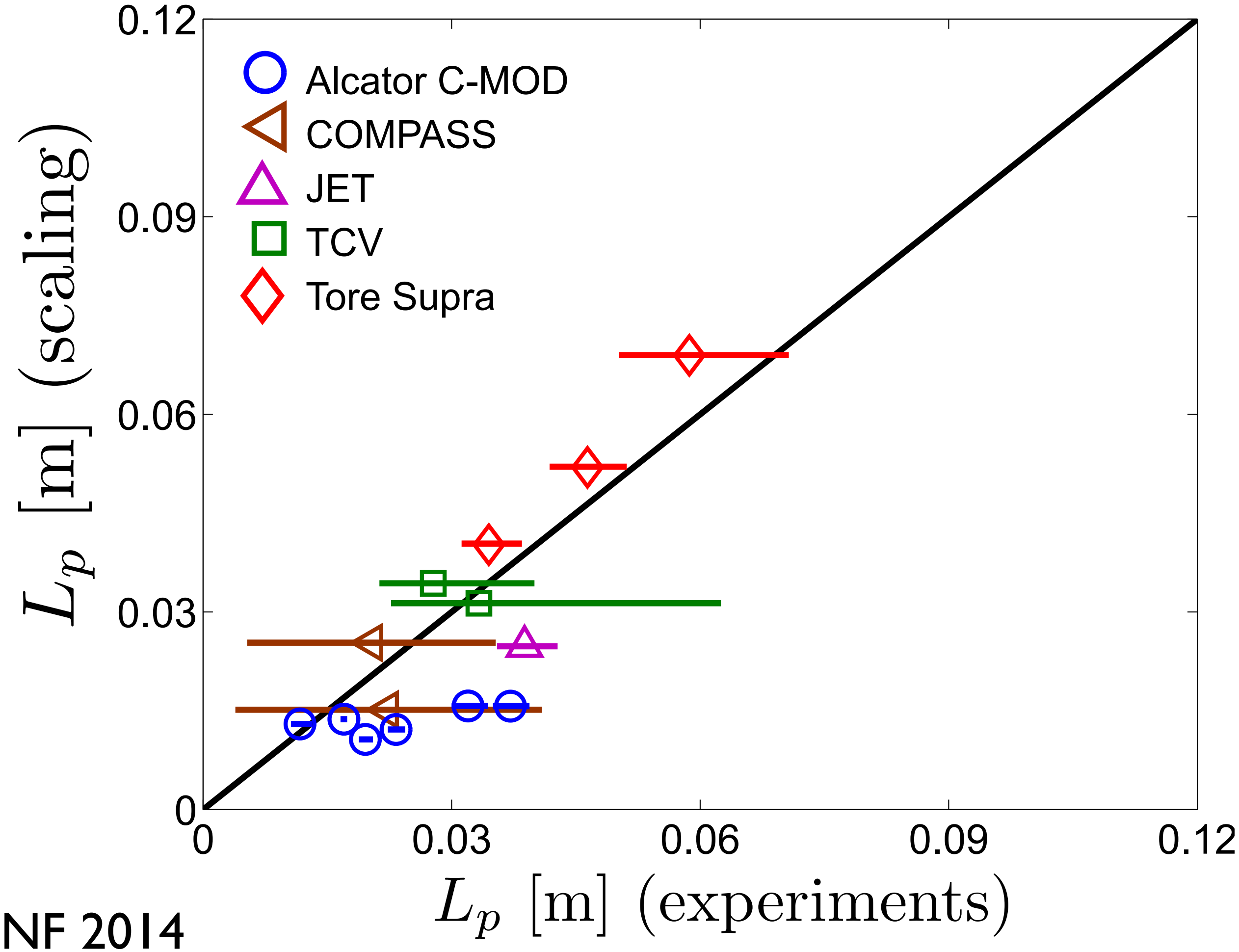
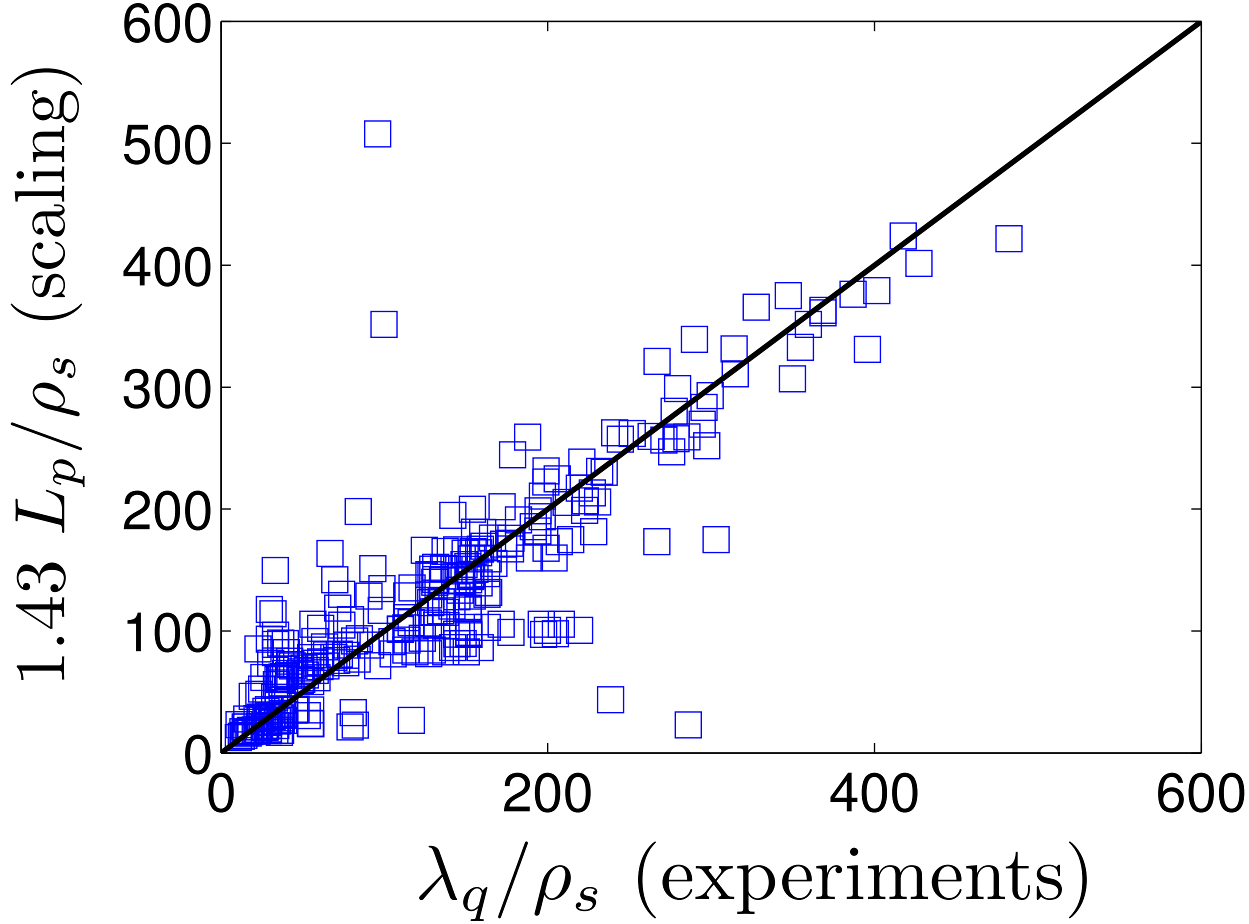
Validation with reciprocating probe measurements of n and T_e



Halpern et al., NF 2013, NF 2014

SOL width – comparison with ITPA database



[Experimental results: ITPA Divertor and SOL topical group, PPCF to be submitted, data courtesy of R.A. Pitts/J. Horacek; comparison with theoretical model: Halpern et al, PPCF, to be submitted]

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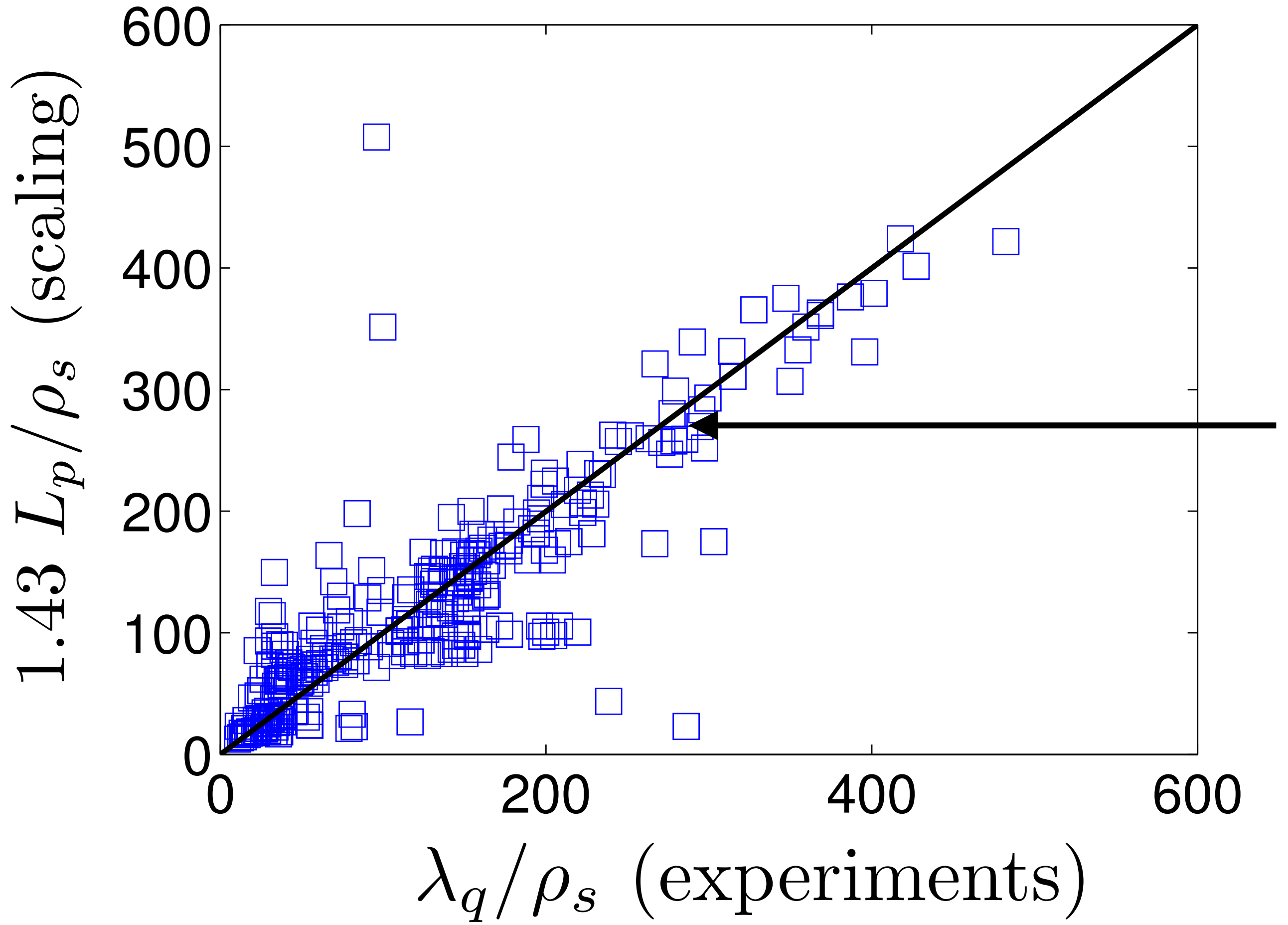
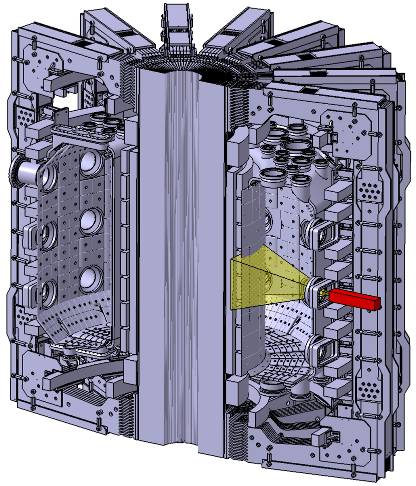


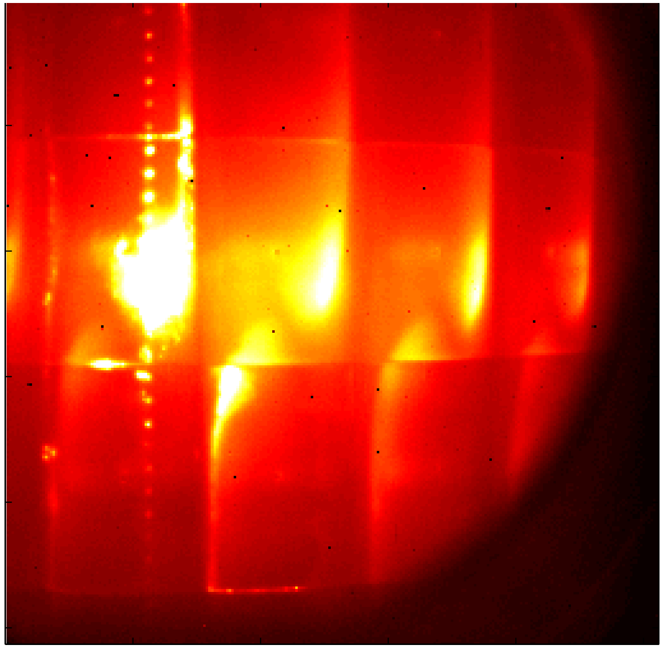
116 discharges
9 tokamaks
(EAST, TCV, Compass, HL-2A, DIII-D, TEXTOR, JET, Castor, ToreSupra)

[Experimental results: ITPA Divertor and SOL topical group, PPCF to be submitted, data courtesy of R.A. Pitts/J. Horacek; comparison with theoretical model: Halpern et al, PPCF, to be submitted]

