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A Reduced-Order Model to Estimate First Wall Particle and Heat Fluxes for Systems Codes

T. Pomella Lobo[1*], S. Peschanyy[1], I. A. Maione[1]

[1] Institute for Neutron Physics and Reactor Technology (INR), Karlsruhe Institute of Technology (KIT), Karlsruhe

Abstract

While most particles ejected from the confined region in tokamak plasmas are directed towards the divertor, some are distributed along the First Wall (FW) of Breeding Blankets (BBs) by following magnetic field lines in the so-called far Scrape-Off Layer (far-SOL). Even though these fluxes are not the only phenomenon contributing to the heat deposited on the FW (*e.g.* photons, charge-exchange), their impact must be assessed since the total heat fluxes expected on FW armour (up to 1 MW/m^2) are a challenging design issue. At the same time, these fluxes also contribute to particle implantation in the FW armour (ion bombardment), which can impact systems-level analyses such as tritium permeation into the FW coolant, tritium retention in BB steel, and effusion fluxes during pump-down.

Current tokamak plasma physics prescribes that the continuous production and expulsion of blobs from the confined plasma region is a main phenomenon contributing to these far-SOL fluxes. Simulation tools based on simplified turbulent transport models, such as the TOKES code, have been under development to provide BB engineers with design-relevant information, *e.g.* prediction of "hot spots" on the FW. Unfortunately, such tools tend to run in timescales that are prohibitive for incorporation in Systems Codes (SCs), which would enable analyses at a systems level.

This work presents a Reduced-Order Model (ROM) built with results from the TOKES code, to serve as a surrogate model for coupling in SCs. The ROM was developed with Principal Components Regression (PCR) and k-fold cross-validation, applied to the results after transformations based on rational powers of the TOKES inputs (blob temperatures, densities and ejection speeds). Model selection was performed with Kullback-Leibler Divergence (KLD), and validation, with withheld cases. Main results include a relatively low number of modes to represent more than 90% of the data variance.

