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model of interchange turbulent transport: on the correlation between scrape off layer width and core confinement in tokamaks

N. Fedorczak, Mathieu Peret, Philippe Ghendrih, Patrick Tamain, Hugo Bufferand

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- Spectral filament paradigm: self consistent prediction of turbulent spectra (n_e, Φ) of flux driven 2D isothermal interchange turbulence
- Predicts macroscopic transport properties (flux, fluctuations) in scrape-off layer (\rightarrow SOL width λ_q) but also in the core (\rightarrow confinement time τ_E)
- SOL transport: quantitative agreement with Tore Supra data (circular plasmas), recovers impact of divertor leg length on SOL width (λ_q) in TCv, recovers multi-machine parametric sensitivity of λ_q
- Core confinement: recovers multi-machine parametric sensitivity of τ_E and correlation between core confinement and heat flux width
- Offers a flexible paradigm for addressing the optimization of power exhaust versus core confinement (key: impact of geometry in model)

2D isothermal interchange model (TOKAM2D)

Y. Sarazin et al. Phys. Plasmas 5 (12) (1998) 4214-4228

Flux driven (source S), control parameters: $g \approx \frac{\rho_S}{R}$, $\sigma_{||} \approx \frac{\rho_S}{q_{cyl} R}$

$$d_t n + D \nabla^2 n = S - \sigma_{||} n e^{\Lambda - \Phi}$$

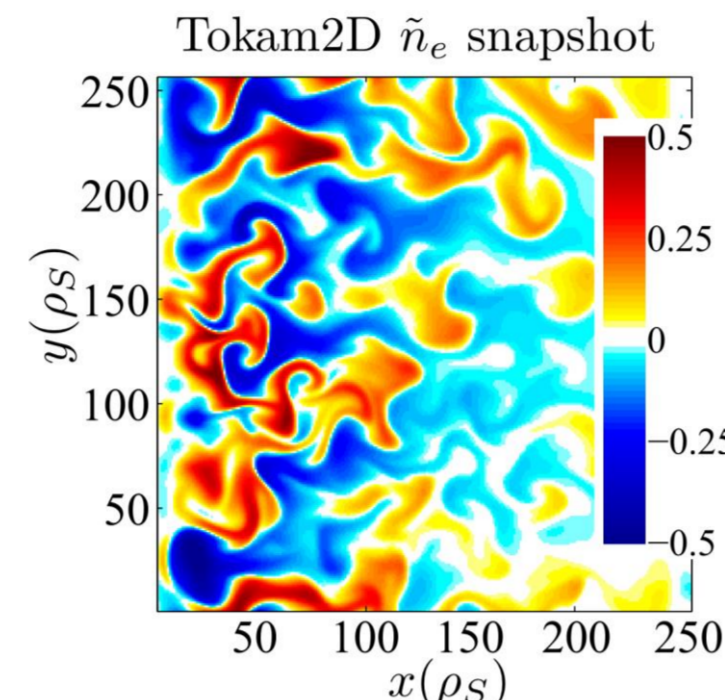
curvature // loss rate

$$d_t = \partial_t + \{\Phi, \cdot\}$$

$$d_t \omega + \nu \nabla^2 \omega = g \frac{\partial_y n}{n} - \sigma_{||} (1 - e^{\Lambda - \Phi})$$

$$\omega = \nabla_{\perp}^2 \Phi$$

Intermittent filamentary transport, exponential SOL, etc



Test isolated filament model

S. I. Krashennnikov et al. J. Plasma Phys. 2008, 74, 679

Density filament: size δ_f & normalized amplitude n_f
 \rightarrow drift velocity (v_f) predicted from vorticity balance

