# Progress in modeling TCVX23 with *k*-model


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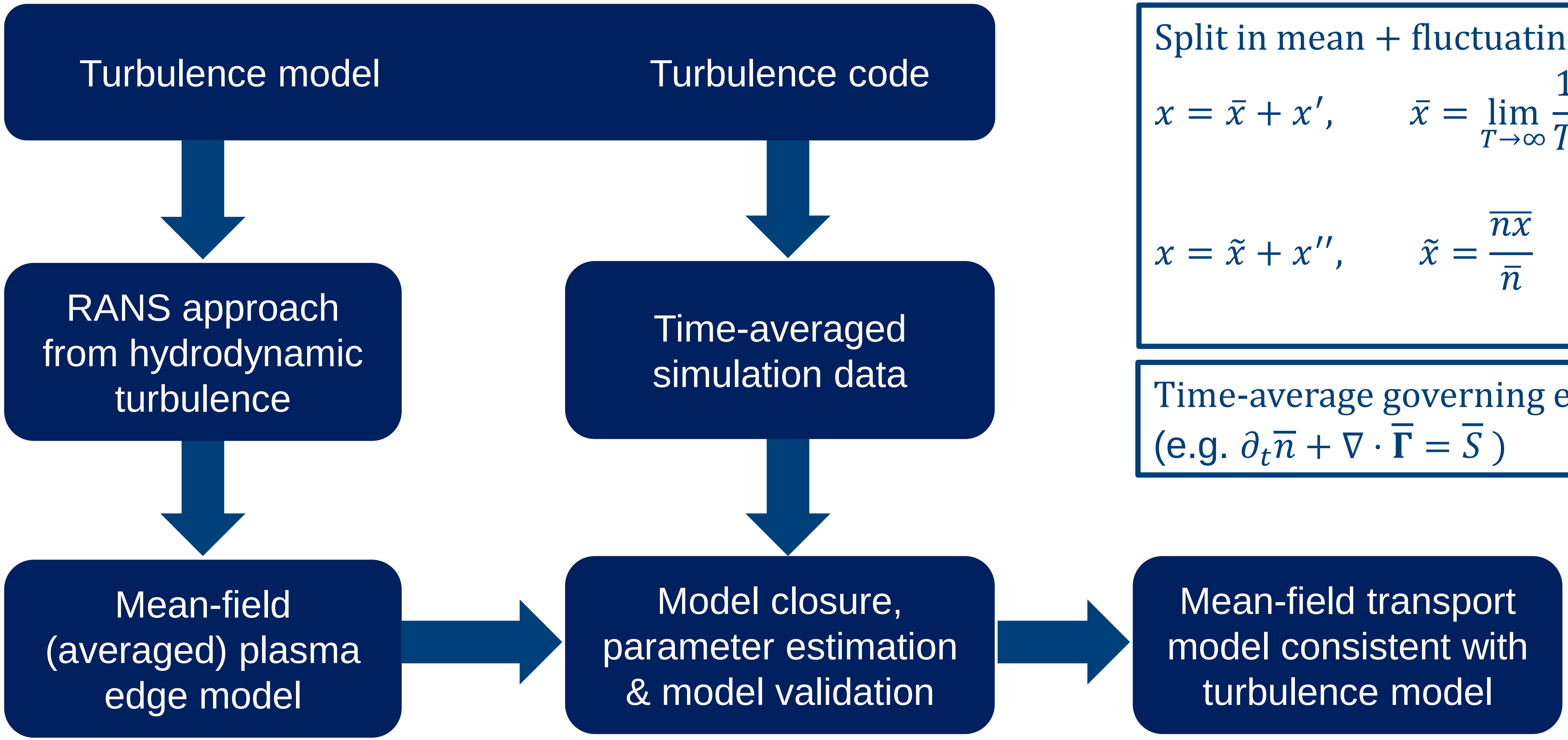
# Approach




Split in mean + fluctuating components

$$x = \bar{x} + x', \qquad \bar{x} = \lim_{T\to\infty} \frac{1}{T}\int_0^T x\,dt$$

$$x = \tilde{x} + x'', \qquad \tilde{x} = \frac{\overline{nx}}{\bar{n}}$$

Time-average governing equations
(e.g. $\partial_t \bar{n} + \nabla \cdot \bar{\boldsymbol{\Gamma}} = \bar{S}$ )