***Contact:** t.pomella-lobo@kit.edu

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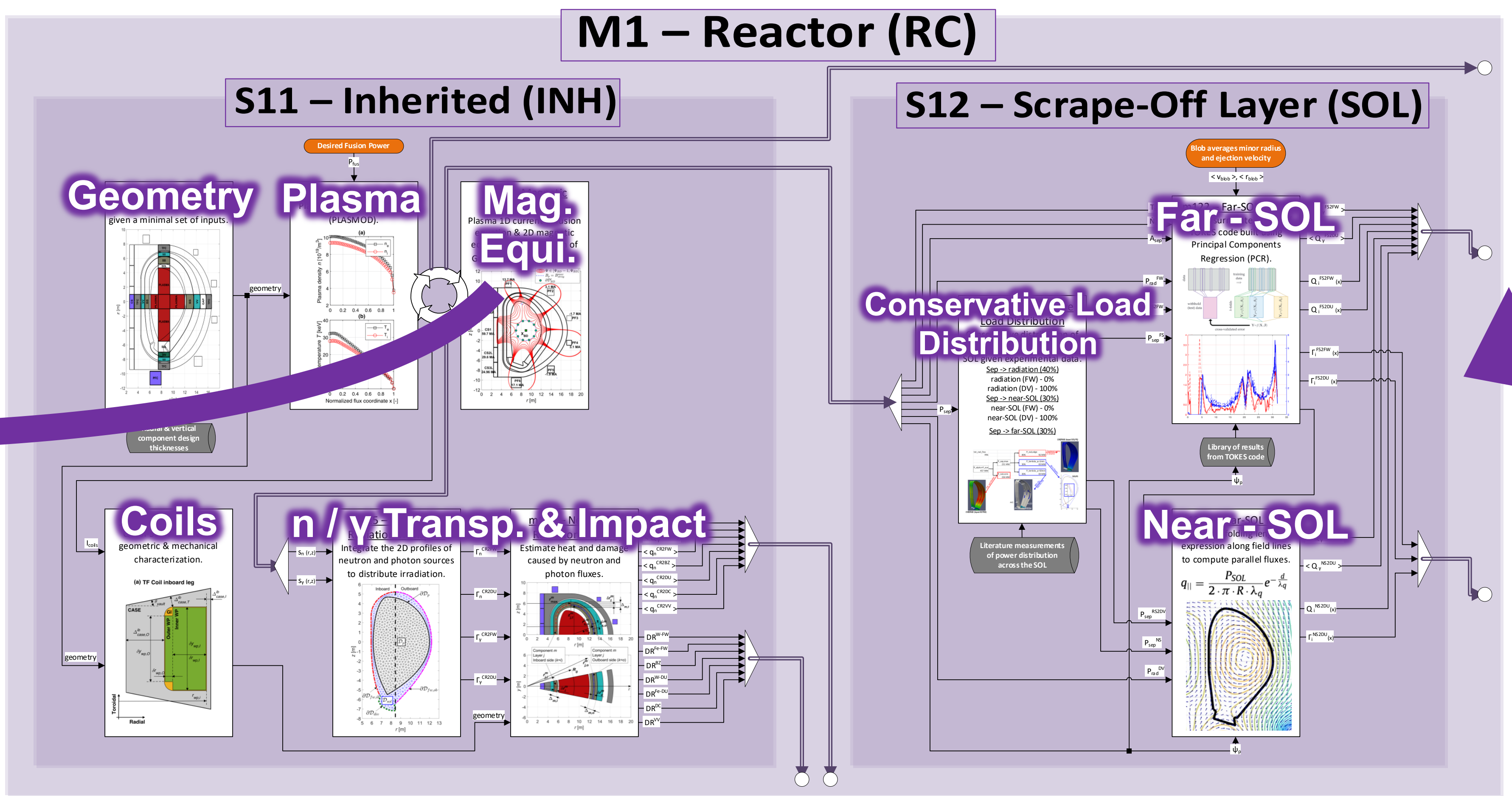
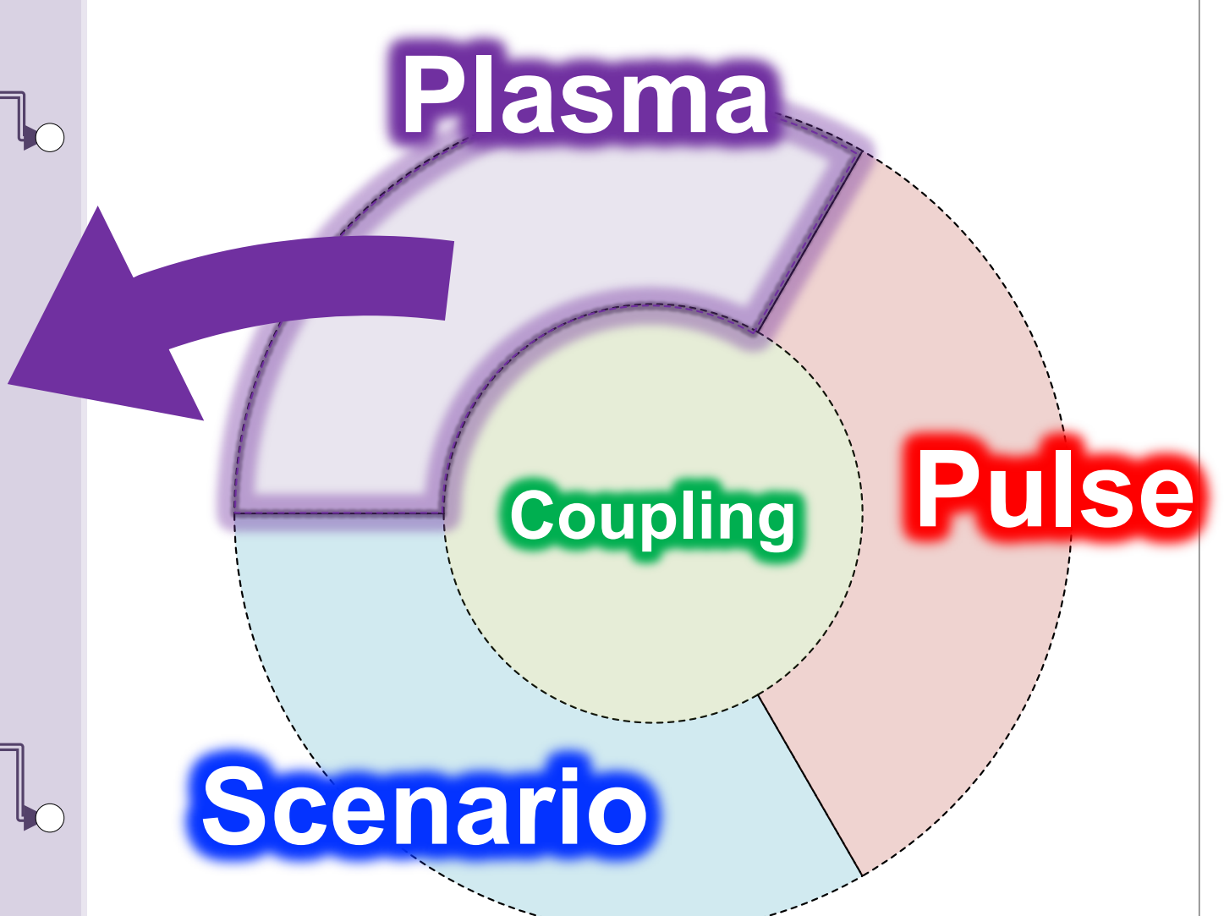
Context & Objectives

- ☐ Develop a **Multi-Timescale** implementation strategy for fusion power-plant systems-codes, using MIRA [1].
- ☐ Plasma timescale coupling: estimate **heat and particle loads** on the plasma chamber inner wall (FW & Divertor).
- ☐ This work: create surrogate model for **SOL** blob dynamics.