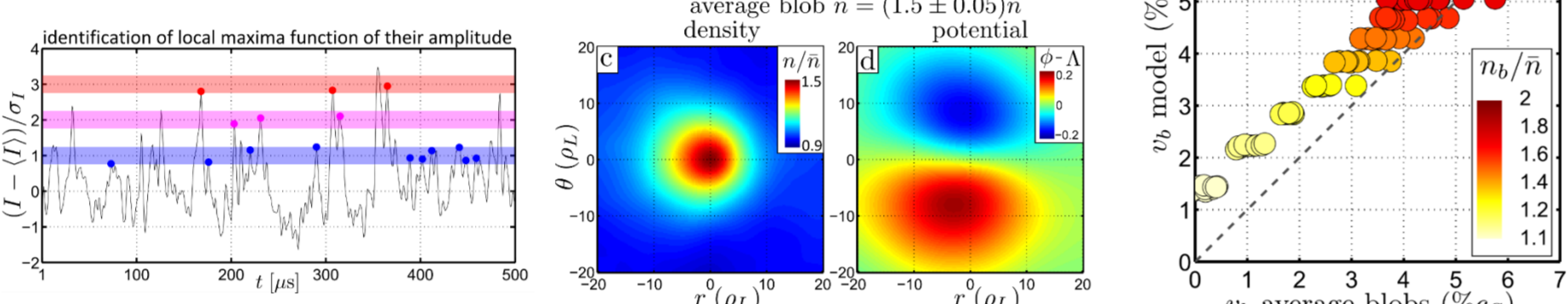
Hyp: well shaped filaments, not the case in simulations

Solution: construction of averaged filaments

\rightarrow conditional average with event amplitude discrimination

Isolated filament model works on TOKAM2D averaged filaments

N. Fedorczak et al. Contrib. Plasma Phys. 2018;58:471-477



$$v_f = \frac{1}{2} \sigma_{||} \delta_b^3 \left[\sqrt{1 + (\delta_0 / \delta_b)^5} + 1 \right]$$

$$\delta_0 = \left(\frac{4g(n_b - 1)}{\sigma_{||}^2} \right)^{1/5}$$

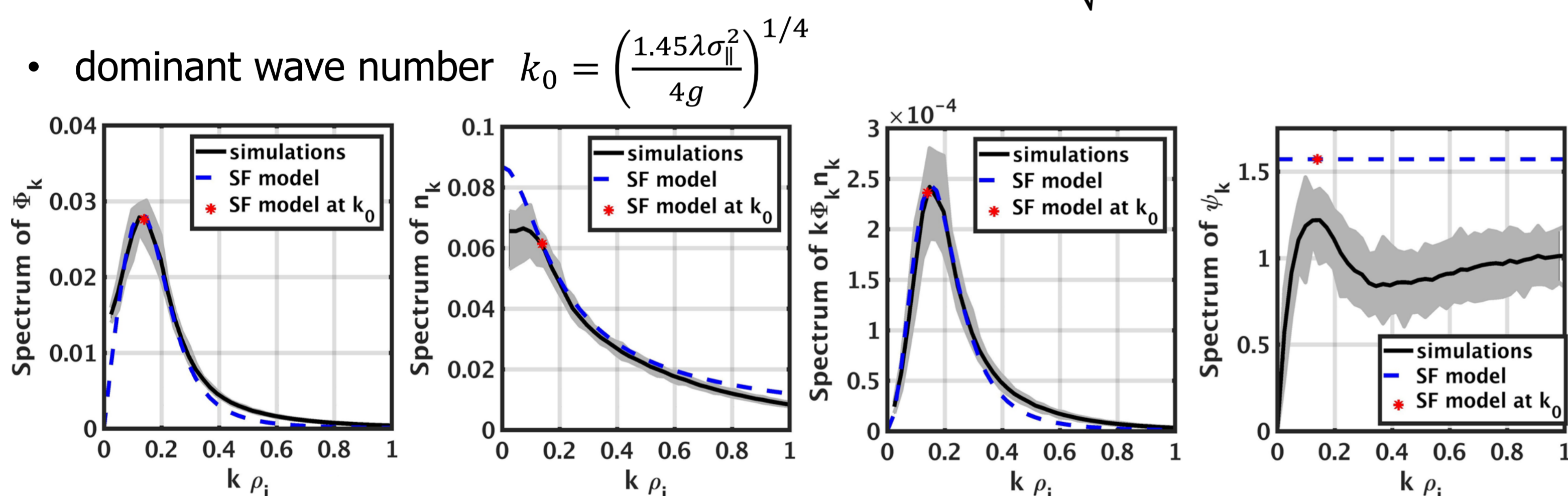
Spectral filament (SF) model

N. Fedorczak et al. Nuc. Mater. & Energy 19 (2019) 433-439

Principle: extend filament model to fluctuation spectra $v_f(\delta_f) \rightarrow \Phi(k_{\theta})$ & $n_b \rightarrow n(k_{\theta})$

Hyp: density & potential spectra in phase quadrature + time independent spectra (it is!)