# Application to electrostatic turbulence (no $B$-fluctuations)

- Average fluxes
  - $\overline{\boldsymbol{\Gamma}} = \bar{n}\widetilde{\boldsymbol{u}} = \bar{n}\tilde{u}_{||}\mathbf{b} + \bar{n}\,\widetilde{\boldsymbol{u}}_* + \bar{n}\widetilde{\boldsymbol{u}}_p + \bar{n}\widetilde{\boldsymbol{u}}_\nu + \bar{n}\,\overline{\boldsymbol{u}}_{E\times B} + \overline{n'\boldsymbol{u}'_{E\times B}}$
  - $\overline{\boldsymbol{Q}}_i = \bar{Q}_{i||}\mathbf{b} + \frac{5}{2}\left(\bar{n}\,\widetilde{\boldsymbol{u}}_* + \bar{n}\widetilde{\boldsymbol{u}}_p + \bar{n}\widetilde{\boldsymbol{u}}_\nu\right)\tilde{T}_i + \frac{3}{2}\bar{n}\,\overline{\boldsymbol{u}}_{E\times B}\tilde{T}_i + \frac{3}{2}\left(\overline{n'\boldsymbol{u}'_{E\times B}}\tilde{T}_i + \overline{n\boldsymbol{u}''_{E\times B}T''_i}\right) - \overline{\kappa_i\nabla T_i}$

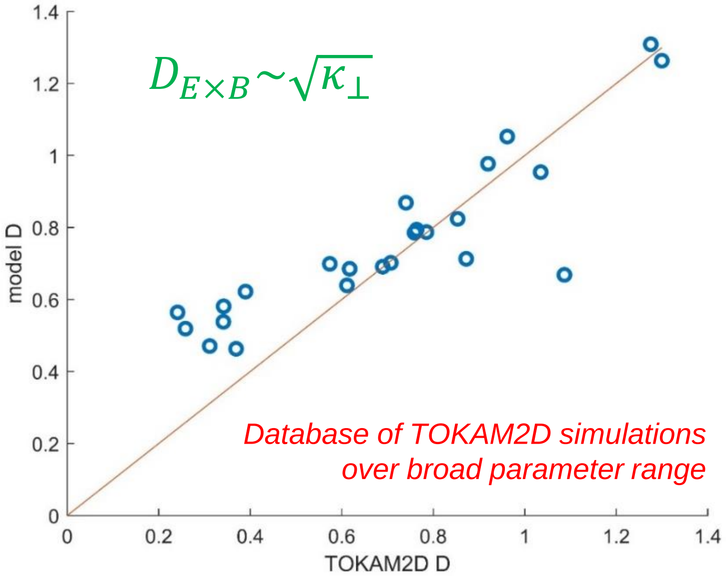
    (for $\overline{\boldsymbol{Q}}_i$, neglecting some fluctuations of smaller drifts)

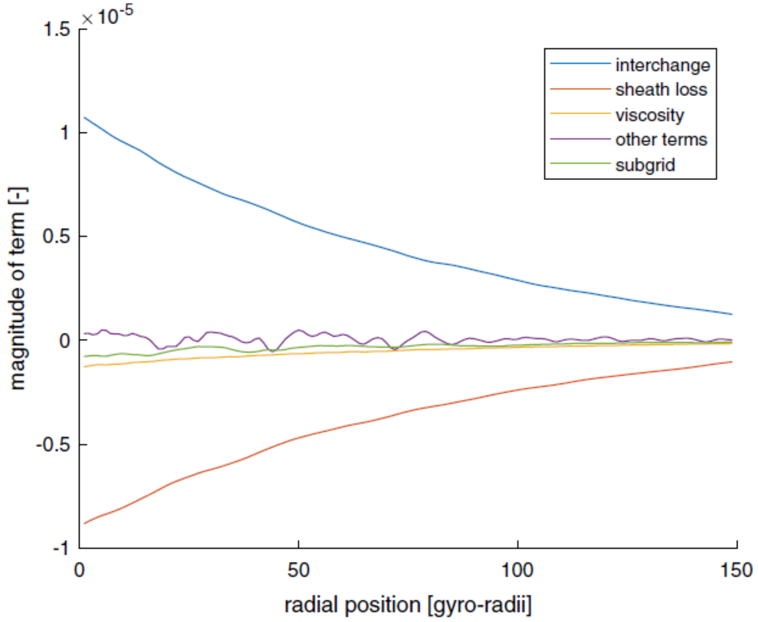
where $\bar{n}\,\widetilde{\boldsymbol{u}}_* = \frac{1}{eB^2}\nabla\,\bar{p}_i \times \boldsymbol{B}$, $\quad \bar{n}\widetilde{\boldsymbol{u}}_p = \frac{\mathbf{b}}{eB}\times\left(\frac{\partial}{\partial t}(m\bar{n}\widetilde{\boldsymbol{u}}) + \nabla\cdot(m\overline{n\boldsymbol{u}\boldsymbol{u}})\right)$, $\quad \bar{n}\widetilde{\boldsymbol{u}}_\nu = \frac{\mathbf{b}}{eB}\times\nabla\cdot\overline{\Pi}_i$,