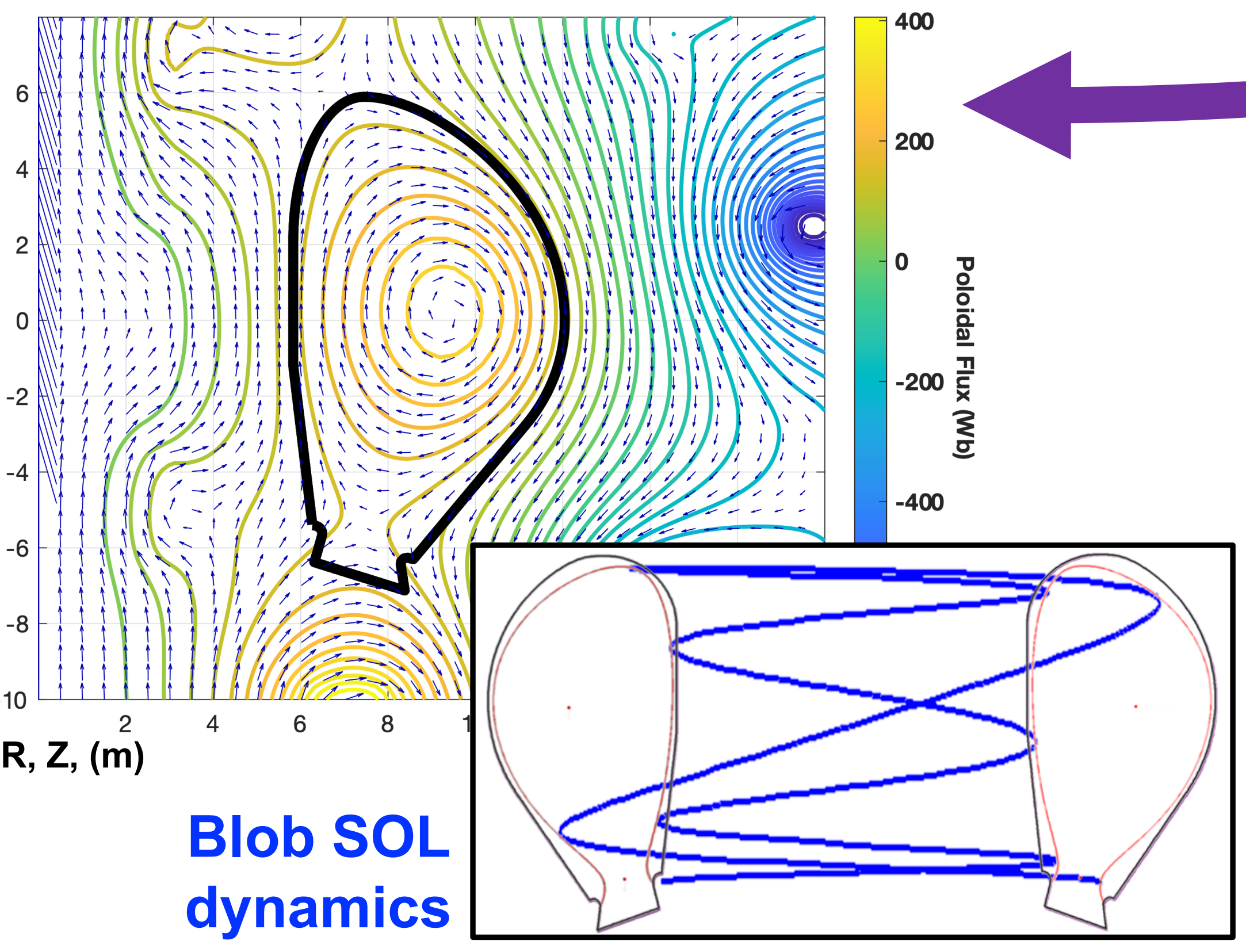
MIRA Process Flow Diagram (PFD)





Multi-Timescale Systems-Code

TOKES Code [2]