Recent measurements: 2 scale lengths

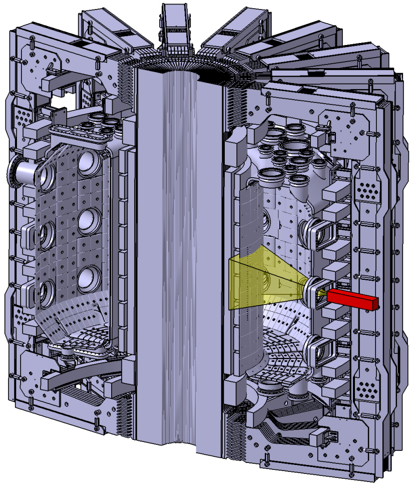


Infrared Measurement in TCV



Nespoli et al., JNM, submitted
Kocan et al., NF, submitted

Recent measurements: 2 scale lengths



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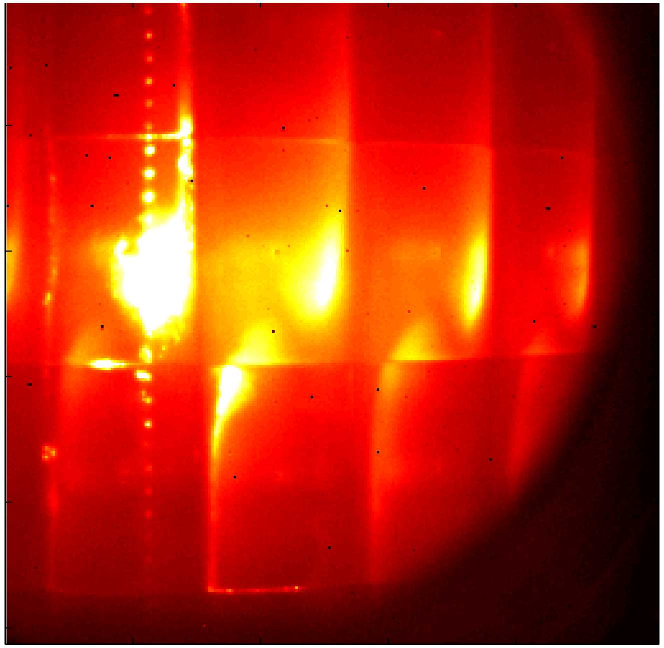

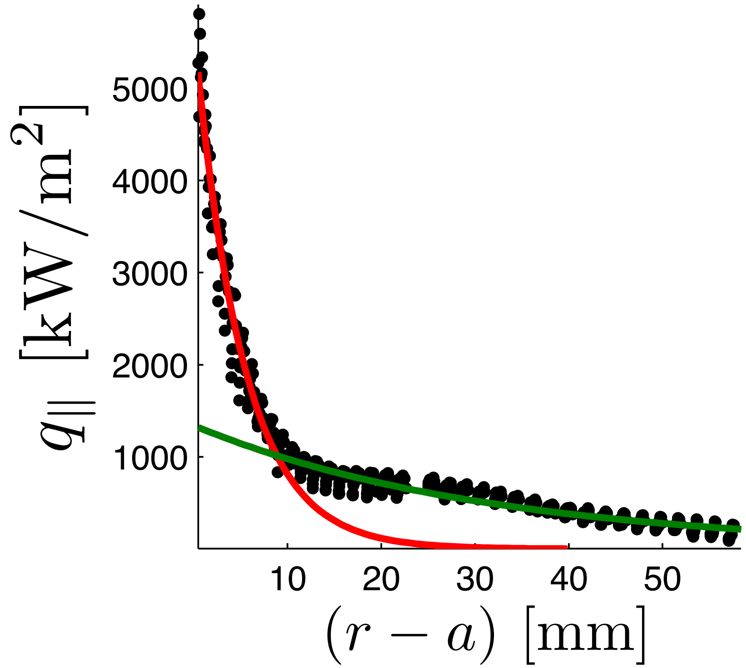

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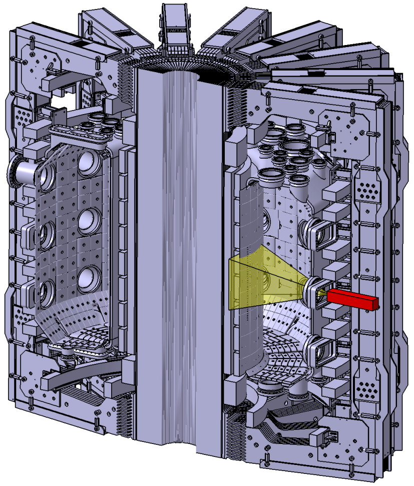

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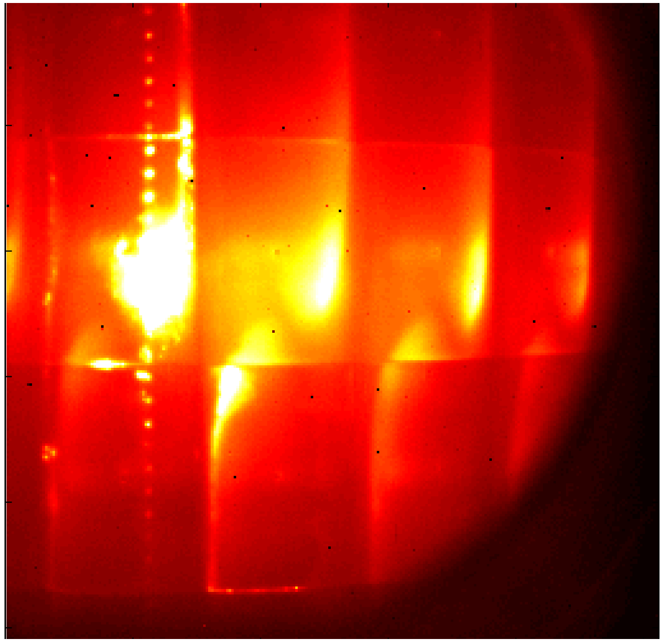

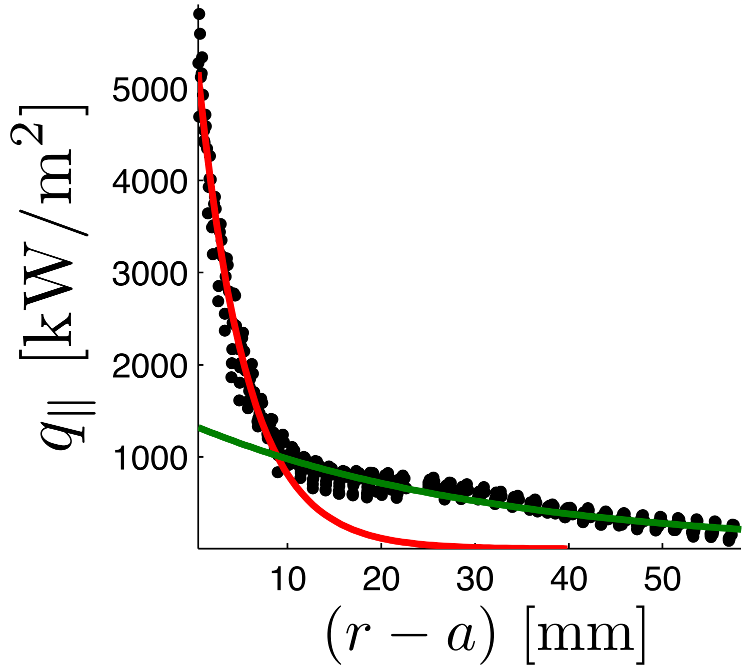

Nespoli et al., JNM, submitted
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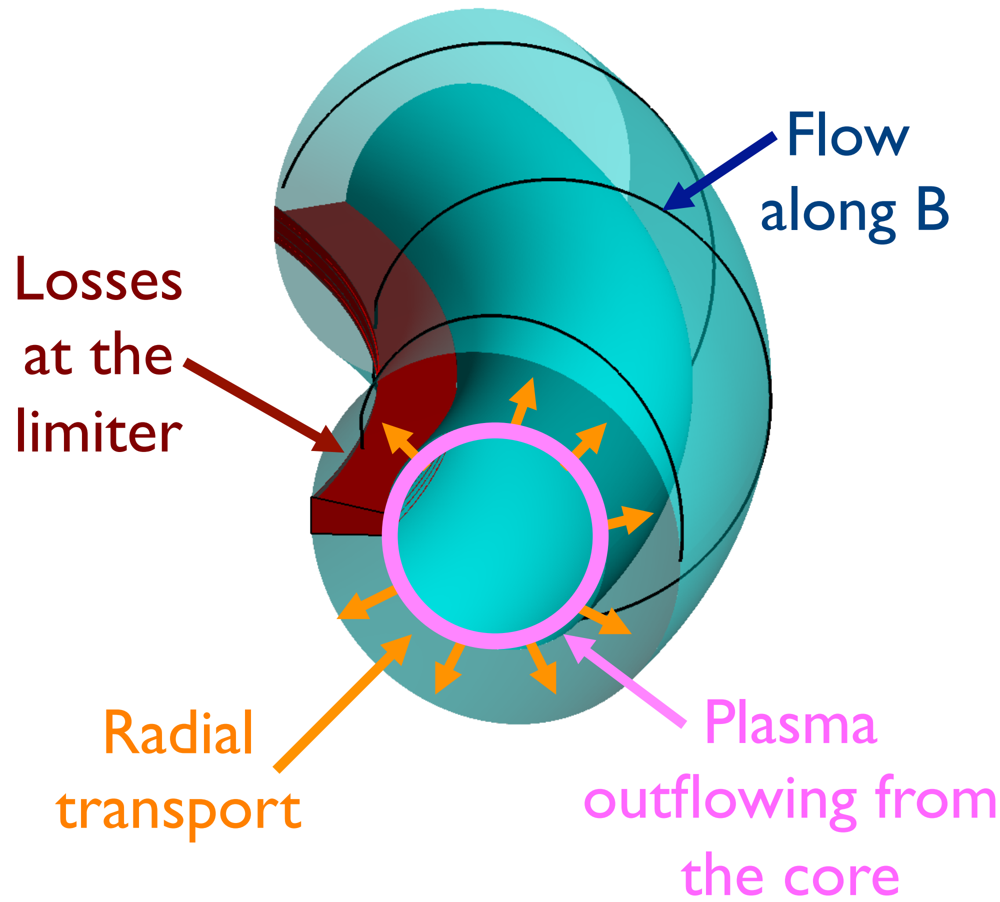
Need nonlinear simulations…

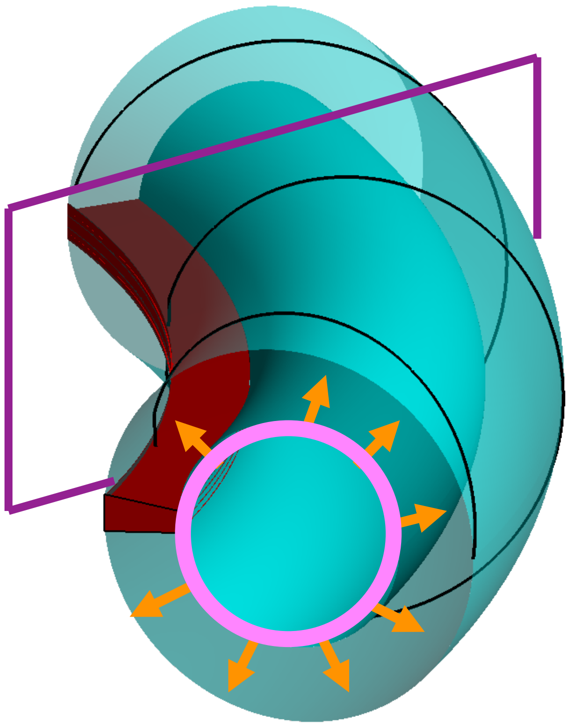
GBS code: a tool to simulate SOL plasmas

3D drift-reduced Braginskii equations,
no separation between equilibrium and fluctuating quantities



Ricci et al., PPCF 2012; Loizu et al., PoP 2012; Riva et al, PoP 2014

GBS code: a tool to simulate SOL plasmas



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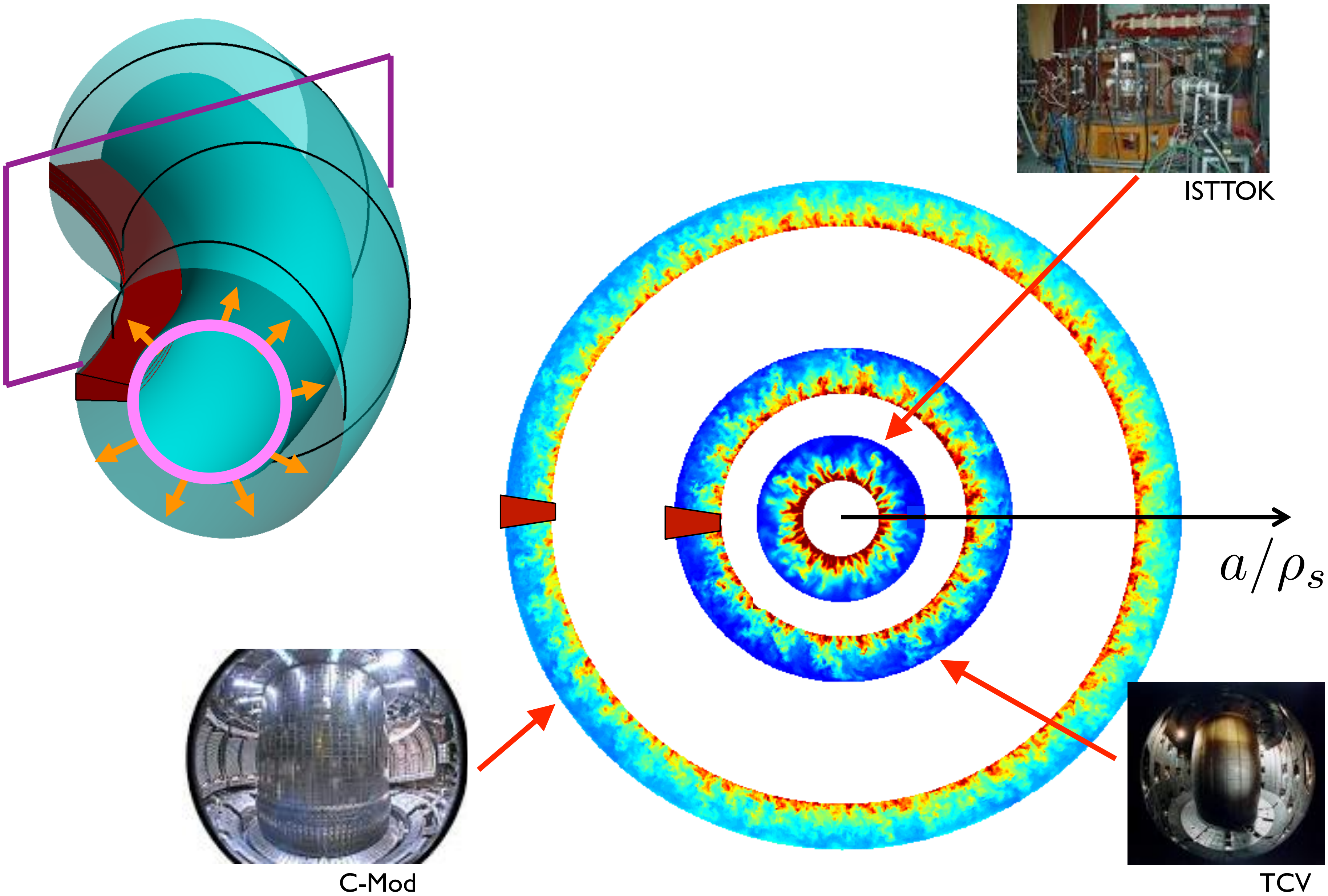