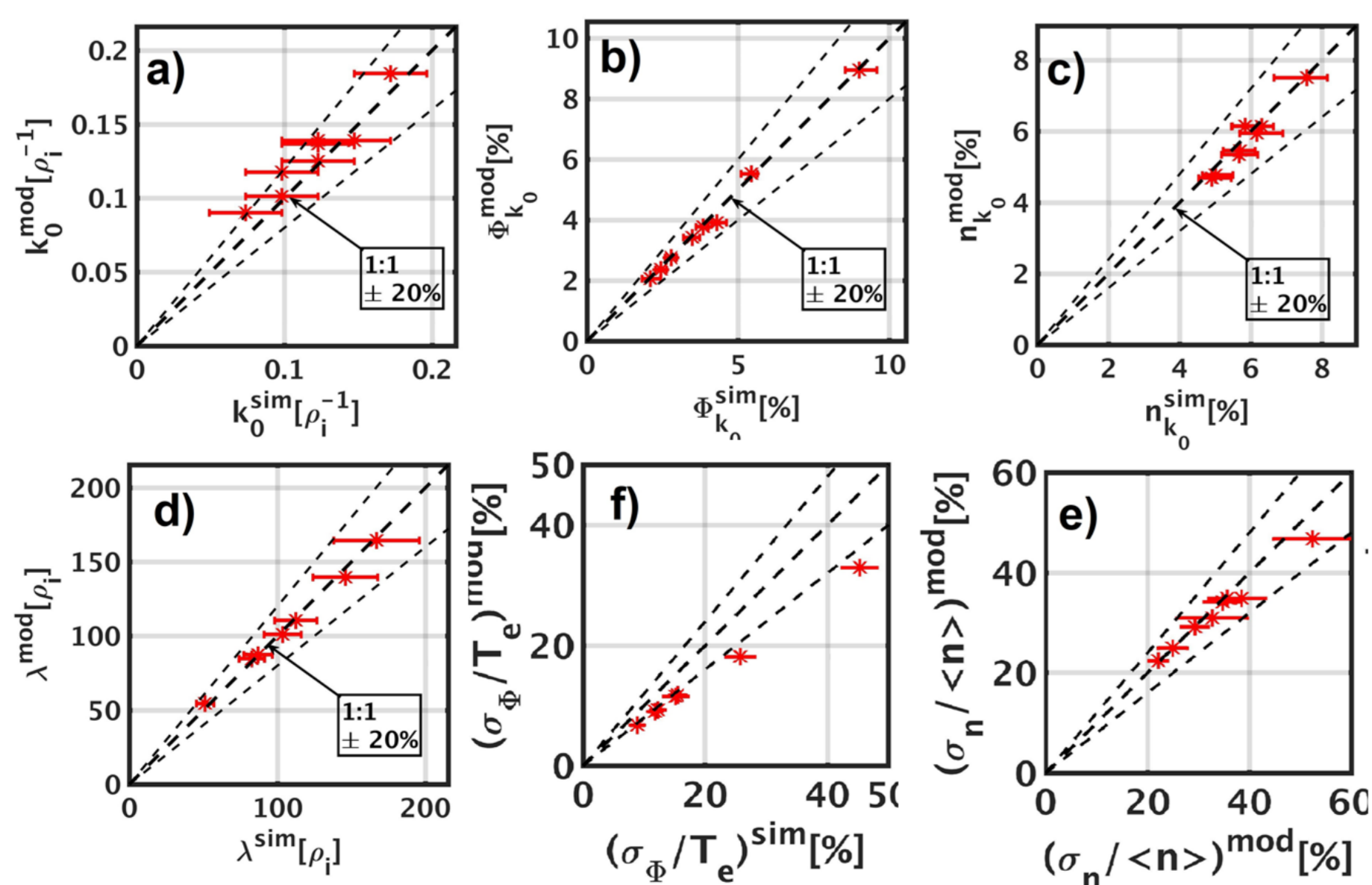
- potential: include effective viscosity from dominant mode $k^4 \Phi_{k_0} \Phi_k + \sigma_{||} \Phi_k = g k n_k$
- density: mixing length + ad-hoc saturation at low k $\sqrt{k^2 + k_0^2} n_k = \lambda_n^{-1}$



Spectral integrals for macroscopic quantities:

- radial flux: $\Gamma_r \equiv 8\pi^2 \int k \Phi_k n_k dk = 41 \lambda_n^{-7/4} g^{3/4} \sigma_{||}^{-1/2} [\bar{n} c_S]$
- fluctuation levels $\frac{\sigma_n}{\bar{n}} = 12.6 \lambda_n^{-9/8} g^{1/8} \sigma_{||}^{-1/4}$ & $\frac{\sigma_{\Phi}}{T_e} = 4.8 \lambda_n^{-7/8} g^{7/8} \sigma_{||}^{-3/4}$
- scrape-off-layer width: $\Gamma_r \equiv \lambda_n \sigma_{||} \rightarrow \lambda_n = 3.9 g^{3/11} \sigma_{||}^{-6/11} [\rho_L]$

\rightarrow Quantitative agreement with TOKAM2D simulations (scan of g & $\sigma_{||}$)



Spectral filament model:

- stiff flux model $\Gamma_r \propto \lambda_n^{-7/4}$
- not diffusive nor convective
- intermittency disappears in spectral paradigm
- key: model of g & $\sigma_{||}$

SF model \rightarrow prediction of heat flux width & confinement time

Heat flux decay length

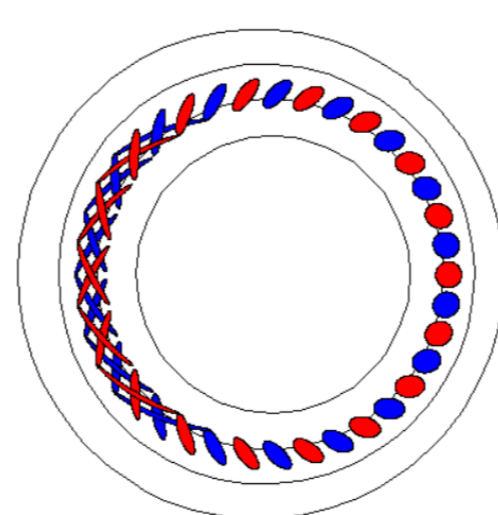
Hyp: $\lambda_q = \alpha_q \lambda_n$, $g = \rho_L / R$ & $\sigma_{||} = \frac{\rho_L}{L_{||}} = \rho_L / \pi q_{cyl} R$, 2-point model for T_{sep}

$$\lambda_q = 50 \alpha_q q_{cyl}^{0.63} B_{[T]}^{-0.65} R_{[m]}^{0.25} \left(\frac{A}{Z} \right)^{0.33} P_{sep[MW]}^{0.09} [mm]$$

Confinement time:

Hyp: density \rightarrow pressure & particle flux \rightarrow heat flux
 vorticity // dissipation still valid (HFS decorrelation of LFS mode)
 gradient scale length $\lambda \approx a$

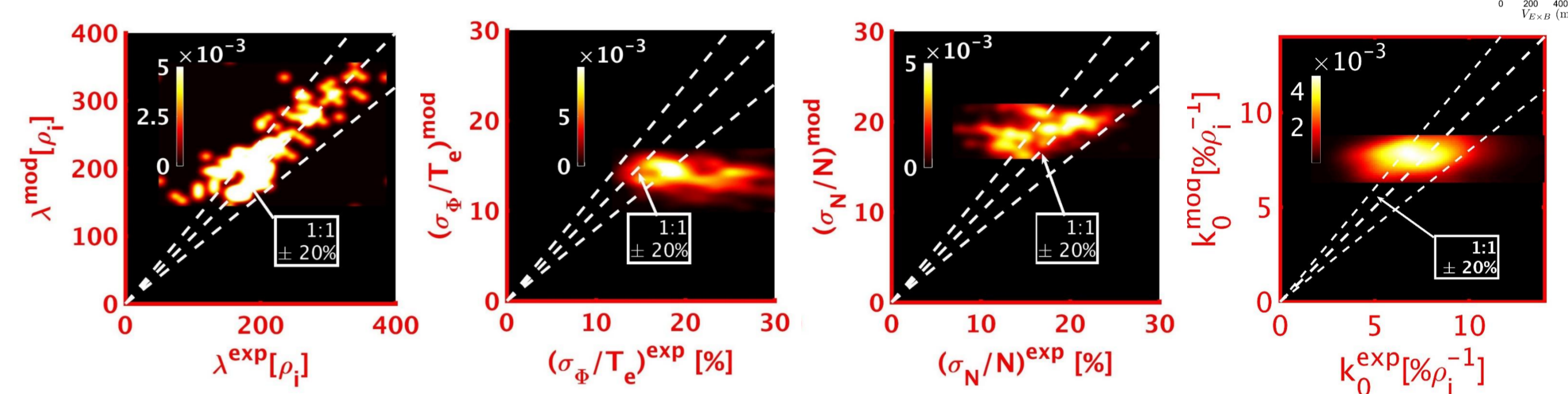
$$\tau_E = 0.007 \alpha_T I_{P[MA]}^{0.2} B_{[T]}^{0.6} P_{TOT[MW]}^{-0.6} n_{e[E19]}^{0.6} M^{0.2} R_{[m]}^{2.8} \left(\frac{a}{R} \right)^{1.9} [s]$$