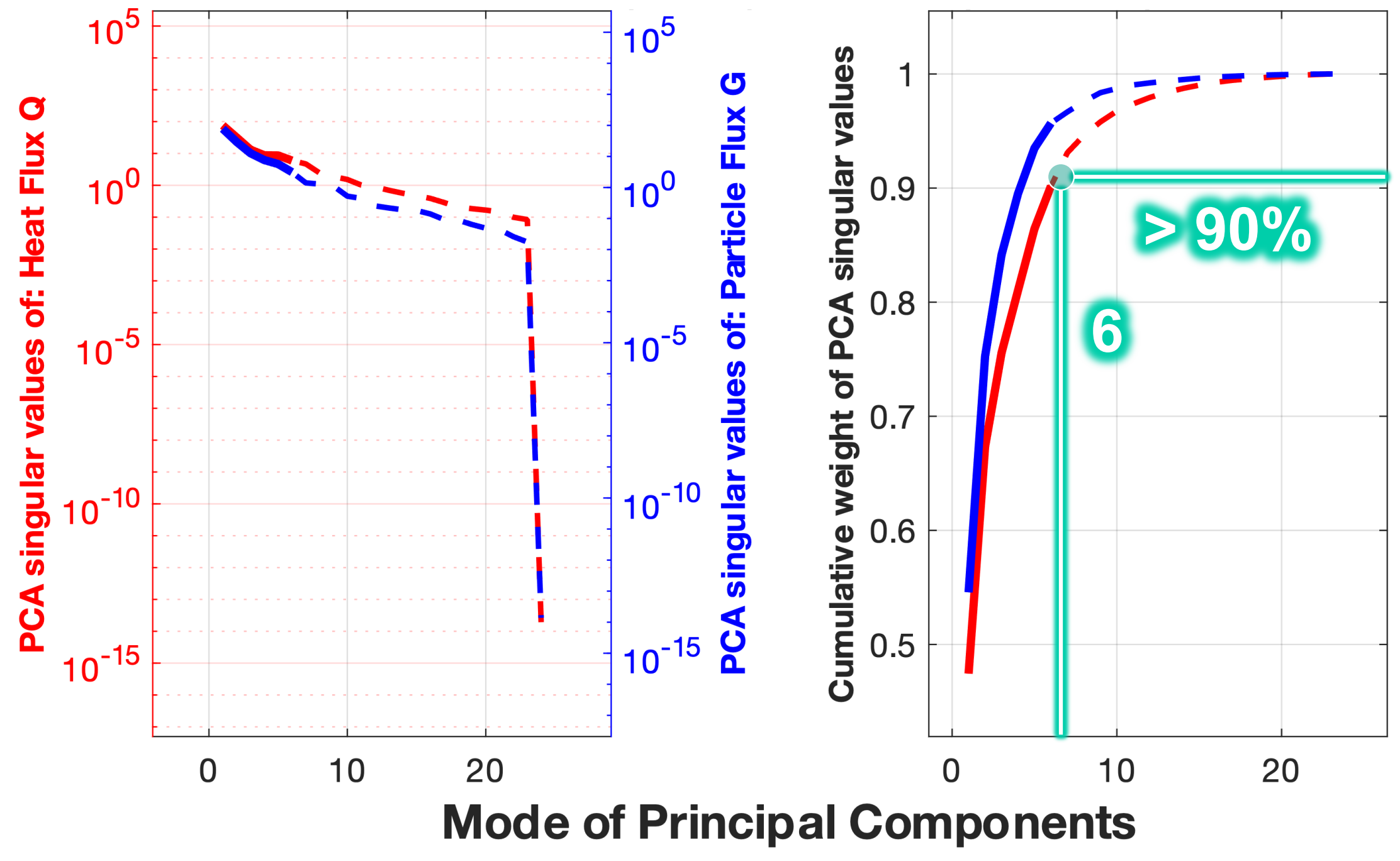
Blob SOL dynamics

- ☐ Calculates **blob dynamics** in SOL by coupling two timescales ($\tau_{\parallel}$ & $\tau_{\perp}$) to compute heat and particle flux distributions, for a set of blob parameters **(T,N,V)**.
- ☐ Requires **poloidal flux** map (S11–INH submodule).

TOKES PCA

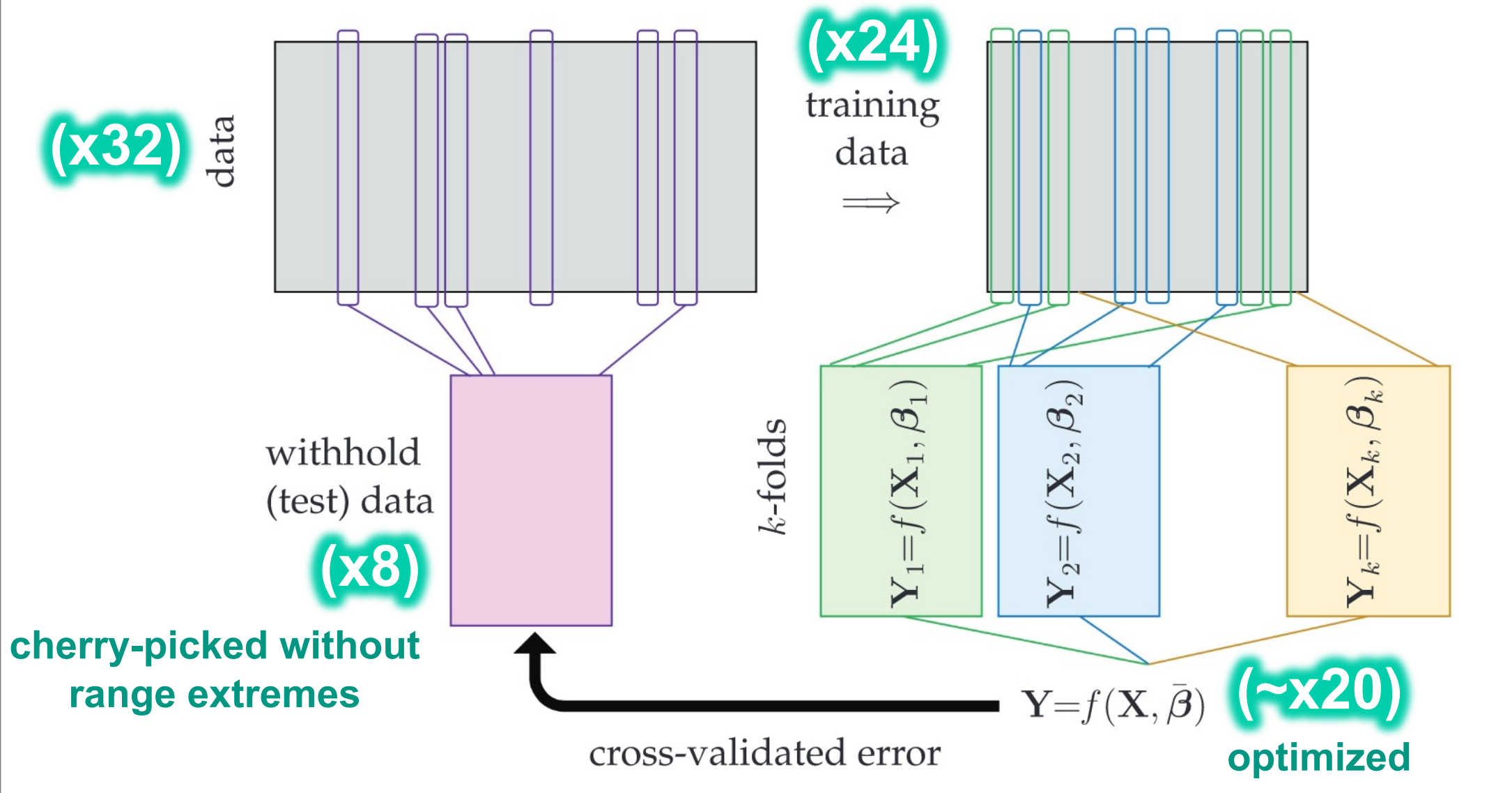
- ☐ Library of 32 cases, combinations of:
  - T ∈ [100, 300, 1000, 3000] temperature (eV)
  - N ∈ [10^{19}, 10^{20}] density (1/m^3)
  - V ∈ [100, 200, 500, 1000] ejection speed (m/s)
- ☐ Principal Components Analysis (**PCA**) identifies "**eigenvectors**" of the standardized distributions.
- ☐ **Truncation** is chosen by taking set of modes that represent more than **90%** of the data variance.