and $\bar{p}_{i/e} = \bar{n}\tilde{T}_{i/e}$, $\quad \overline{\boldsymbol{u}}_{E\times B} = \frac{1}{B^2}\boldsymbol{B}\times\nabla\,\bar{\phi}$

- Fluctuating $E\times B$-terms need closure; stick to diffusive closure (for now):
  - $\overline{\boldsymbol{\Gamma}}_{i/e,E\times B} = \overline{n'_i\boldsymbol{u}'_{E\times B}} \sim -D_{E\times B}\nabla\bar{n}_i$
  - $\overline{\boldsymbol{Q}}_{i/e,E\times B,c} = \frac{3}{2}\overline{n_i\boldsymbol{u}''_{E\times B}T''_i} \sim -\chi_{i/e,E\times B}\,\bar{n}_{i/e}\nabla_\perp\tilde{T}_i$
  - $\overline{\boldsymbol{Q}}_{i/e,E\times B} = \frac{3}{2}\overline{n'_i\boldsymbol{u}'_{E\times B}} + \overline{\boldsymbol{Q}}_{i/e,E\times B,c}$

# RANS approach for electrostatic interchange turbulence




- Proposal: relate to turbulent kinetic energy $\kappa_\perp$ as measure of local intensity of the turbulence/transport

$$\bar{n}_i \kappa_\perp = \frac{\overline{n_i m_i \boldsymbol{u}''^2_{E\times B}}}{2}$$

- Diffusive transport model based on 2D interchange simulations
  [Coosemans et al., CPP 2022, e202100193.]
  - $D_{E\times B} = C_D \rho_L \sqrt{\frac{\kappa_\perp}{m_i}}$
  - $\chi_{i/e,E\times B} = C_{i/e} D_{E\times B} \sim \frac{3}{2} D_{E\times B}$

- Need transport equation for $\kappa_\perp$!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# Sources and transport of $\kappa_\perp$ for interchange turbulence

[R. Coosemans et al., J. Plasma Phys. 90 (2024) 90590020.]

- Transport equation for $\kappa_\perp$ for 2D electrostatic interchange turbulence

$$\frac{\partial}{\partial t}\bar{n}\kappa_\perp + \nabla\cdot\left(\bar{\boldsymbol{\Gamma}}_{\boldsymbol{i}}\kappa_\perp + \overline{\phi' \boldsymbol{J}'_{||}}\right) = \bar{S}_{IC} + \bar{S}_{||}$$

- Total heat flux due to $E \times B$ fluctuations drives production of $\kappa_\perp$

$$\bar{S}_{IC} = -\frac{2}{3}\overline{\boldsymbol{Q}}_{i+e,E\times B}\cdot\nabla \ln B^2$$