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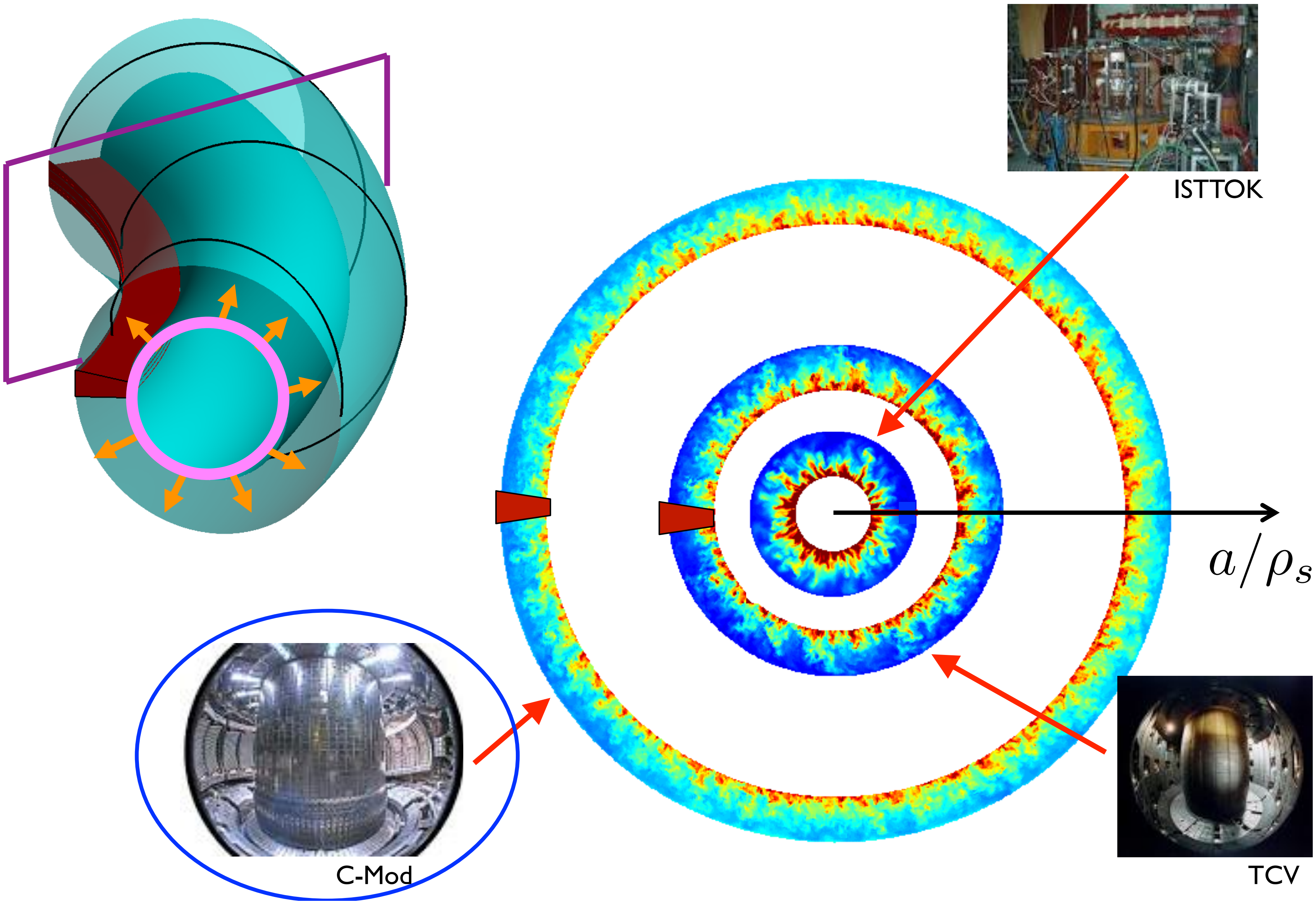
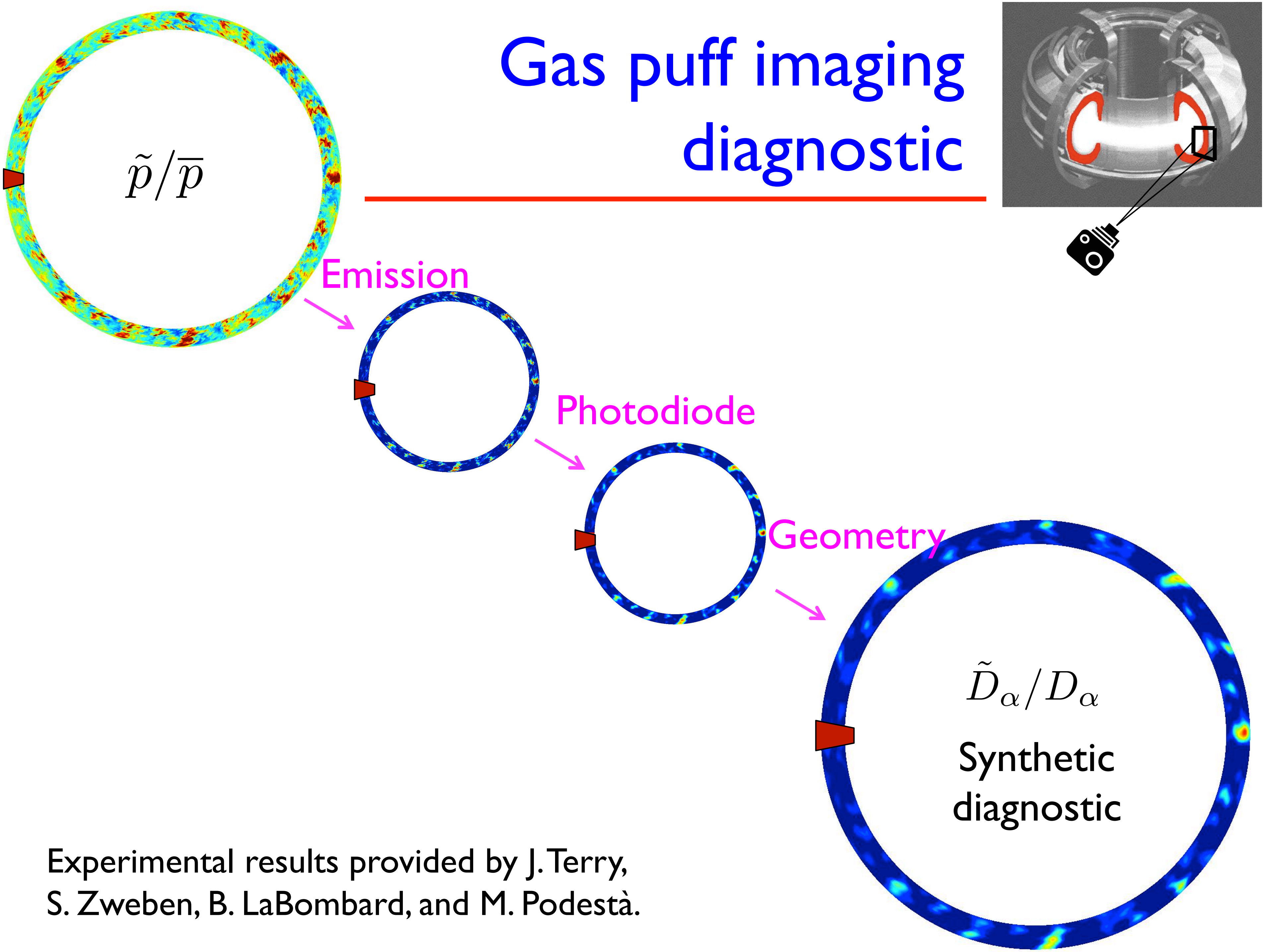
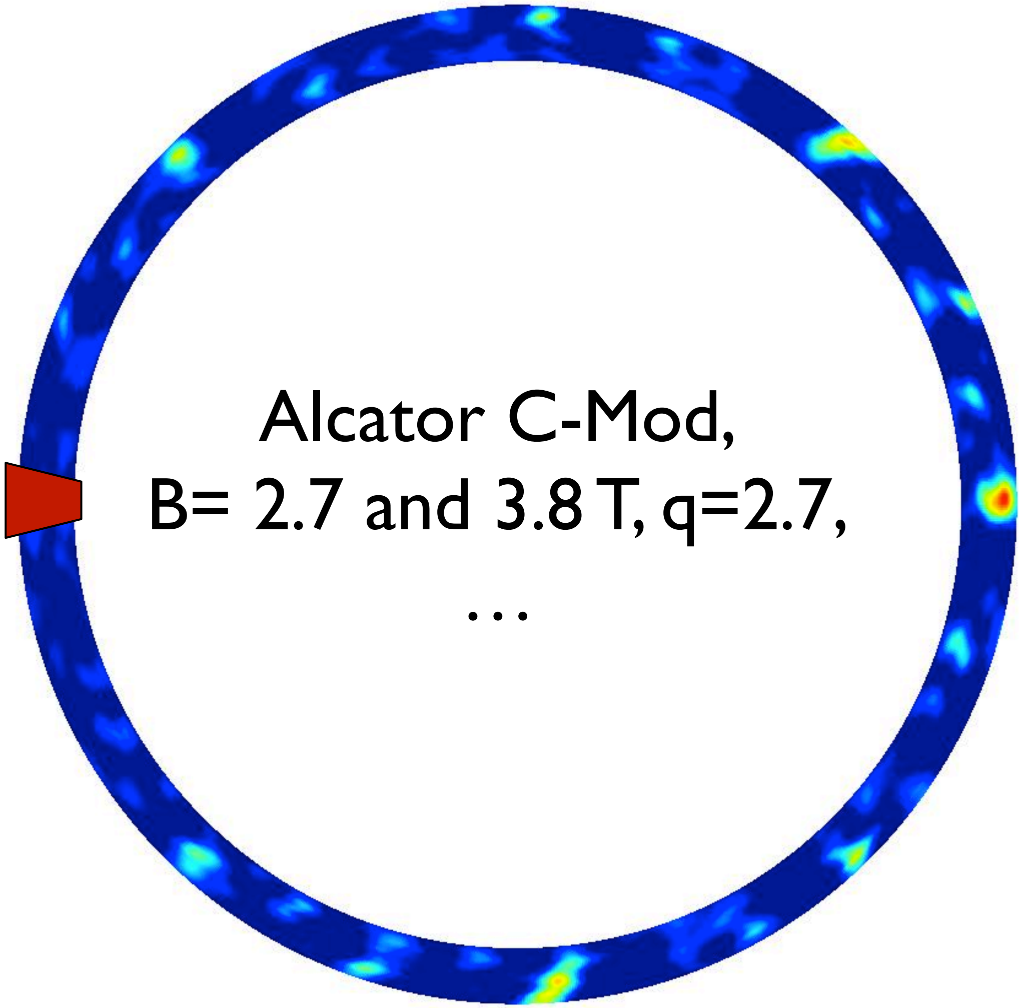


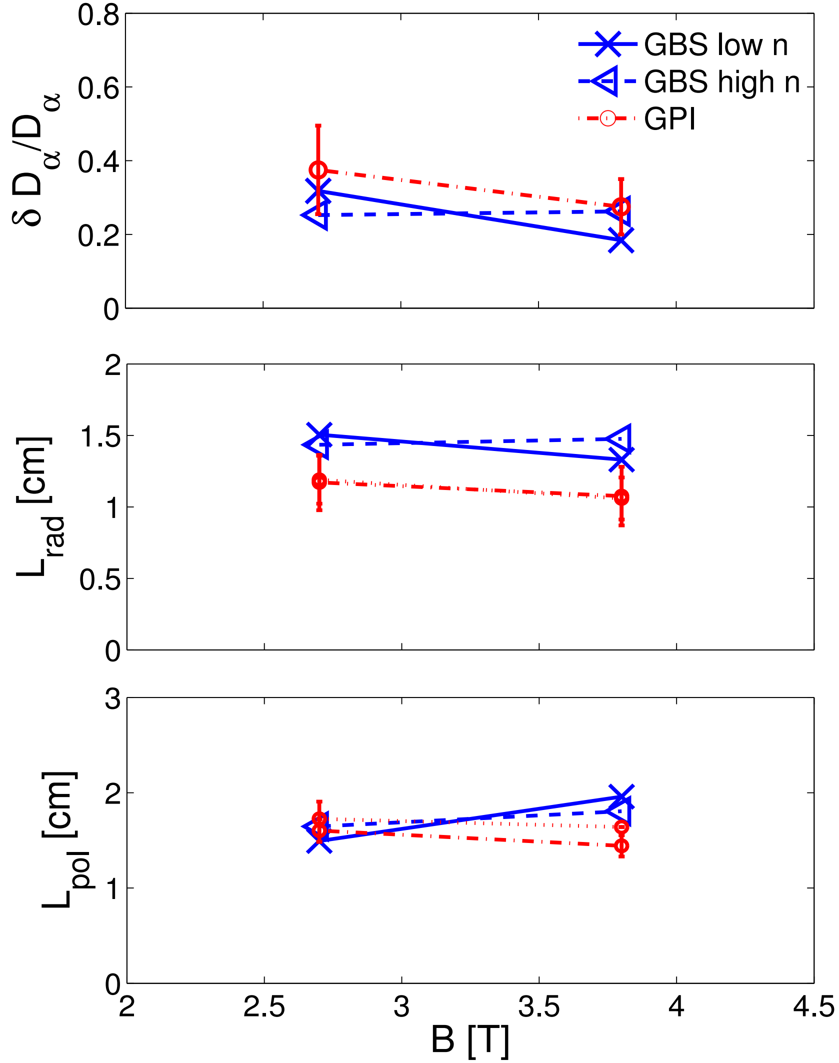
Gas puff imaging diagnostic



Experimental results provided by J. Terry, S. Zweben, B. LaBombard, and M. Podestà.