Model validated against broad SOL database from Tore Supra

>100 probe reciprocations with turbulence (1MHz θ -rake) & profile (tunnel) collectors

- ExB velocities of averaged filaments match with isolated filament model
- fluctuation amplitudes (n_e & Φ) and main k_{θ} well reproduced
- density profile decay length (λ_n) quantitatively matched



Recovers multi-machine scaling of ITER startup heat flux width

N. Fedorczak et al. Nuc. Mater. & Energy 19 (2019) 433-439

Hyp: $\lambda_q = 0.5 \lambda_n$ (correlation from Tore Supra database)

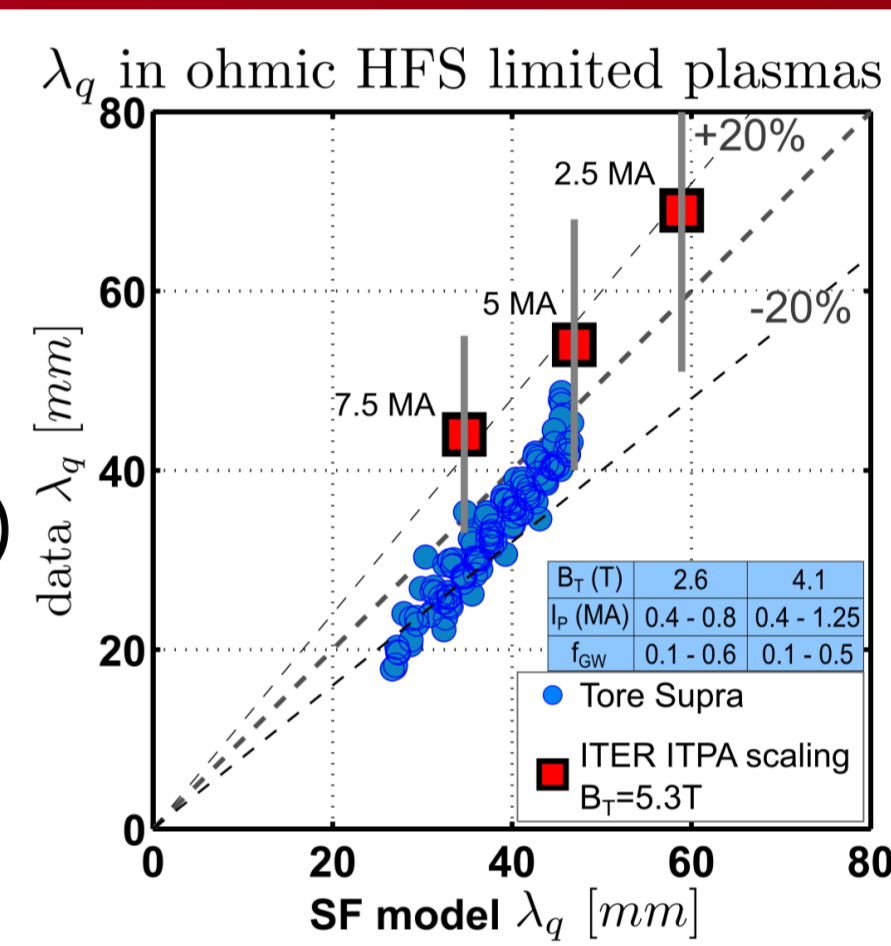
$$\lambda_q = 25 q_{cyl}^{0.63} B^{-0.65} R^{0.25} \left(\frac{A}{Z} \right)^{0.33} P_{sep[MW]}^{0.09} [mm]$$

- quantitative agreement with Tore Supra λ_q (ITER database)