  - Source in 'bad-curvature' regions, sink in 'good-curvature' regions

- Parallel transport of $\kappa_\perp$ governed by plasma conductivity

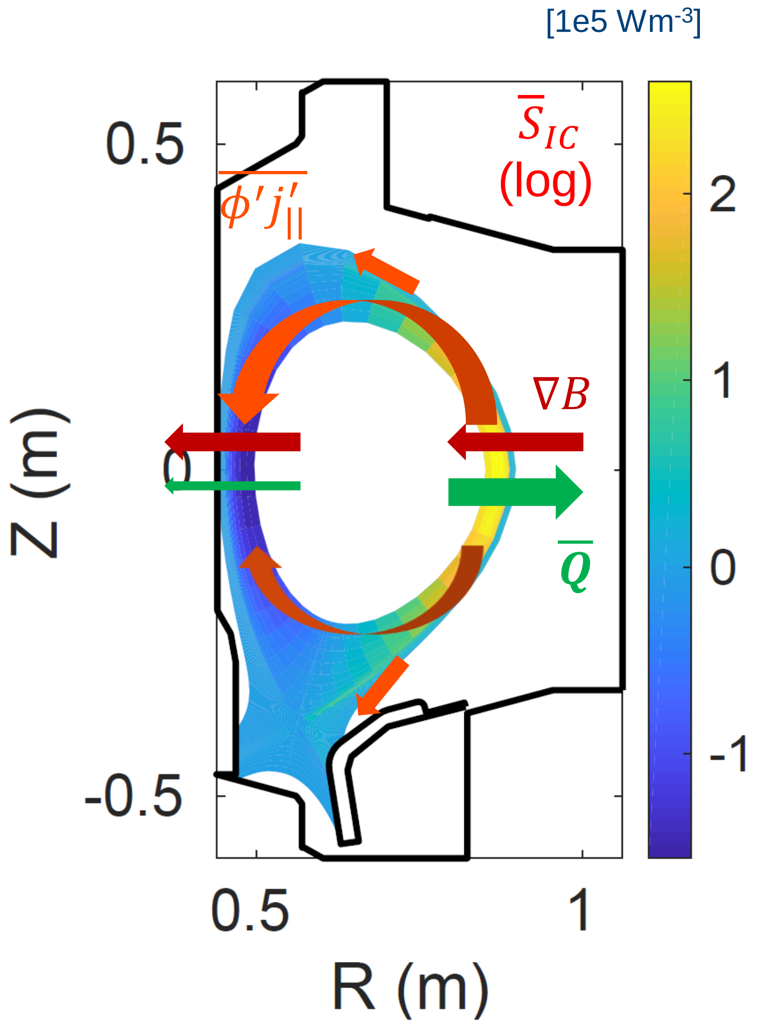
$$\overline{\phi' j'_{||}} \sim -\sigma_{||}\nabla_{||}\frac{\overline{\phi'^2}}{2} \sim -C_{\sigma 1}\sigma_{||}\rho_L^2 B^2 \nabla_{||}\kappa_\perp$$

  - *Strongly exceeds parallel convection with $\tilde{u}_{||}$*

- Proxy to account for mean ExB flow shear $S_m$ suppressing anomalous transport

$$D_{E\times B} = C_D \frac{\kappa_\perp/m_i}{\sqrt{\kappa_\perp/m_i}/\rho_L + C_S|S_m|}$$