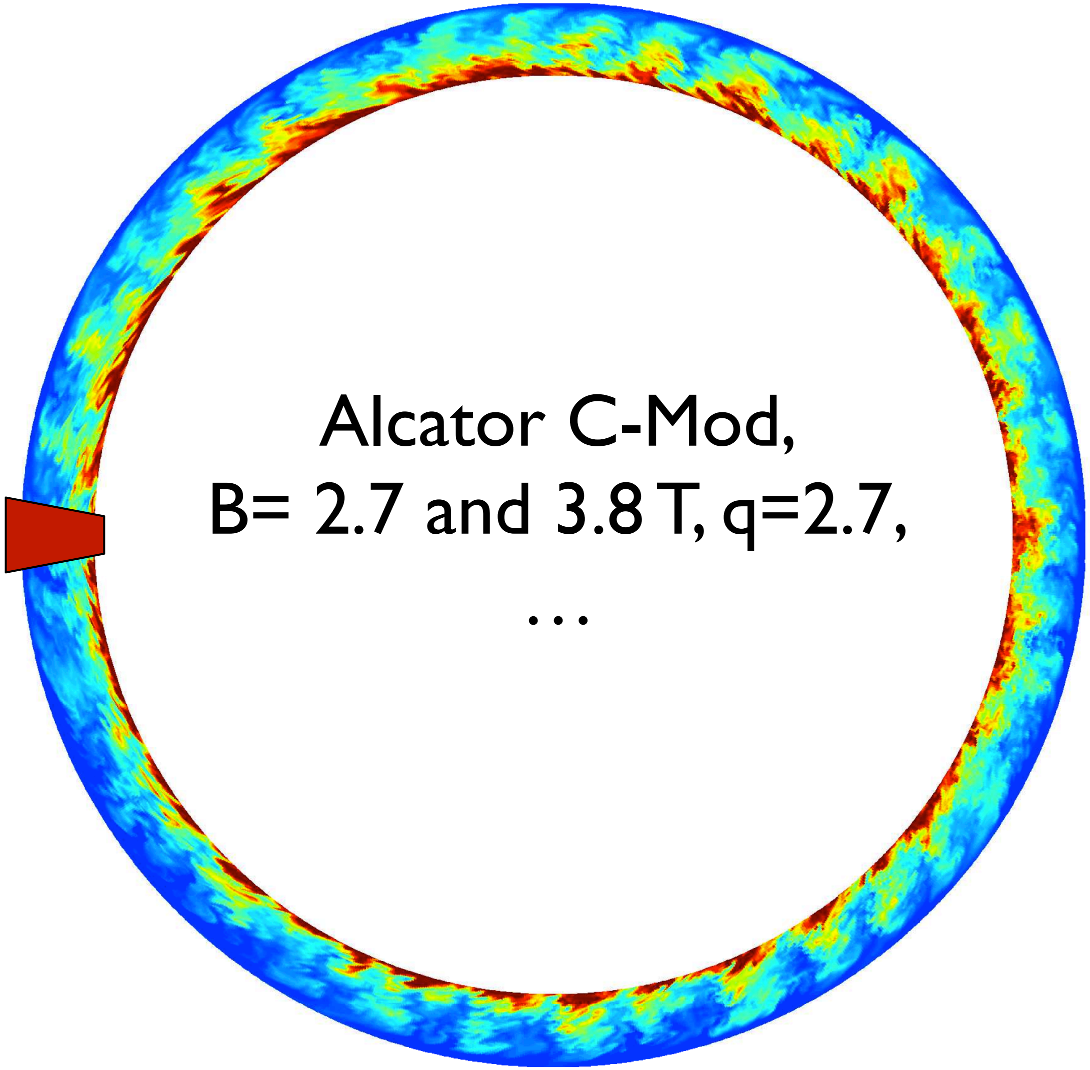
C-Mod fluctuation properties well captured



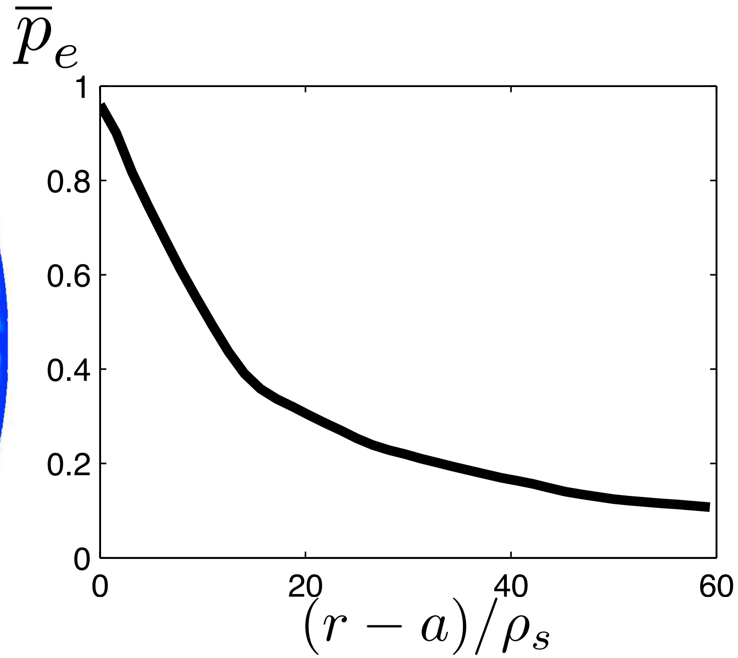


Halpern et al, PPCF, submitted

C-Mod simulations: pressure profile



Alcator C-Mod,
B= 2.7 and 3.8 T, q=2.7,
...



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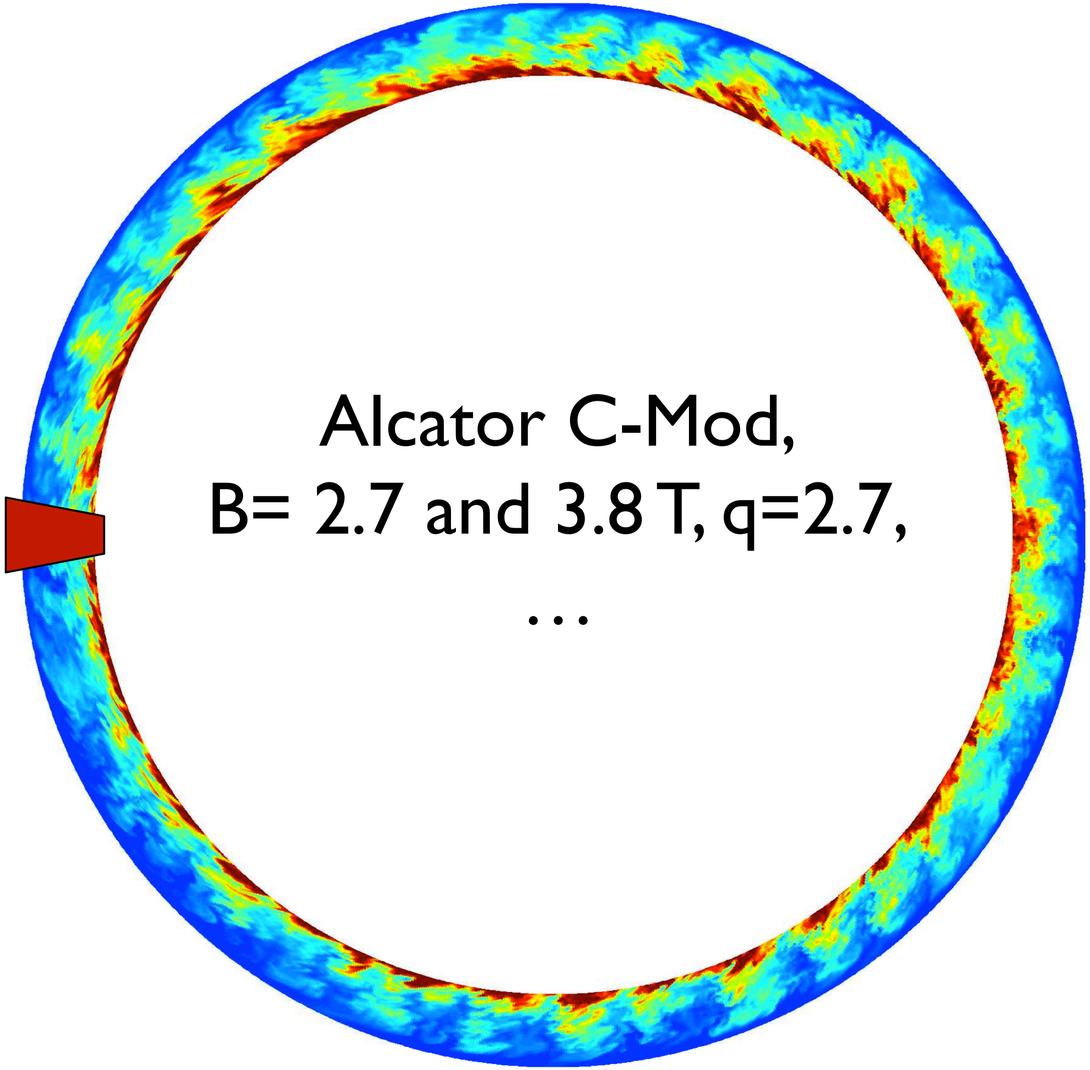

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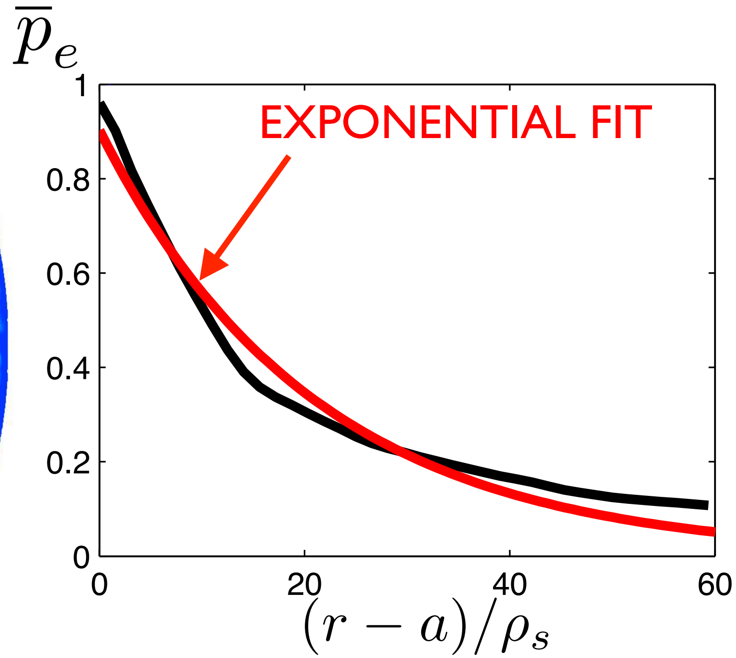
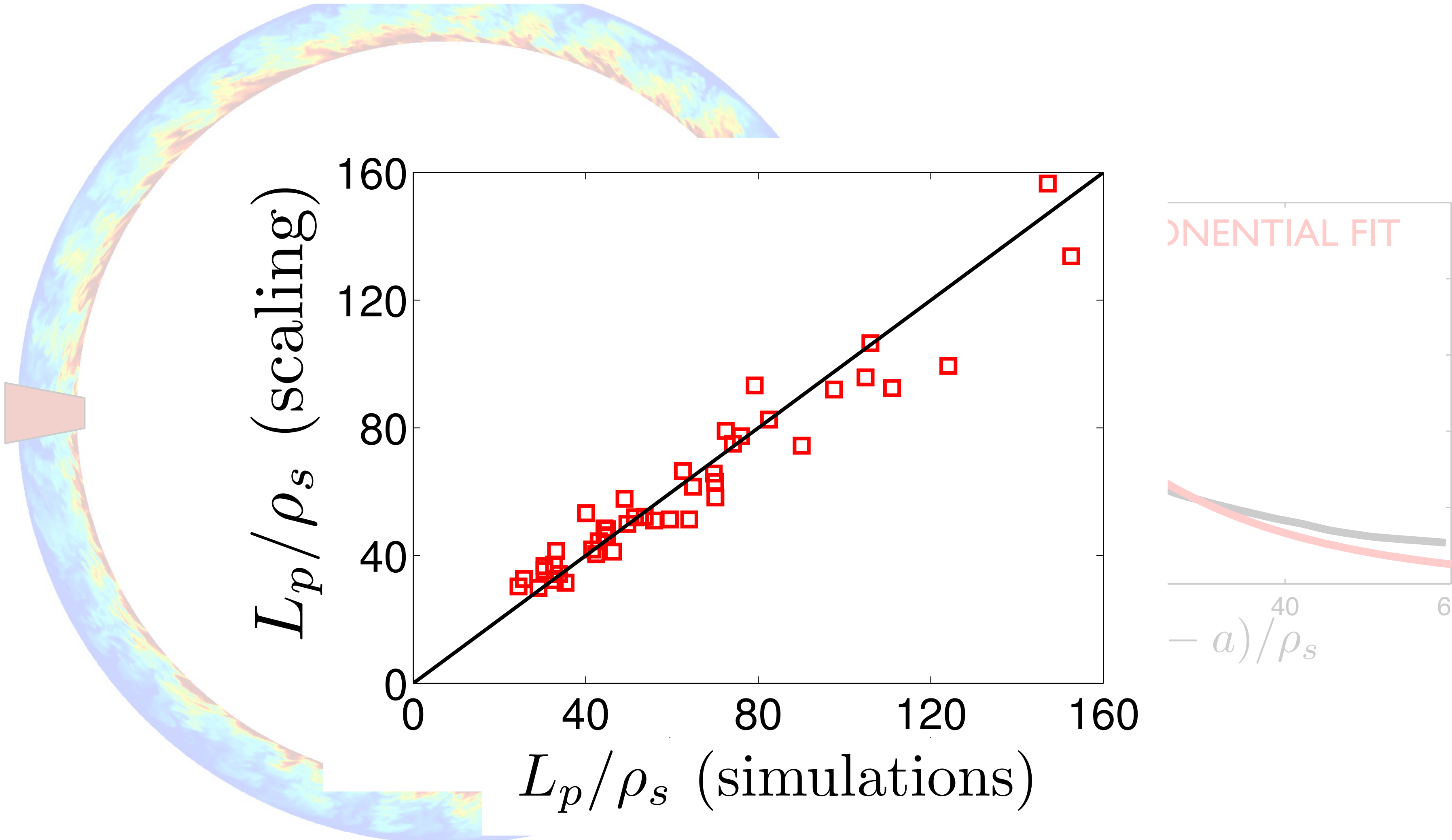