J. Gunn et al. J. Nucl. Mater. 438 (Suppl) (2013) S184-S188.

- quantitative agreement with multi-machine prediction of ITER startup SOL width

J. Horacek et al. Plasma Phys. Controlled Fusion 58 (7) (2016) 074005.



Recovers multi-machine scaling sensitivity of λ_q in H-mode

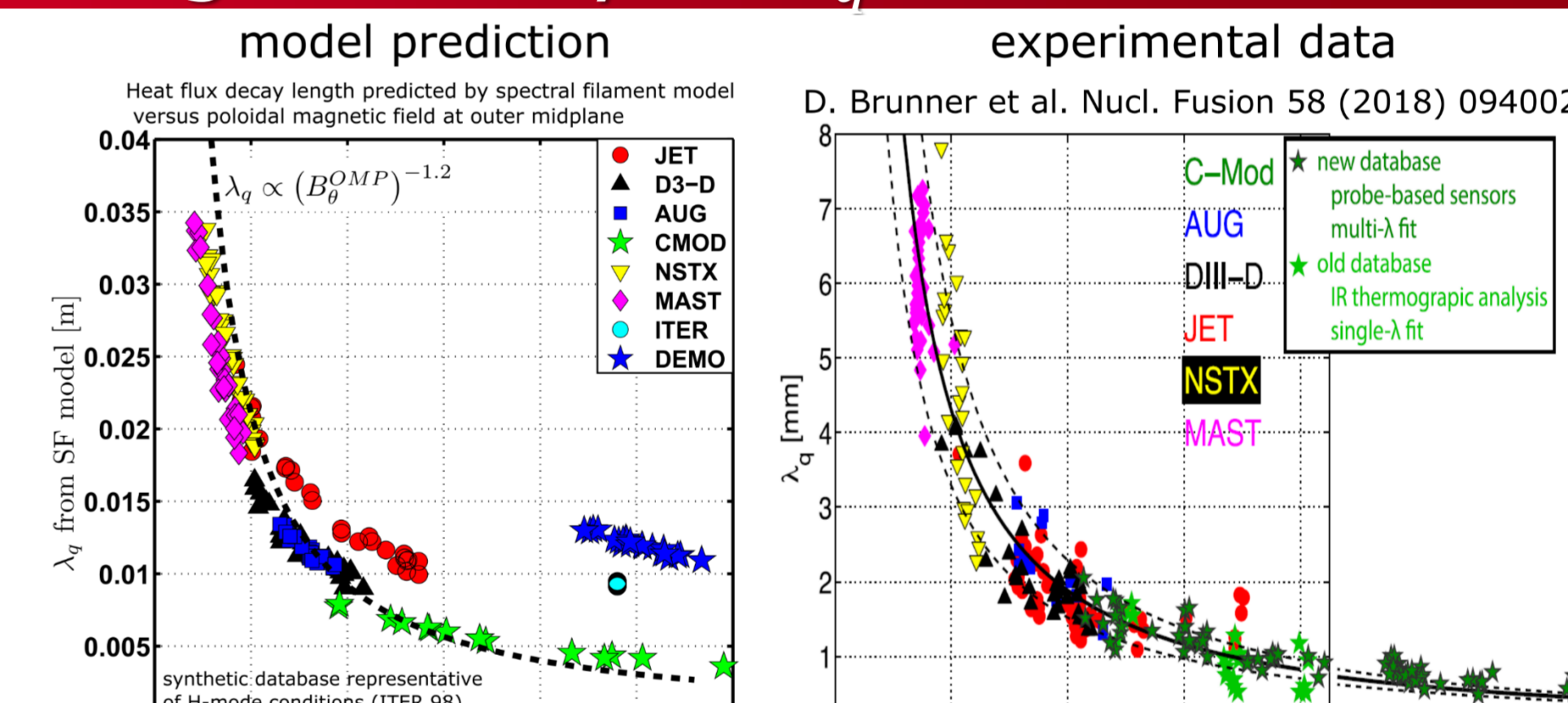
Model: $\lambda_q \propto R^{0.25} \dots$

- λ_q X3-4 for ITER & DEMO compared to B_{θ} scaling

T. Eich et al. Nucl. Fusion 53 (9) (2013) 093031

- sounds with XGC1 results (different interpretation)