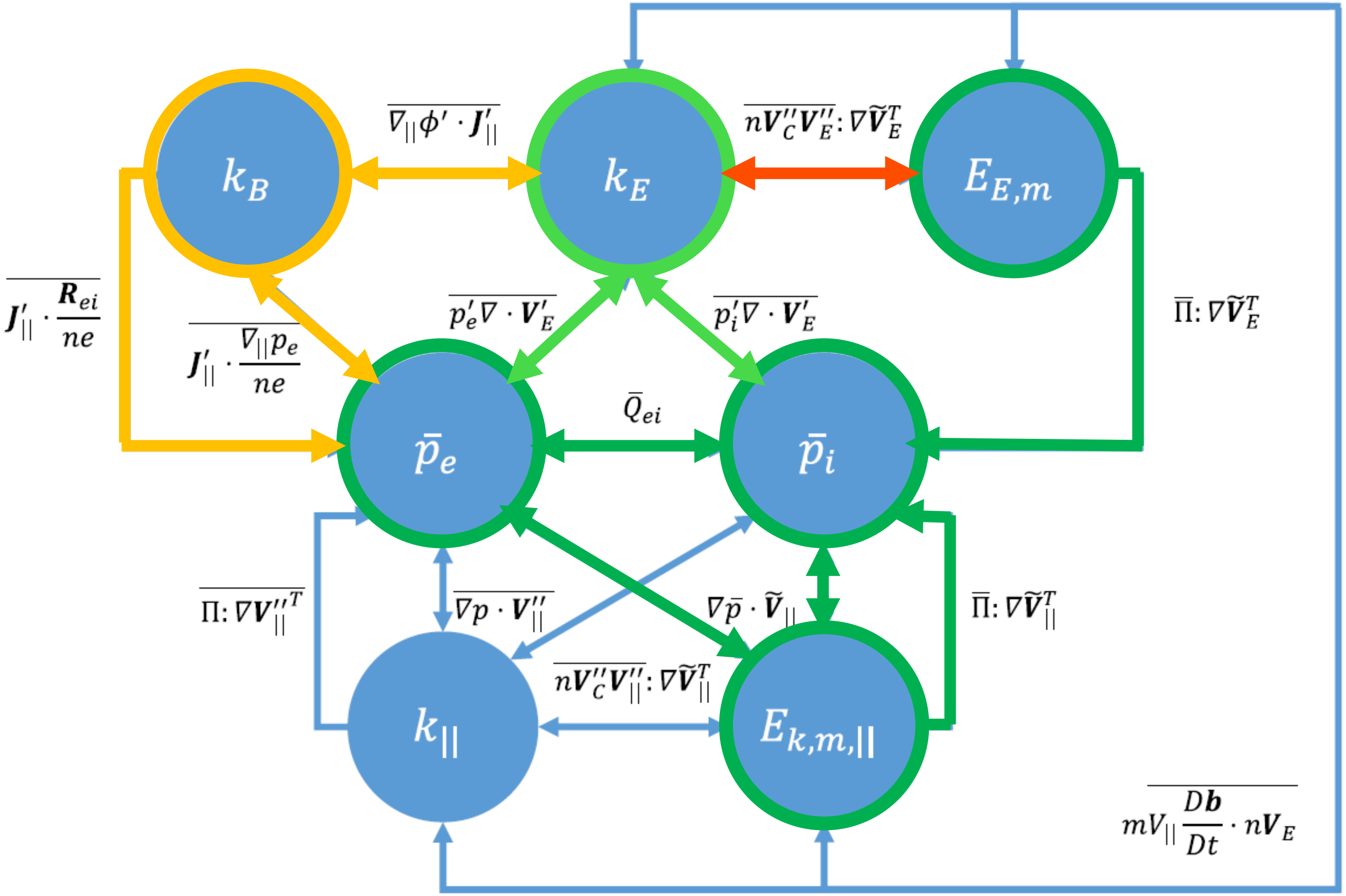
*…coupled to 'regular' mean field equations* [Dekeyser et al., CPP 2022, e202100190.]




*Intrinsic ballooning character and 'self-saturation'*

# Energy transfer channels

[Coosemans et al., JPP 2024, 905900202.]