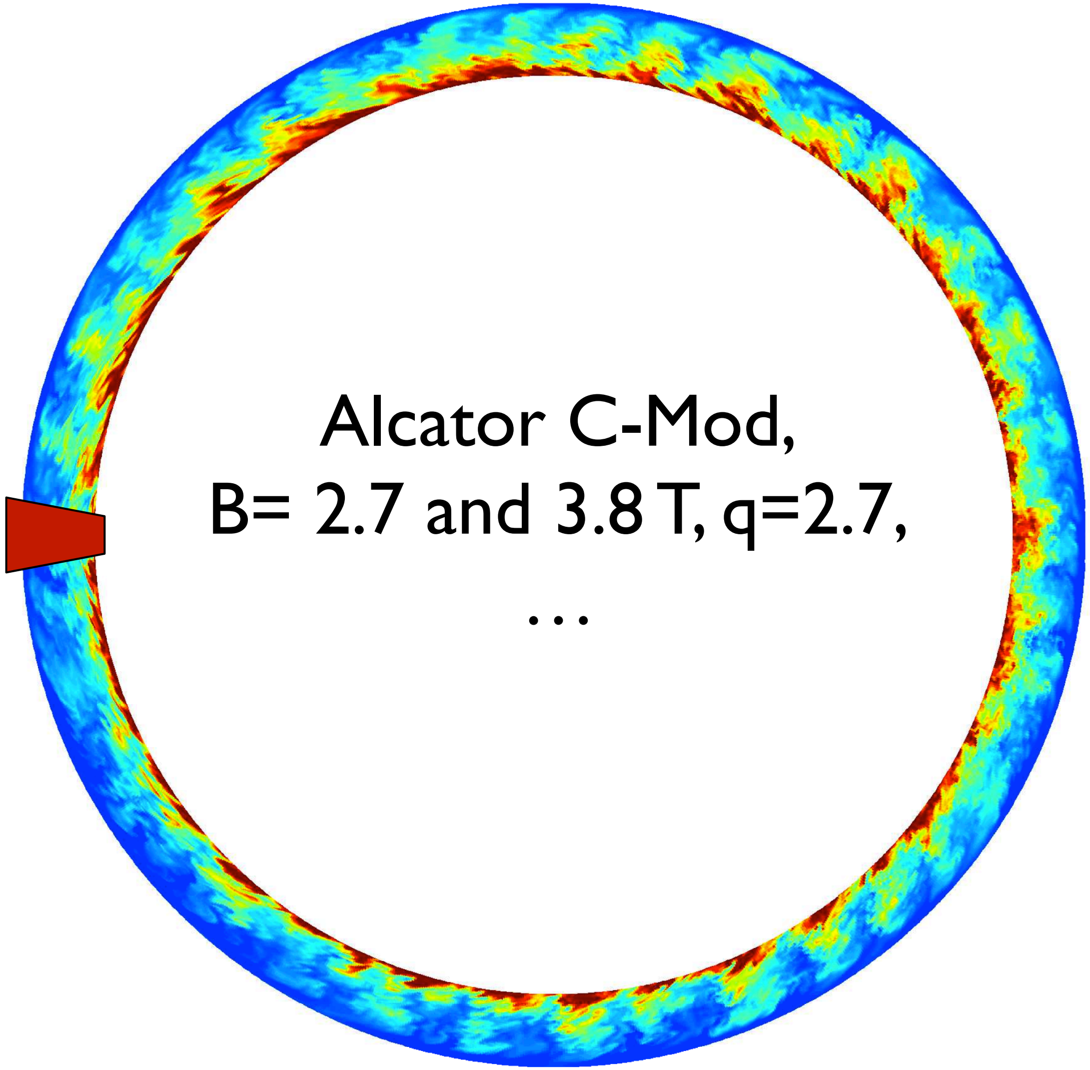
Agreement between theory and simulations