C.S. Chang et al 2017 Nucl. Fusion 57 116023



Recovers impact of divertor leg length on λ_q in TCv L-mode

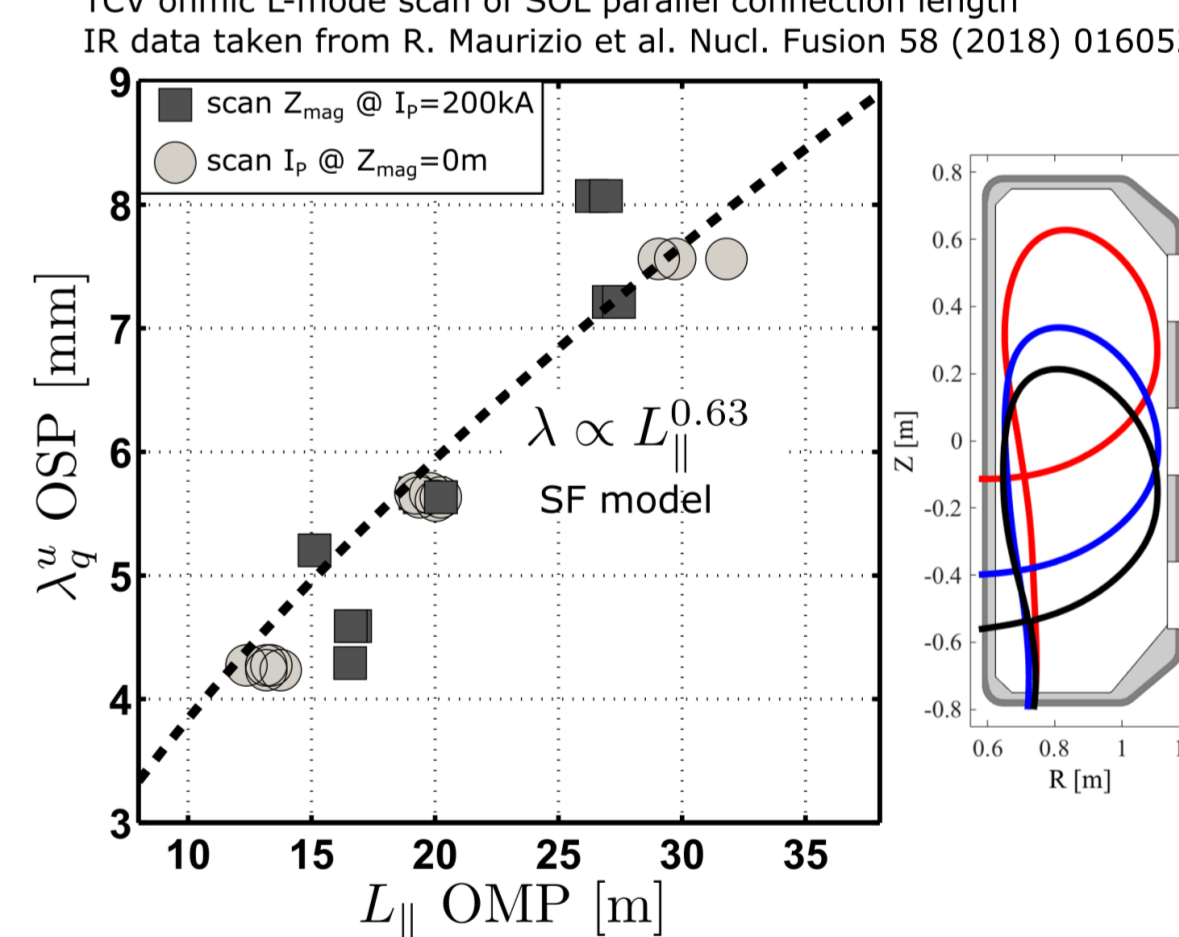
TCv ohmic pulses: scan of plasma current and divertor geometry gives same $\lambda_q(L_{||})$

R. Maurizio et al. Nucl. Fusion 58 (2018) 016052

Model: $\lambda_q \propto L_{||}^{0.63}$

- sensitivity recovered by the SF model
- 3D turbulent simulations show interchange along divertor leg, as the model considers