*Default* in mean-field codes

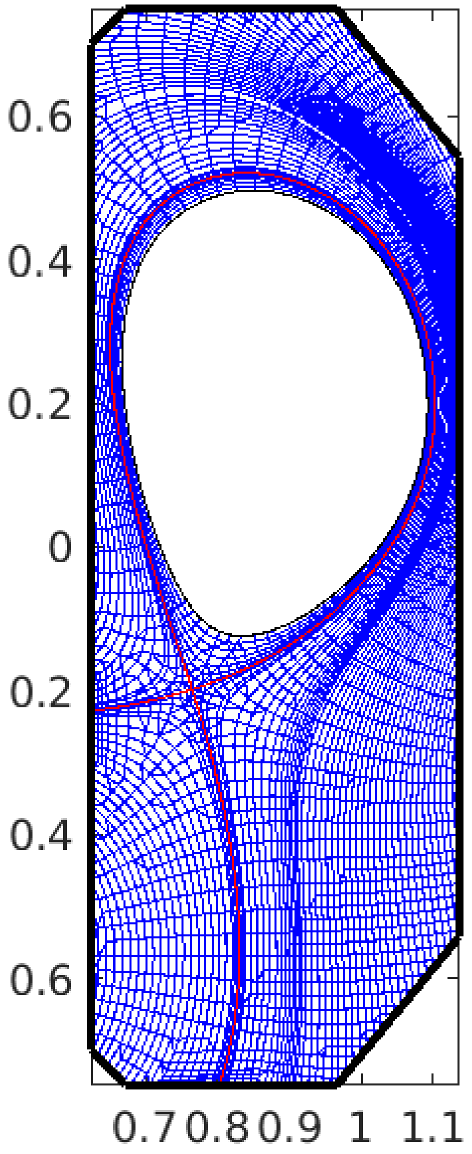
*k*-model

Simplified parallel dynamics in *k*-model

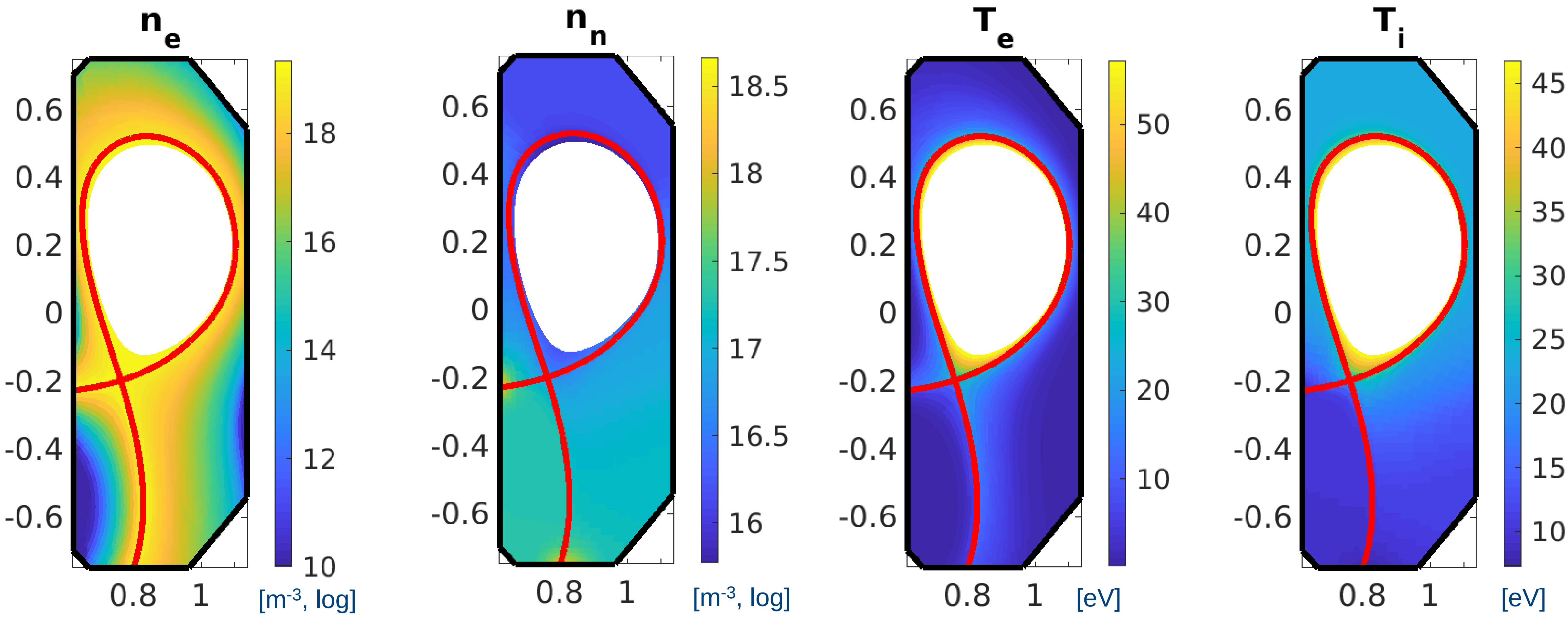
Ad-hoc RS model

# TCV-X23 showcase

- First-of-a-kind simulations including
  - Extended grids
  - AFN model
  - *k*-model for anomalous transport
  - Drifts
- Grid built with GOAT, exploiting new *boundary layer grid* option
  [S. Van den Kerkhof et al., PET 2025]
- Simulation setup based on TCV-X23 experiment
  [D. Mancini et al. Nucl. Fusion 64 (2024) 016012.]
- $\kappa_\perp$ -model parameters optimized via LSQ [S. Carli et al., PET 2025] based on TCV-X21 data [D.S. Oliveira et al 2022 Nucl. Fusion 62 096001]; compare with constant $D_\perp$ ~ *0.4 m²/s*