Model comparison: untrimmed (dashed) X truncated (continuous).



TOKES PCR

- ☐ Apply **regression** on mode distributions vs. simulation (blob) parameters to derive a surrogate model.
- ☐ Use **k-fold cross-validation** [3] when building matrix of regression parameters to avoid overfitting:

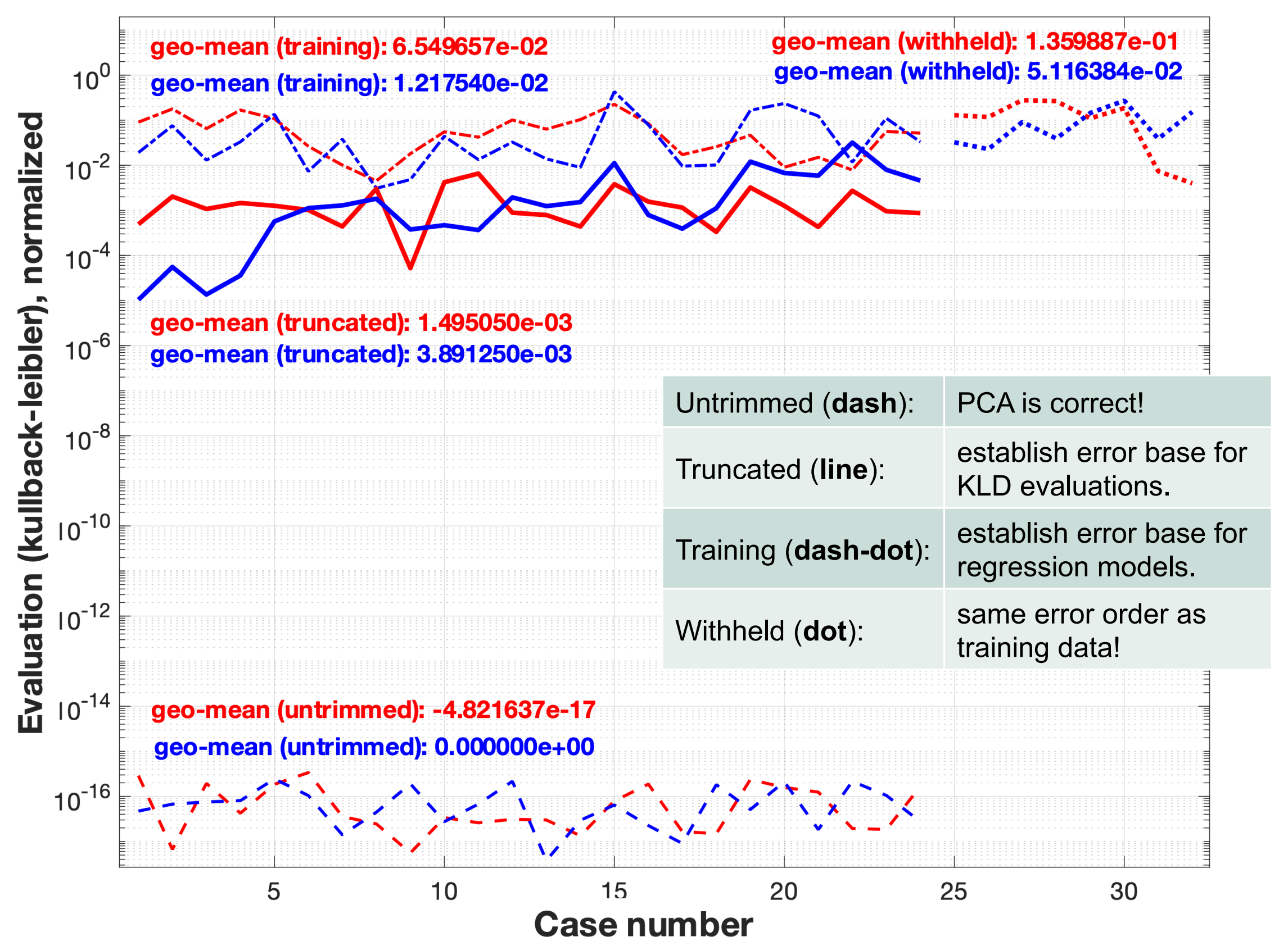


- ☐ Methodical model evaluation with the **Kullback-Leibler Divergence** (KLD) and variants (Jensen-Shannon, Jeffreys), from Information Theory:

$$I(f,g) = \int f(\mathbf{X},\boldsymbol{\beta}) \log\left[\frac{f(\mathbf{X},\boldsymbol{\beta})}{g(\mathbf{X},\boldsymbol{\mu})}\right] d\mathbf{X}$$