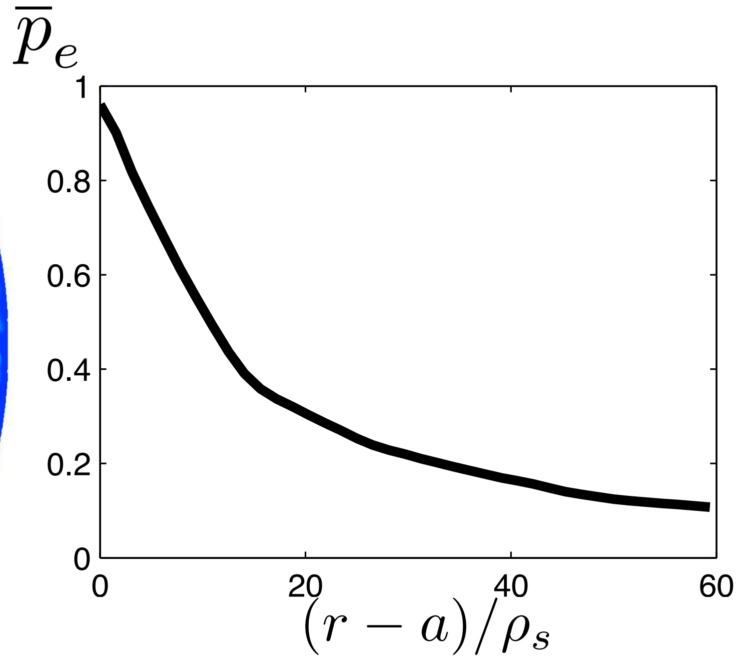
By considering one scale length



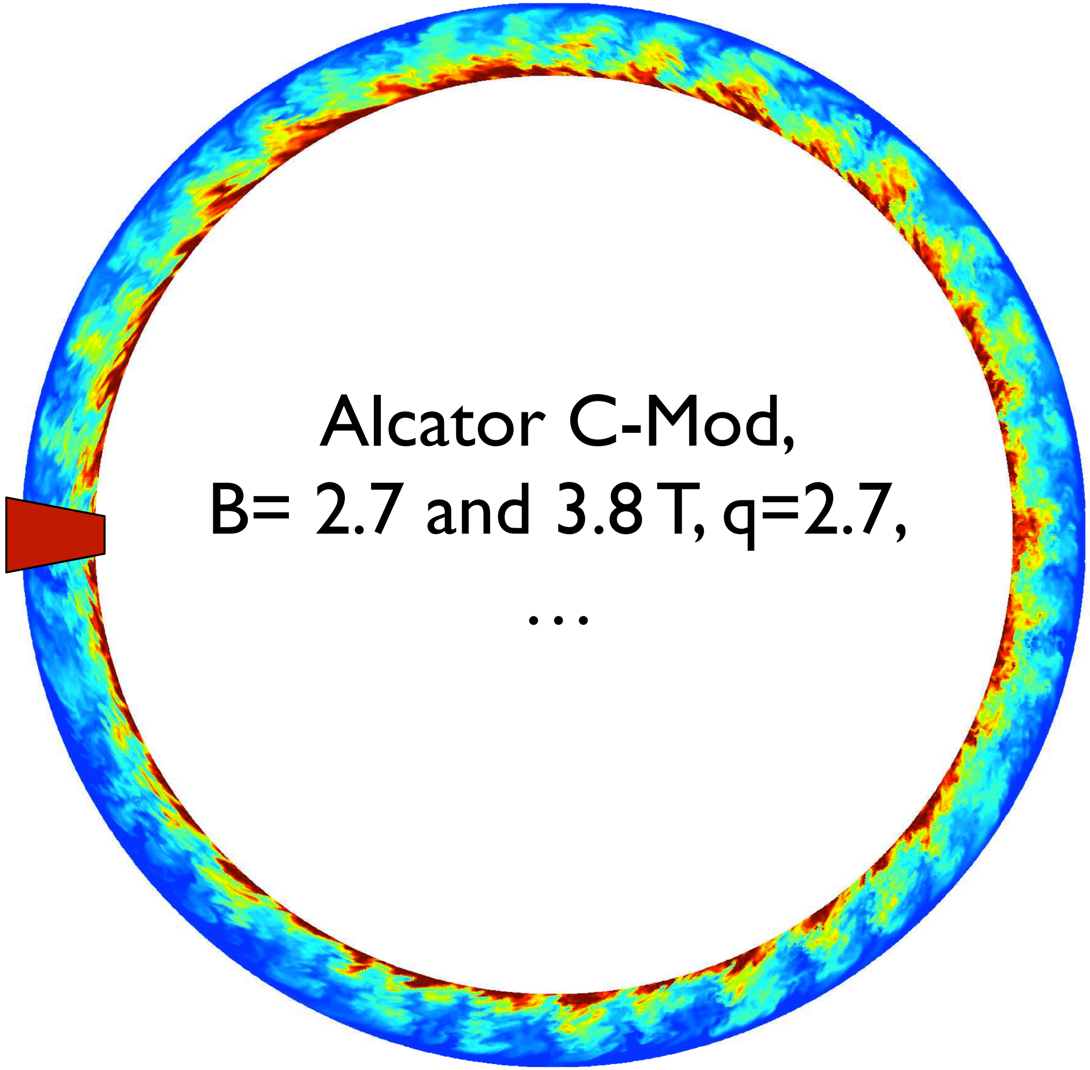
Halpern et al., NF 2013, NF 2014

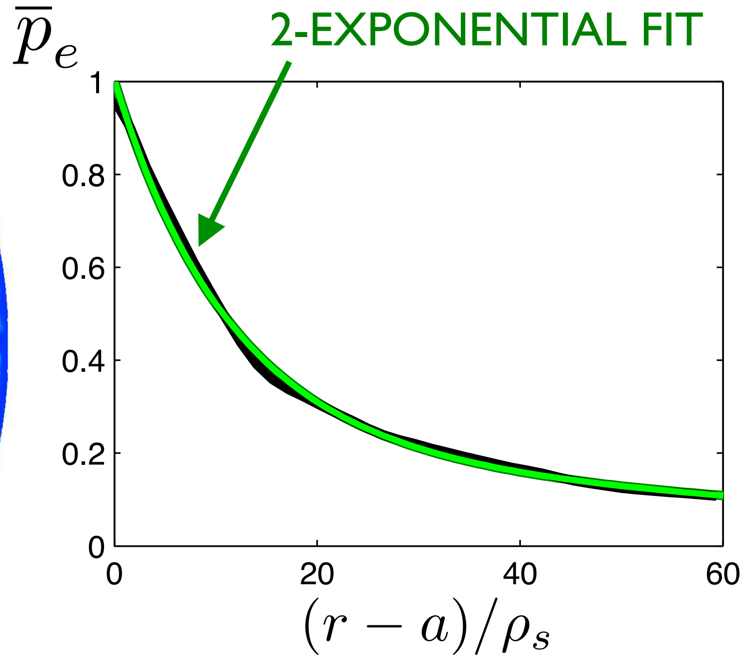
C-Mod simulations: pressure profile





C-Mod simulations: 2 pressure scale lengths





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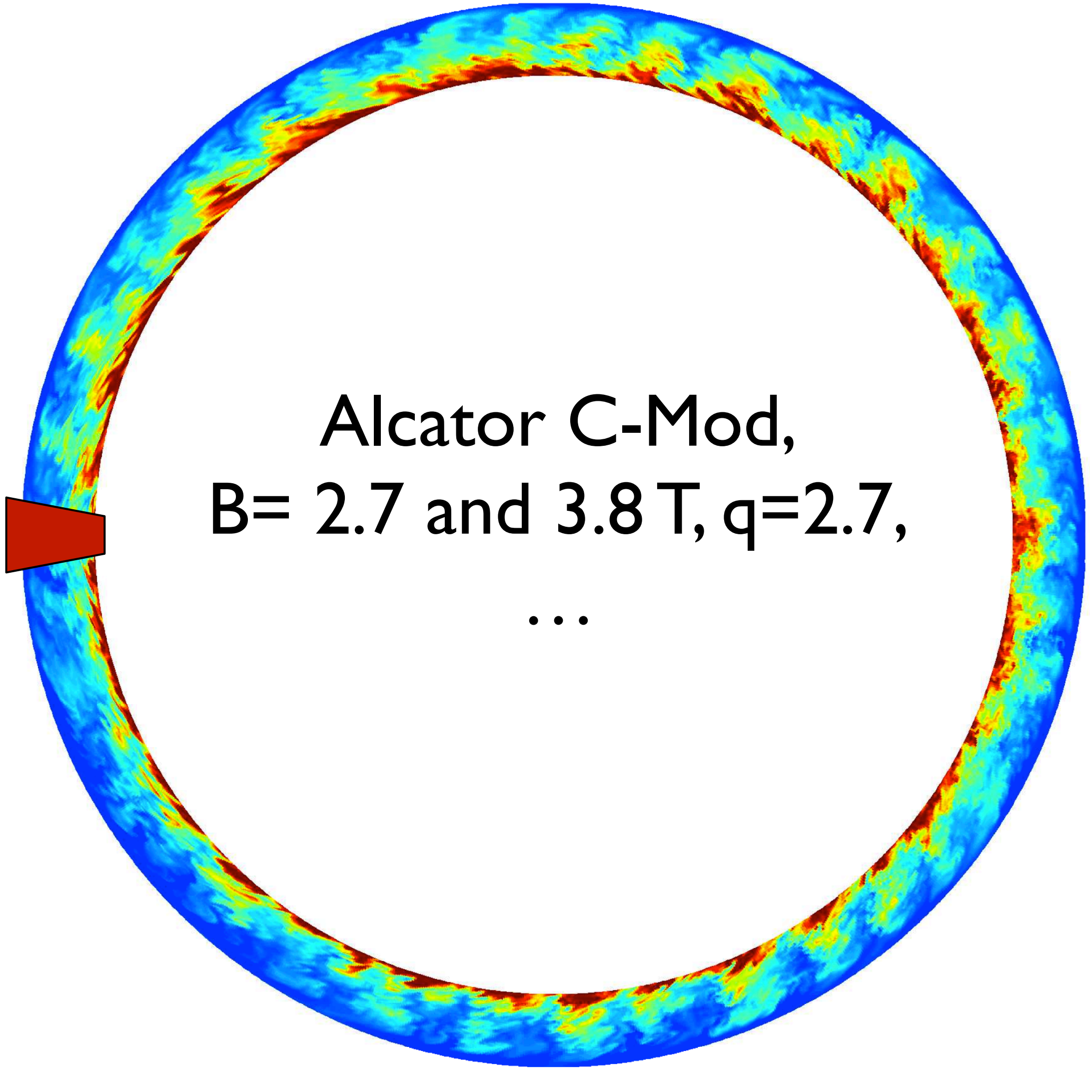
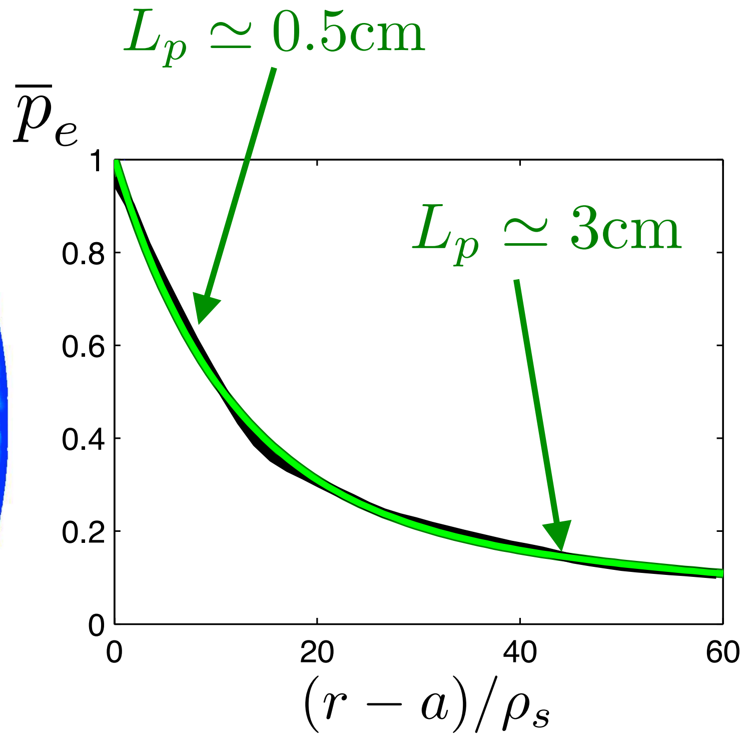
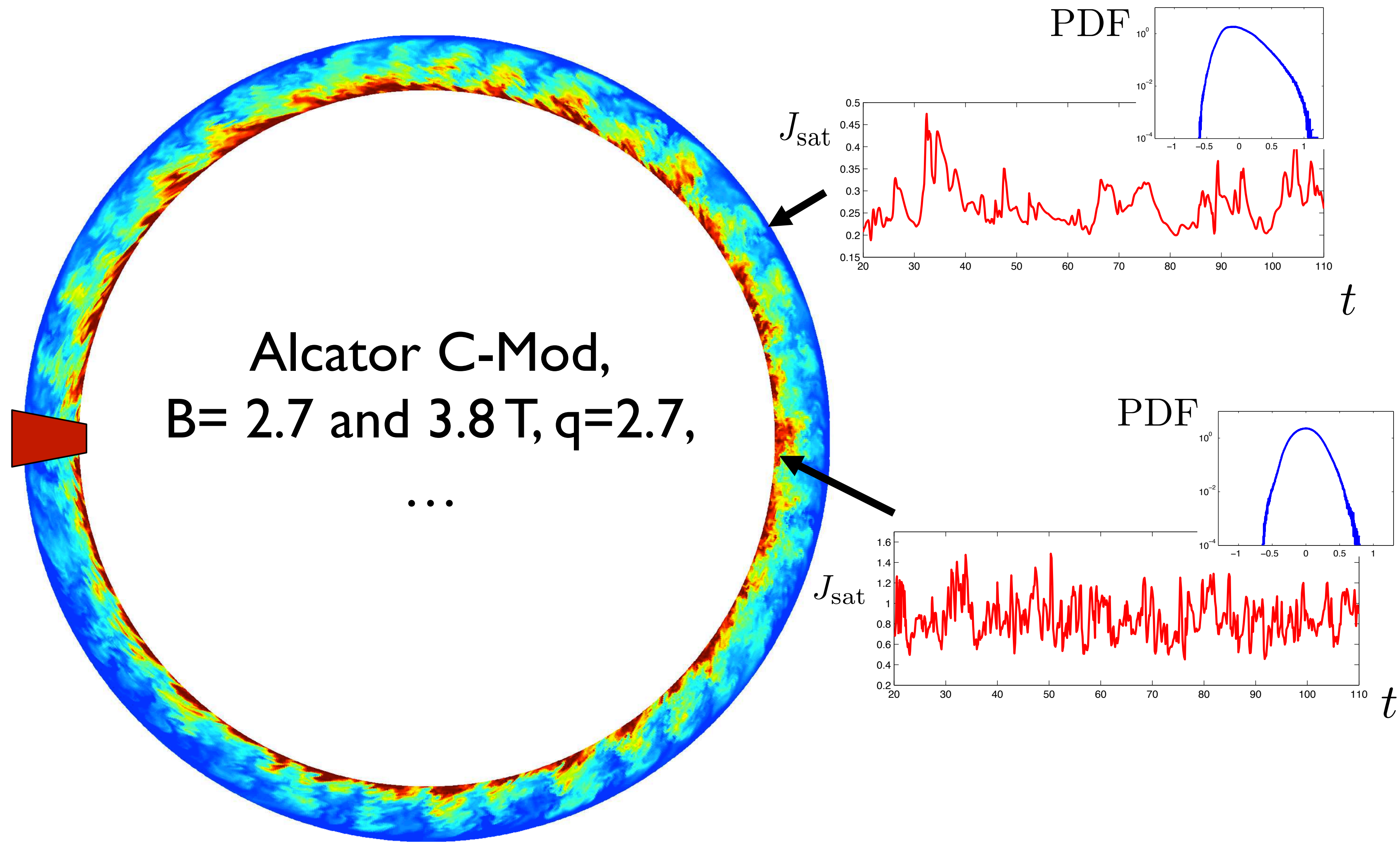




Different turbulent properties in near and far SOL



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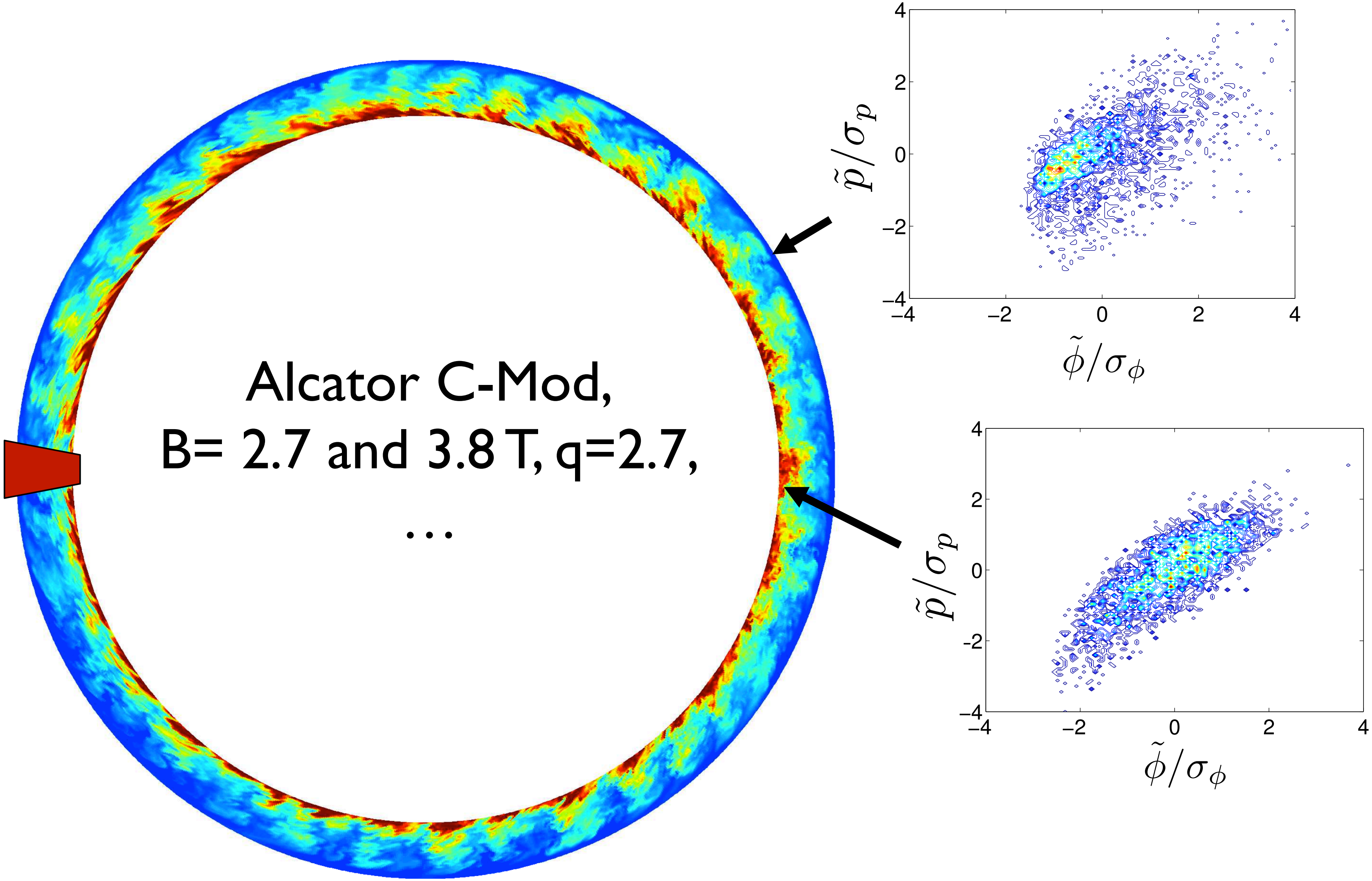

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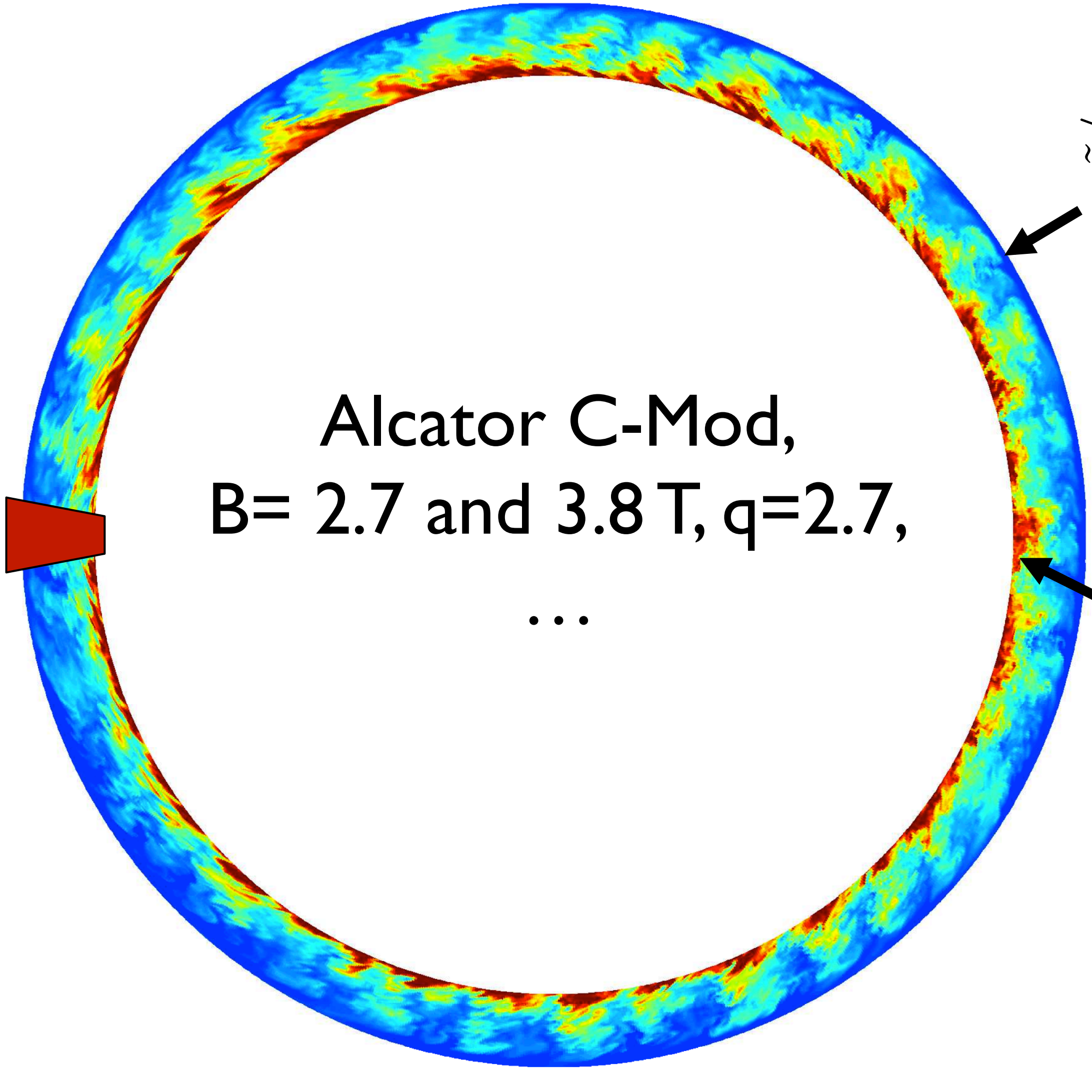