# TCV X23 edge plasma parameters



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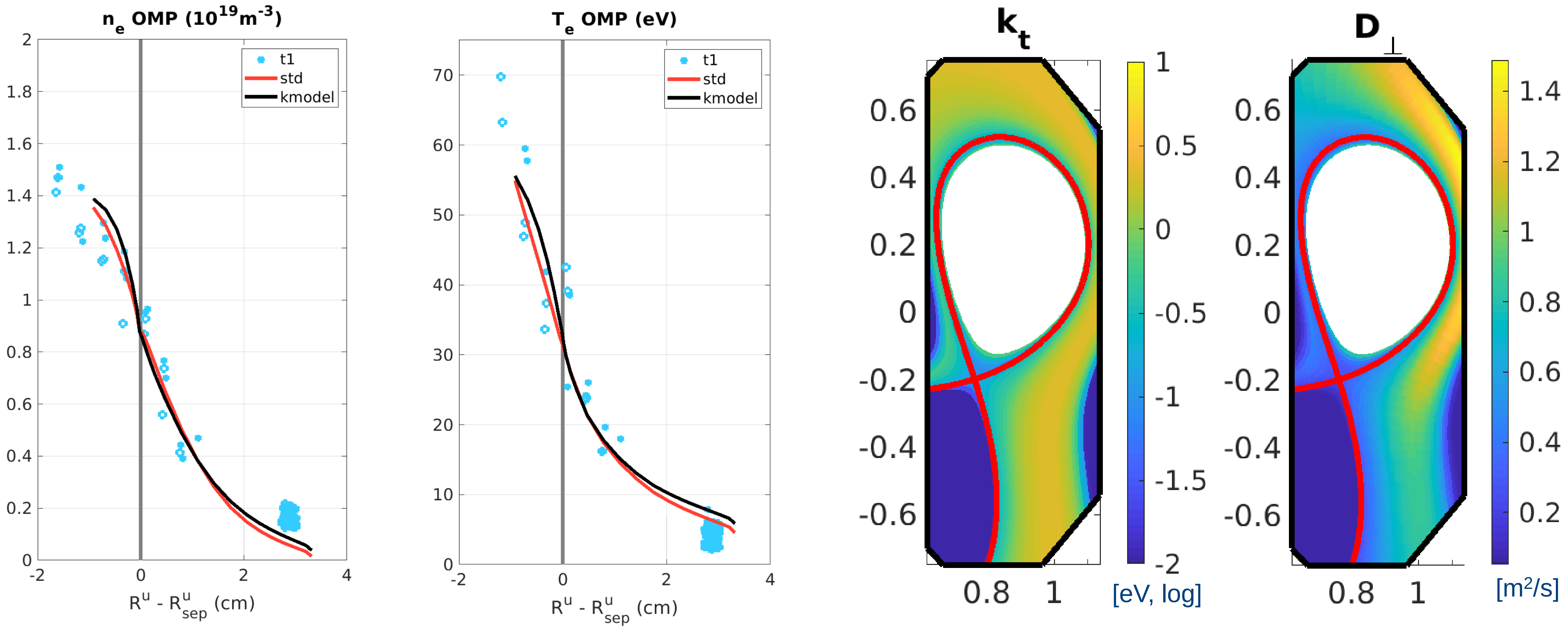
# TCV-X23 showcase: turbulent kinetic energy and $D_\perp$