f: data
g: model

Model evaluation comparison, case-by-case

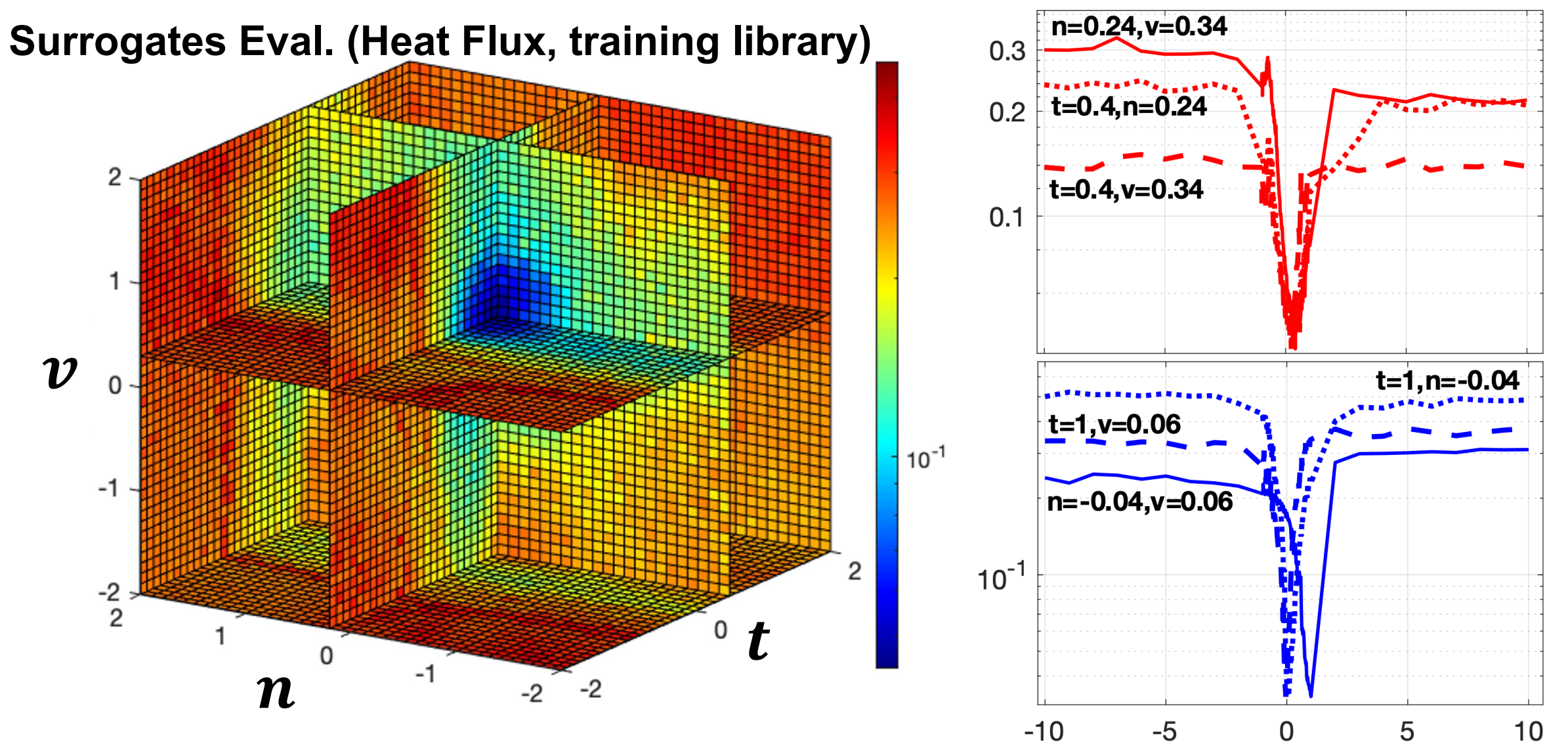


Untrimmed (**dash**):	PCA is correct!
Truncated (**line**):	establish error base for KLD evaluations.
Training (**dash-dot**):	establish error base for regression models.
Withheld (**dot**):	same error order as training data!