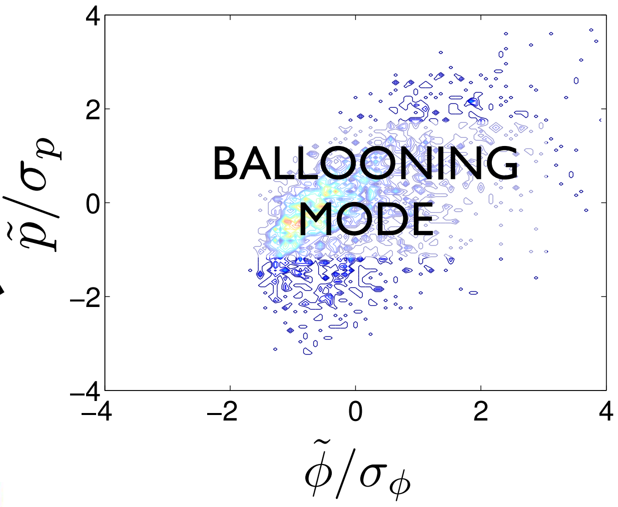

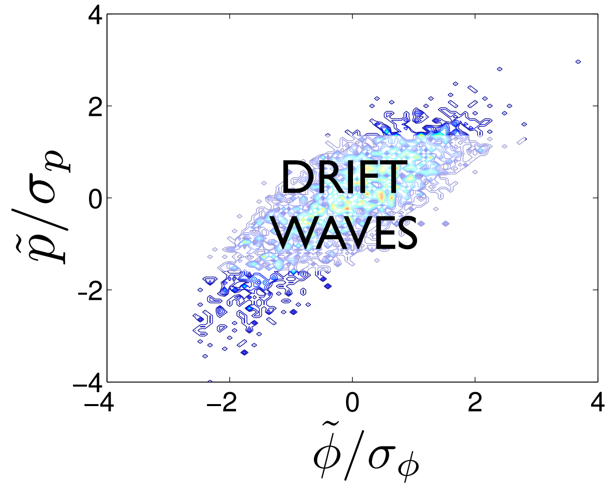

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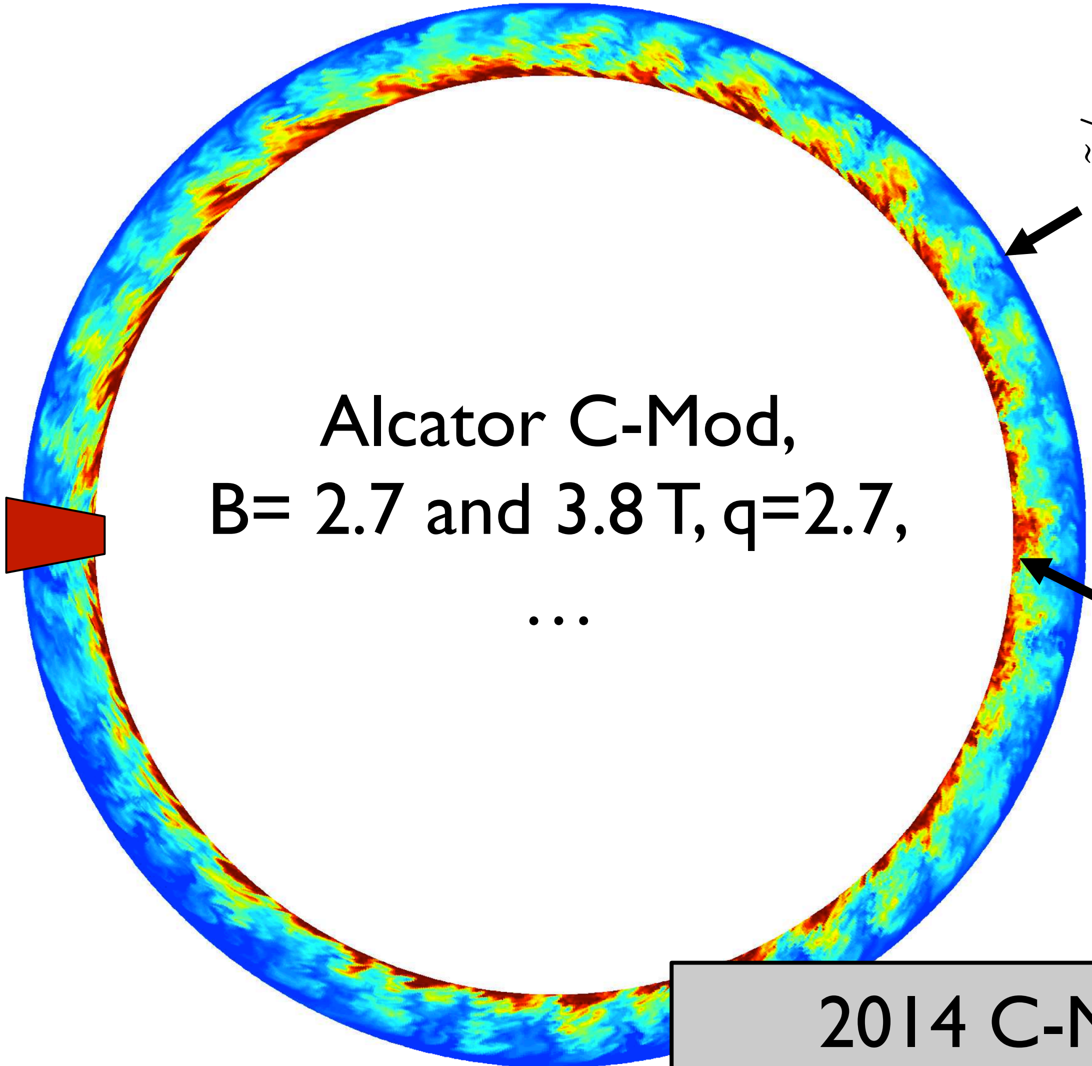

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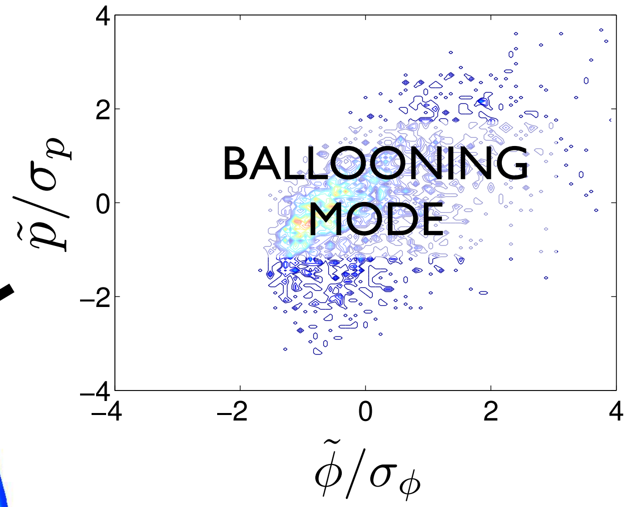
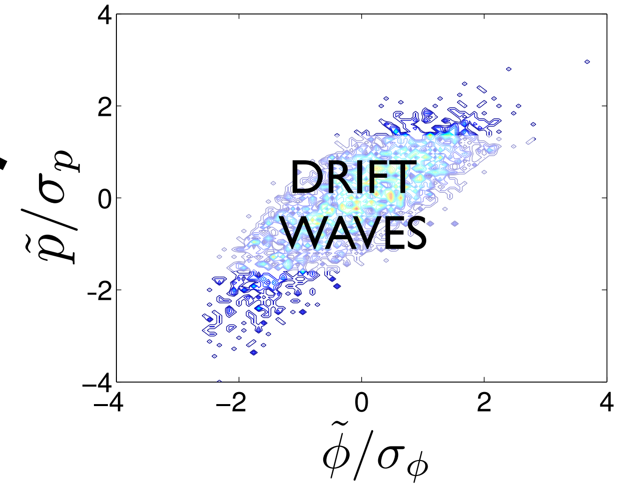


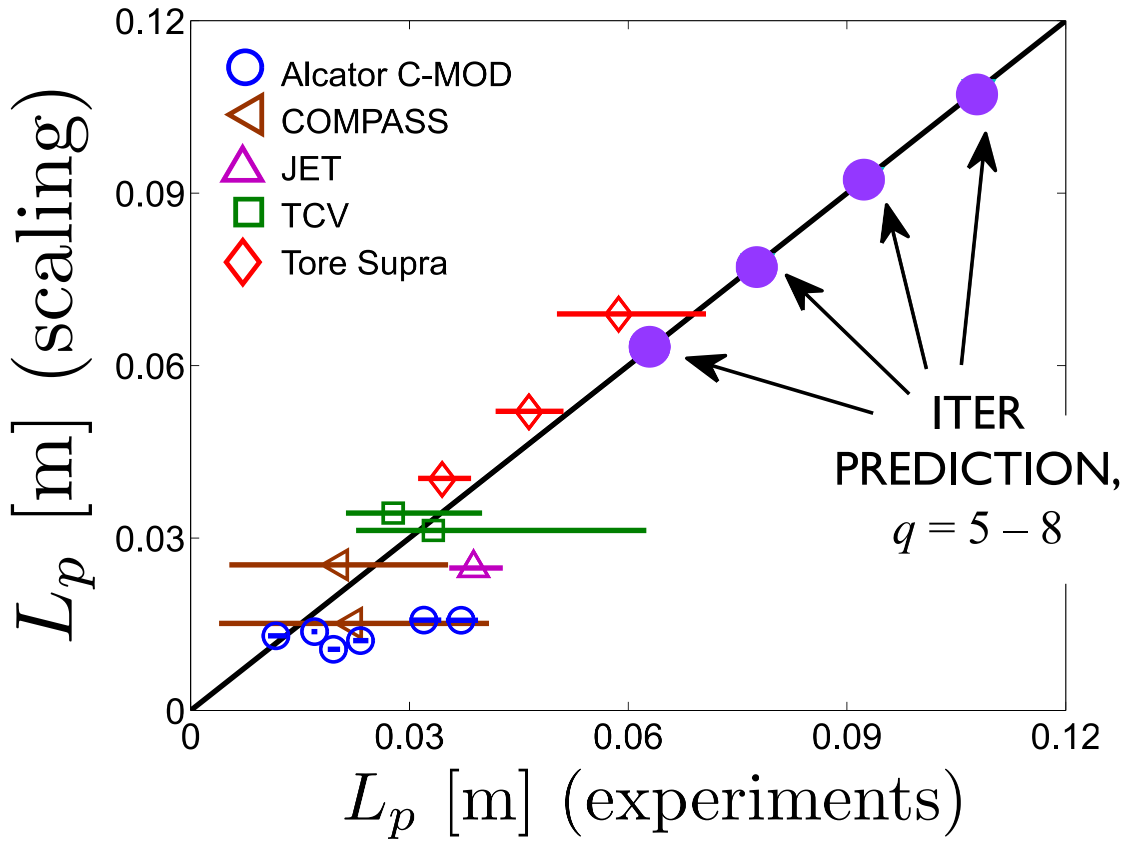


2014 C-Mod campaign and other tokamaks will allow further progress

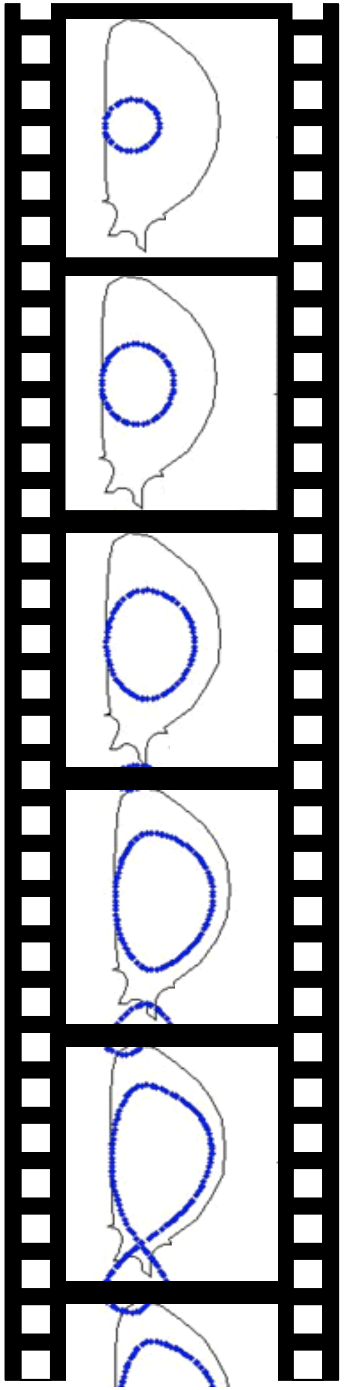
Predictions and implications for ITER

The ballooning scaling, in SI units:

$$L_p \simeq 7.22 \times 10^{-8} q^{8/7} R^{5/7} B_\phi^{-4/7} T_{e,\mathrm{LCFS}}^{-2/7} n_{e,\mathrm{LCFS}}^{2/7} \left(1 + \frac{T_{i,\mathrm{LCFS}}}{T_{e,\mathrm{LCFS}}}\right)^{1/7}$$



One scale length fit of several centimeters; further analysis needed for narrow feature



SOL width?