A. Gallo et al. Plasma Phys. Control. Fusion 60 (2018) 014007



Recovers global multi-machine τ_E sensitivity & correlation with λ_q

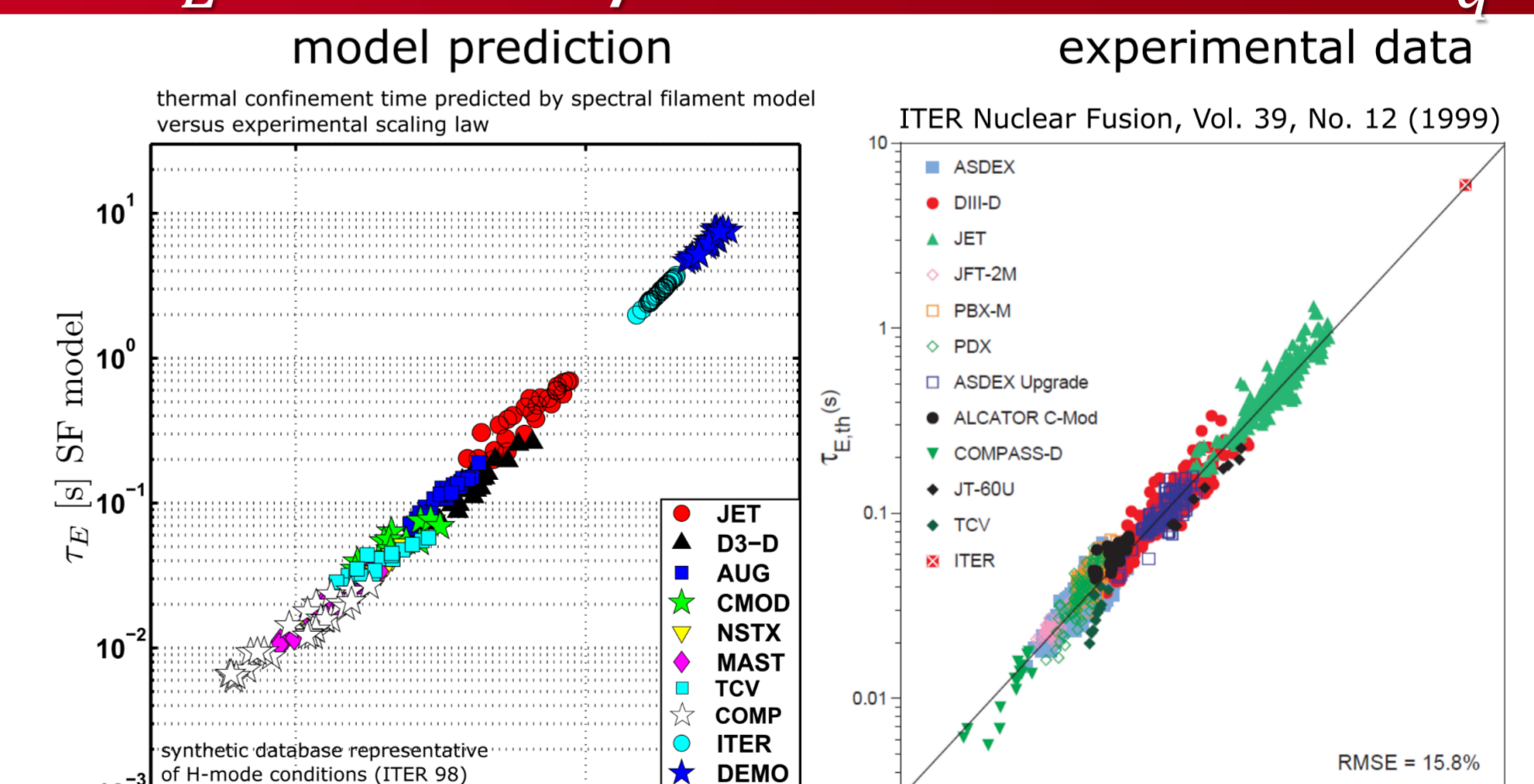
Model:

$$\tau_E \propto I_P^{0.2} B^{0.6} P_{TOT}^{-0.6} n_e^{0.6} M^{0.2} R^{2.8} \left(\frac{a}{R} \right)^{1.9}$$

Scaling law ITER 98:

$$\tau_E \propto I_P^{1.0} B^{0.1} P_{TOT}^{-0.6} n_e^{0.4} M^{0.2} R^{1.9} \left(\frac{a}{R} \right)^{0.2}$$

- significant difference in I_P & B
- **global trend is well matched**
- hints of correlations in exp. scaling



Correlation confinement vs λ_q

D. Brunner et al. Nucl. Fusion 58 (2018) 094002

- experimental correlation $\lambda_q \propto \bar{p}^{-0.48}$ across L-I-H modes in C-mod

- recovered in exp. H-mode scaling

- recovered by model on current machines, but not for ITER/DEMO