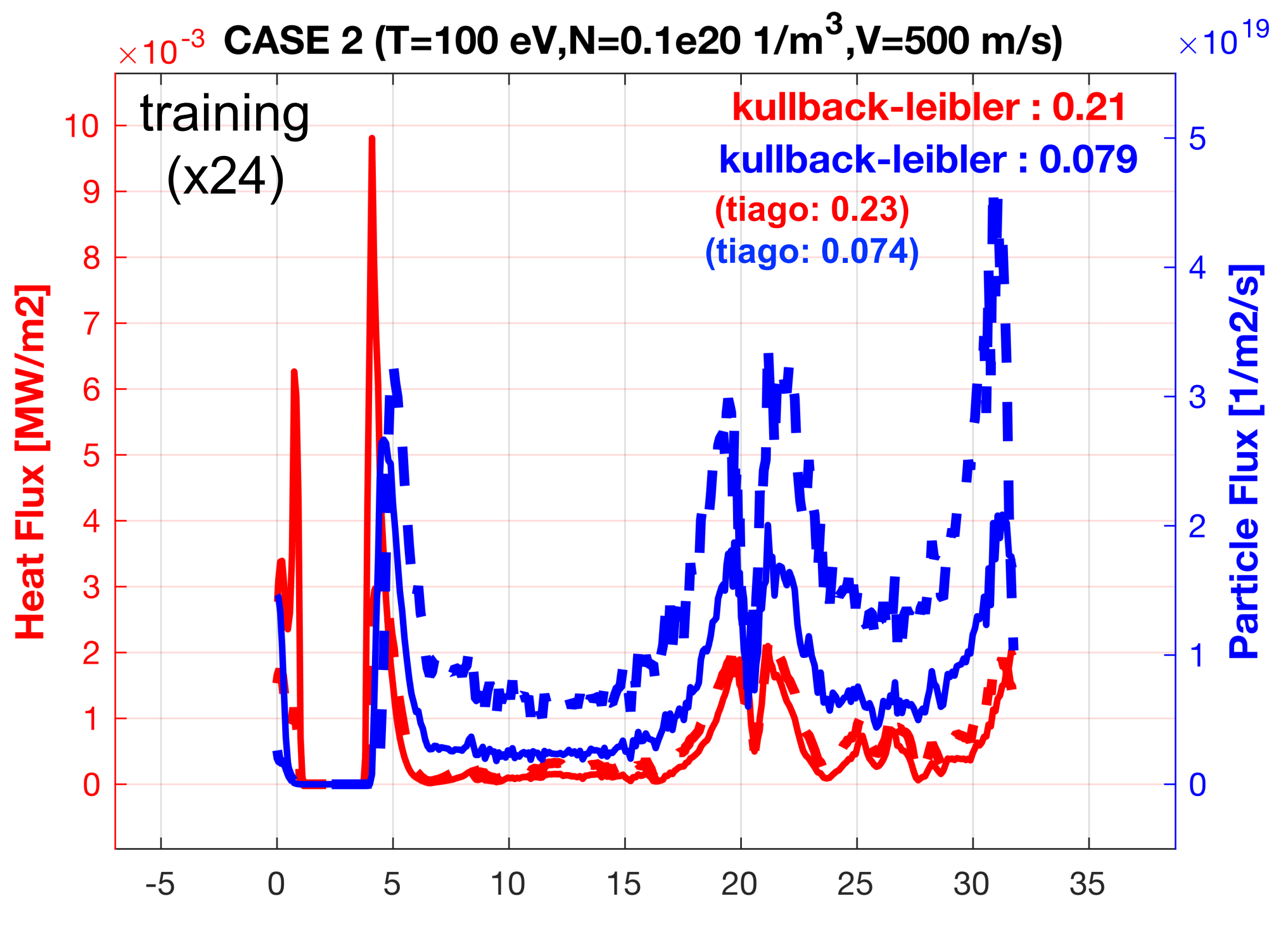
TOKES-Transform PCR

- ☐ **Transform** data ($X \cdot T^t \cdot N^n \cdot V^v$) before PCA / PCR to potentially find a linear basis for regression, *i.e.* find flux distributions dependencies to blob parameters: novel!
- ☐ To each set (t,n,v): create surrogate and apply geometric avg. (⇐ logscale) to all KDL cases to **evaluate full library**.

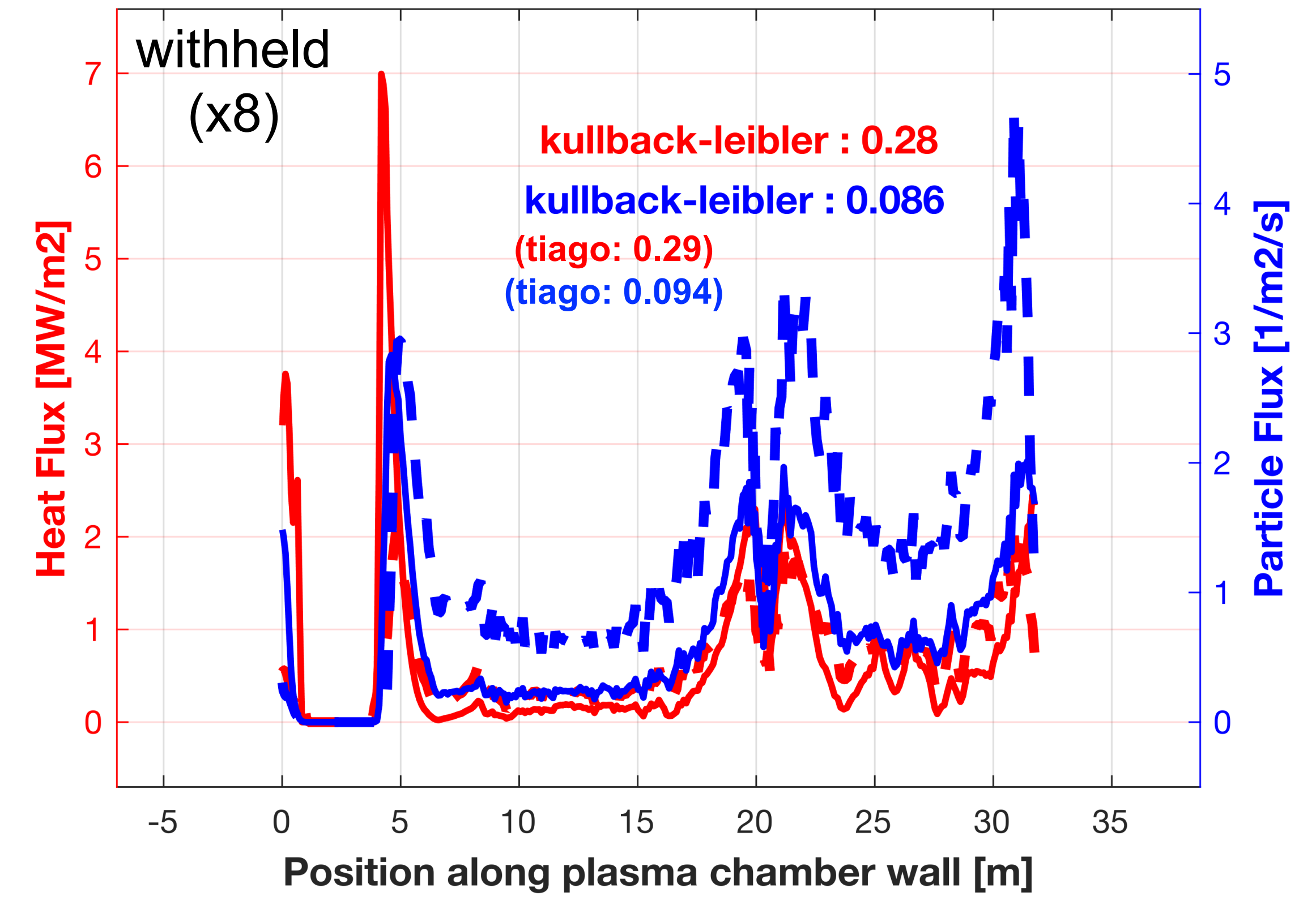
Surrogates Eval. (Heat Flux, training library)