- Use of a first-principles approach
- Analytical scaling derived, good agreement with one scale length fit of experiments and simulations
- Narrow feature recovered in simulations
- ITER prediction – one scale length fit of several centimeters; further analysis needed for narrow feature

Tools ready to investigate more advanced SOL configurations

crpp.epfl.ch/research_theory_plasma_edge

The GBS code, a tool to simulate SOL turbulence

Collisional Plasma → **Braginskii model** → $\rho_i \ll L,\ \omega \ll \Omega_{ci}$ → **Drift-reduced Braginskii equations**

E×B Convection | Magnetic curvature | Parallel dynamics | Outflow from core

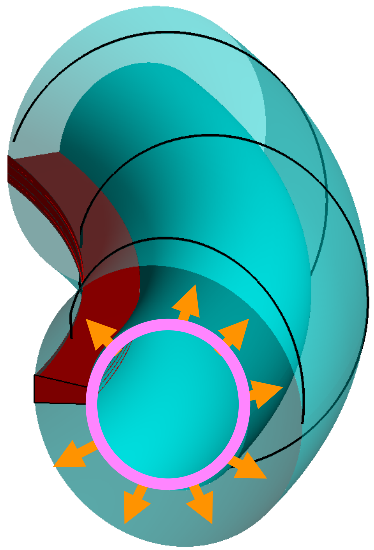
$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_{\|}(nV_{\|e}) + S$$

T_e, T_i, Ω (vorticity) → similar equations

$V_{\|e}$, $V_{\|i}$ → parallel momentum balance

$\nabla_{\perp}^2 \phi = \Omega,\ \nabla_{\perp}^2 \psi = j_{\|}$

Solved in 3D, dynamics resulting from: plasma outflow, turbulent transport, and parallel losses



The GBS code, a tool to simulate SOL turbulence

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$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_{\parallel}(nV_{\parallel e}) + S$$

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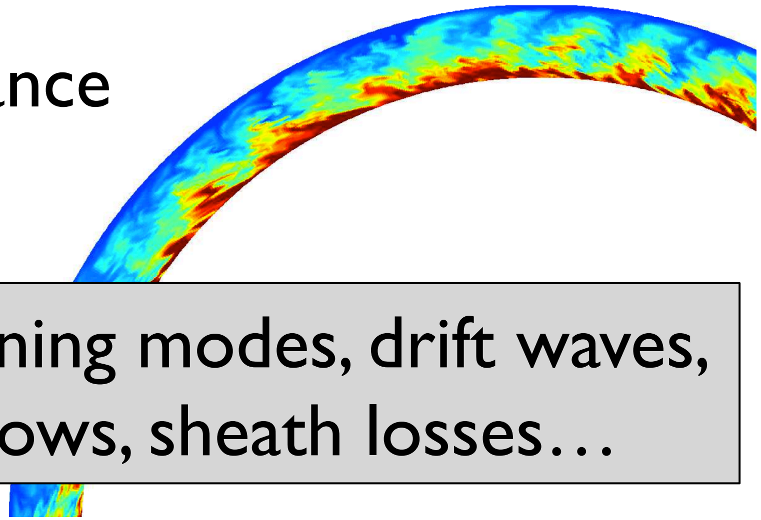
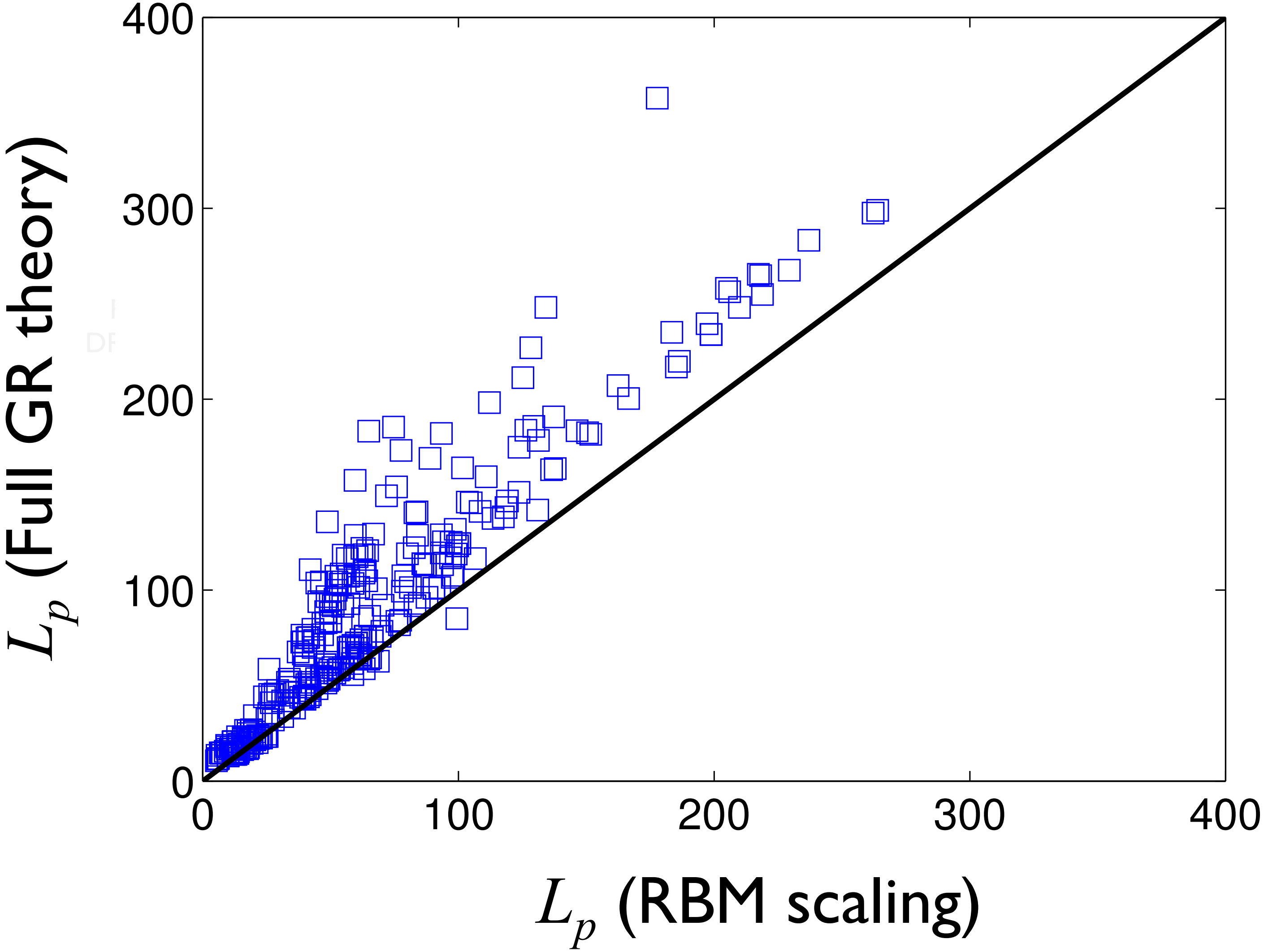


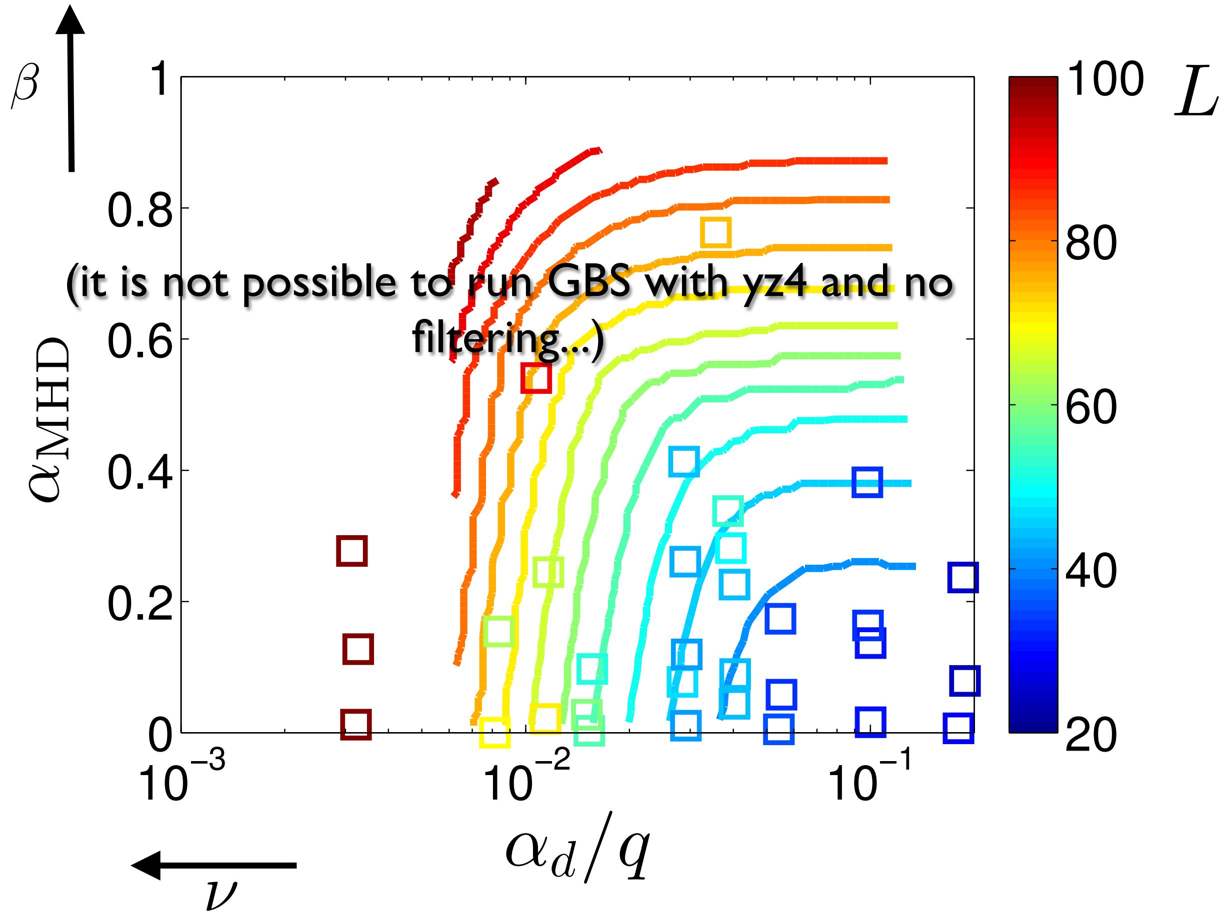
Simulations contain physics of ballooning modes, drift waves, Kelvin-Helmholtz, blobs, parallel flows, sheath losses…

RBM estimate works with ITPA database

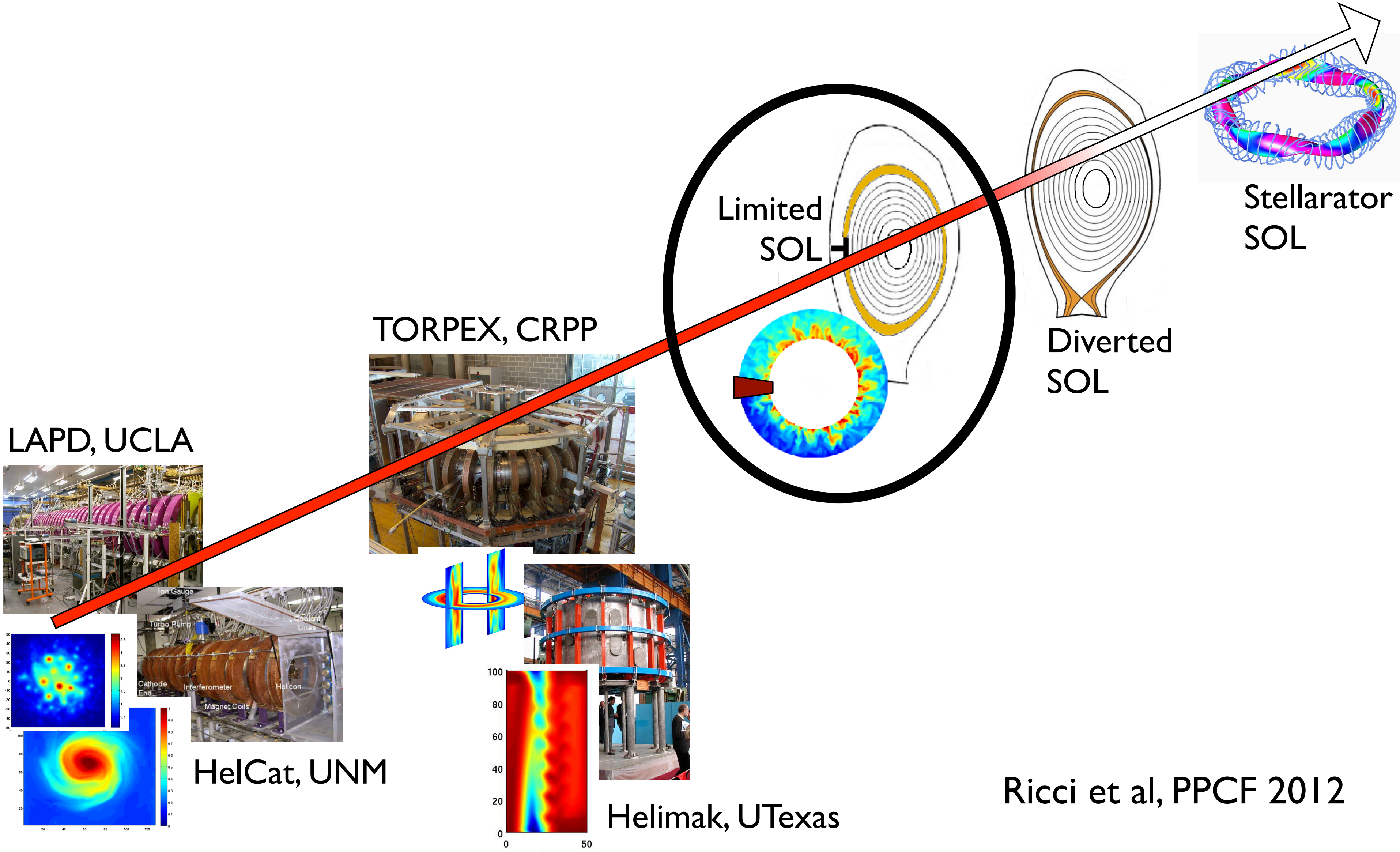


Limited SOL transport increases with β and ν

$$L_p = R^{1/2}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]^{-1/2}$$



GBS code: a tool to simulate SOL-like plasmas



Ricci et al, PPCF 2012