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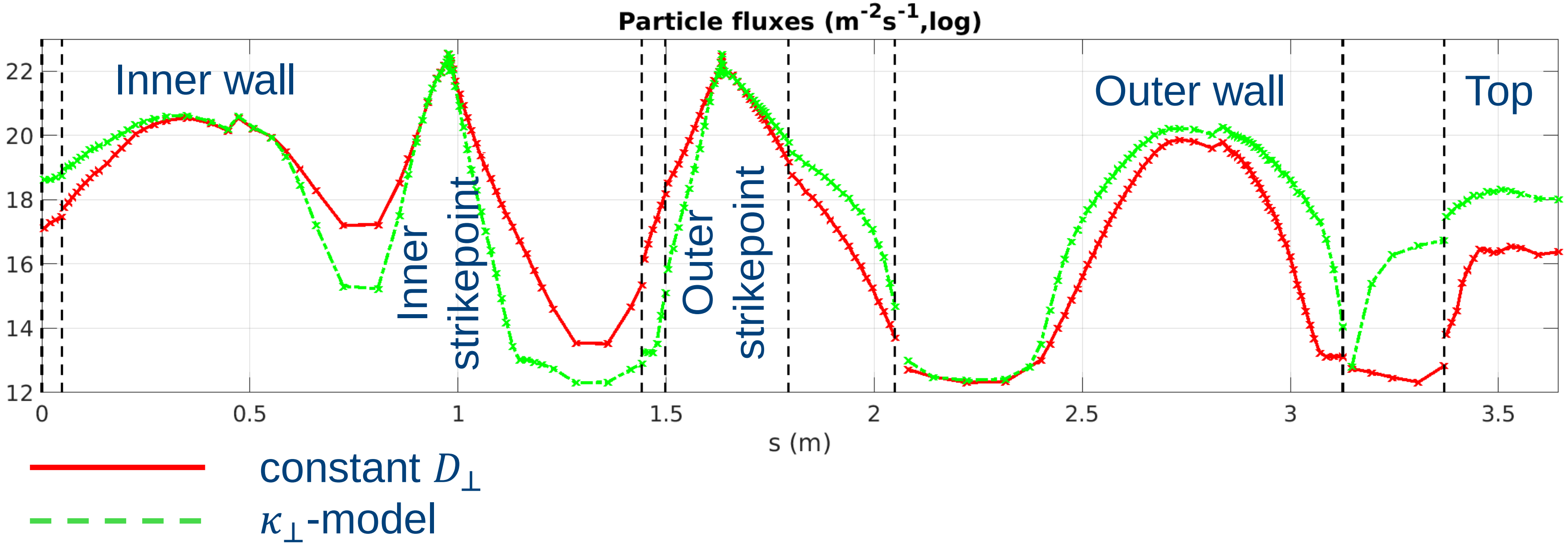
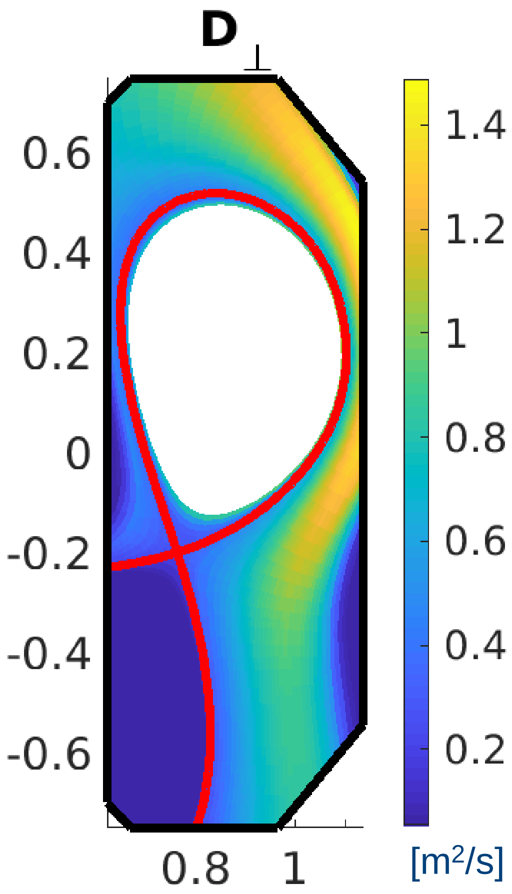
# TCV-X23 showcase: wall fluxes

- Clear signature of magnetic field structure on wall loads
- Peak loads near strike points similar
- Up to factor two higher wall fluxes near outboard side for $\kappa_\perp$ -model, despite nearly identical density/temperature profiles





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# Summary and challenges

- Anomalous transport model based on RANS approach integrated in SOLPS-ITER
  - Includes features such as ballooned transport and self-saturation, but also remaining uncertain closure constants
  - Need for extensive validation with turbulence simulation data and experiment, incl. predicted turbulence characteristics
  - Need for continued development: additional energy exchange mechanisms, updated closures, BCs,…

- First application to TCV-X23 case
  - Including drifts and grids-to-the-wall
  - As for TCV-X21: limited ballooning in near SOL for the selected model parameters
  - Pronounced increase in *k* towards outer wall, and 'notable' changes in wall fluxes. Potential to discriminate between models?



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# Thank you! Questions?