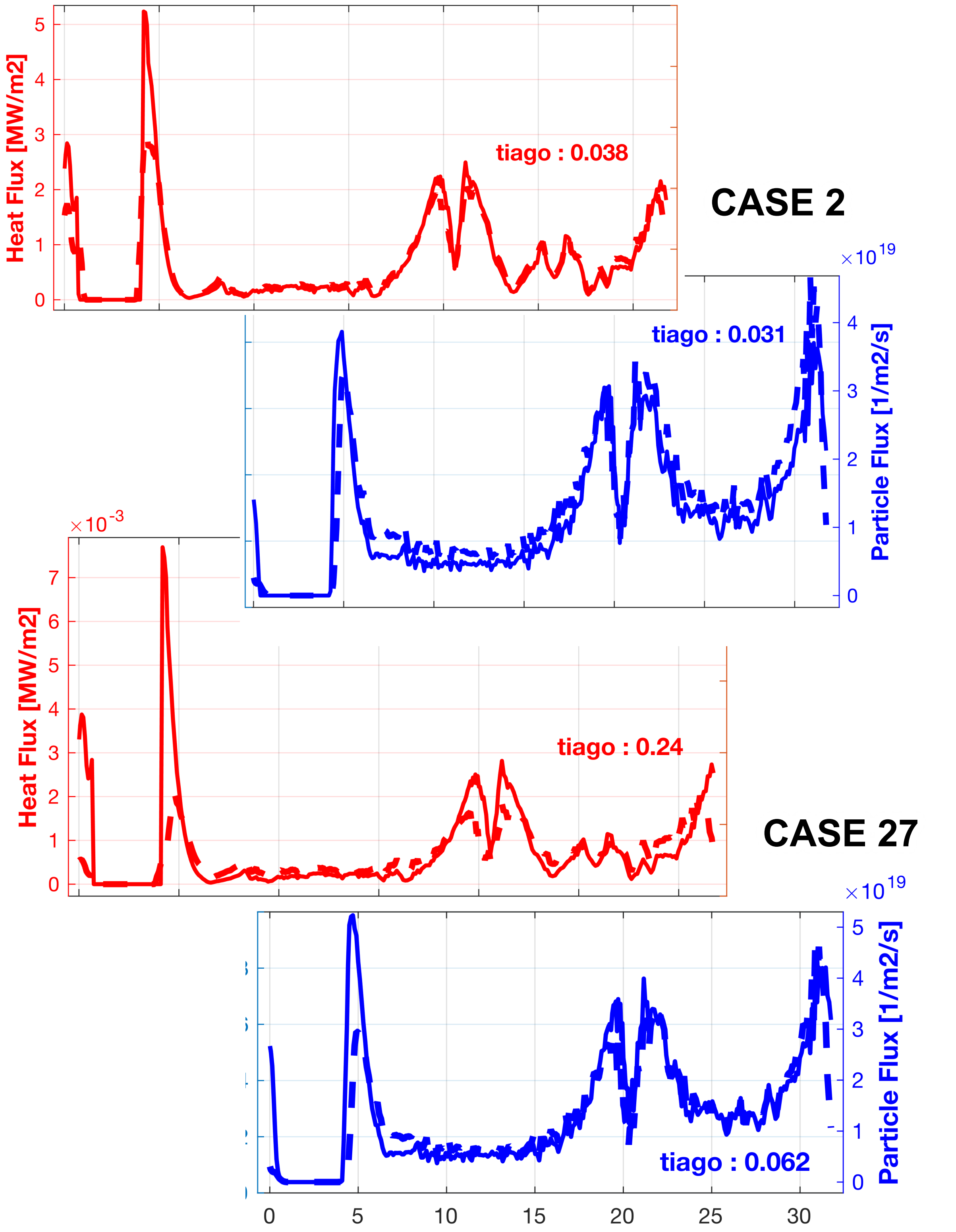
CASE 2 (T=100 eV,N=0.1e20 1/m^3,V=500 m/s)



CASE 27(T=100 eV,N=1e20 1/m^3,V=500 m/s)



CASE 2 (T=100 eV,N=0.1e20 1/m^3,V=500 m/s)



- ☐ Use regression model to estimate cases in both training (**24 cases**) and withheld (**8 cases**) libraries.
- ☐ Distributions must be normalized to total transport power across separatrix computed by plasma model (S11) ⇒ computed shape > computed values.
- ☐ Total particle flow to Far-SOL follows from: $\Gamma_{FS} = N \cdot V$.

Conclusions & Outlook

- ☐ Linear **heat** flux basis: $(t,n,v) = (0.43,0.23,0.38) \pm 0.02$.
- ☐ Linear **particles** flux basis: $(t,n,v) = (1,-0.03,0.65) \pm 0.02$.
- ☐ Expand **transformation/evaluation basis** to potentially identify better dependency between blob parameters (T,N,V) and heat flux modes: develop higher-fidelity surrogate.
- ☐ MIRA sensitivity analysis to identify **systemic impact** of blob.

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[3] S.L. Brunton, J.N. Kutz, Data-Driven Science and Engineering: Machine Learning, Dynamical Systems, and Control, 1st ed., Cambridge University Press, 2019. https://doi.org/10.1017/9781108380690.

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