UK Atomic Energy Authority

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# Diagnosing Turbulence in the Tokamak Divertor

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SYSTEMS • ENGINEERING • TECHNOLOGY

# Acknowledgement

UK Atomic Energy Authority

The vast majority work described within this presentation was undertaken whilst working for the UKAEA funded by EPSRC and EUROfusion – my thanks to all of my friends, collaborators, and colleagues who contributed to this work during that time

# Overview

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**What is divertor turbulence, and why is it important?**

**Can we *understand* divertor turbulence?**

**Summary**

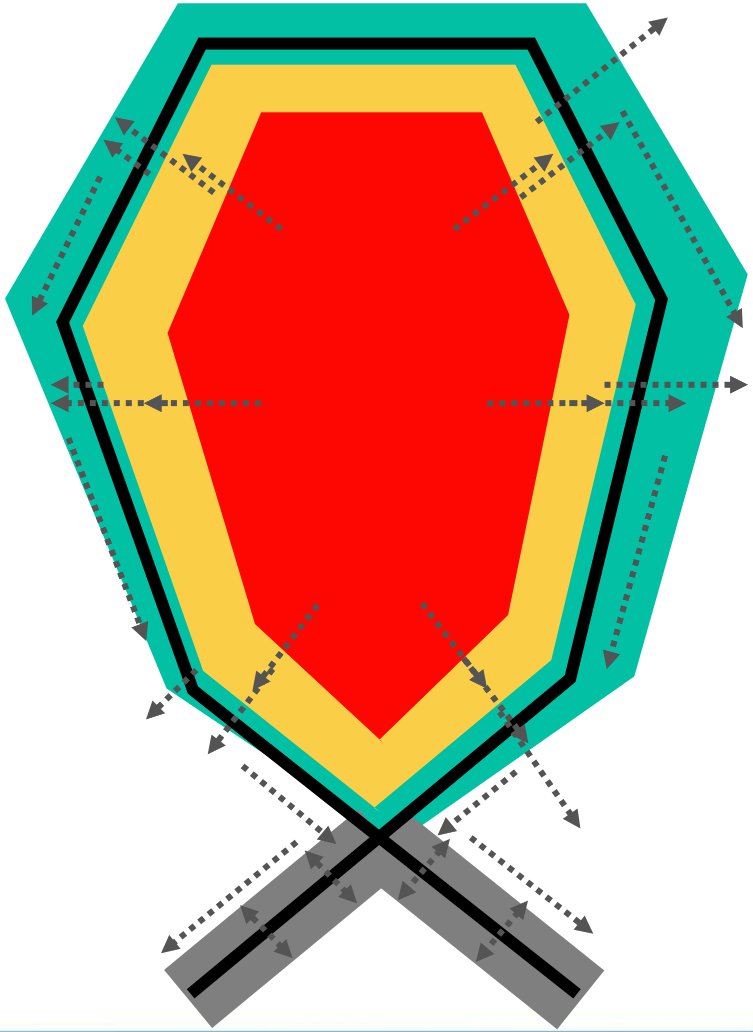
# Overview

**What is divertor turbulence, and why is it important?**

Can we *understand* divertor turbulence?

Summary

# A ’Cubists’ view of heat transport



→ Core turbulence moves heat towards the edge determining the core pressure

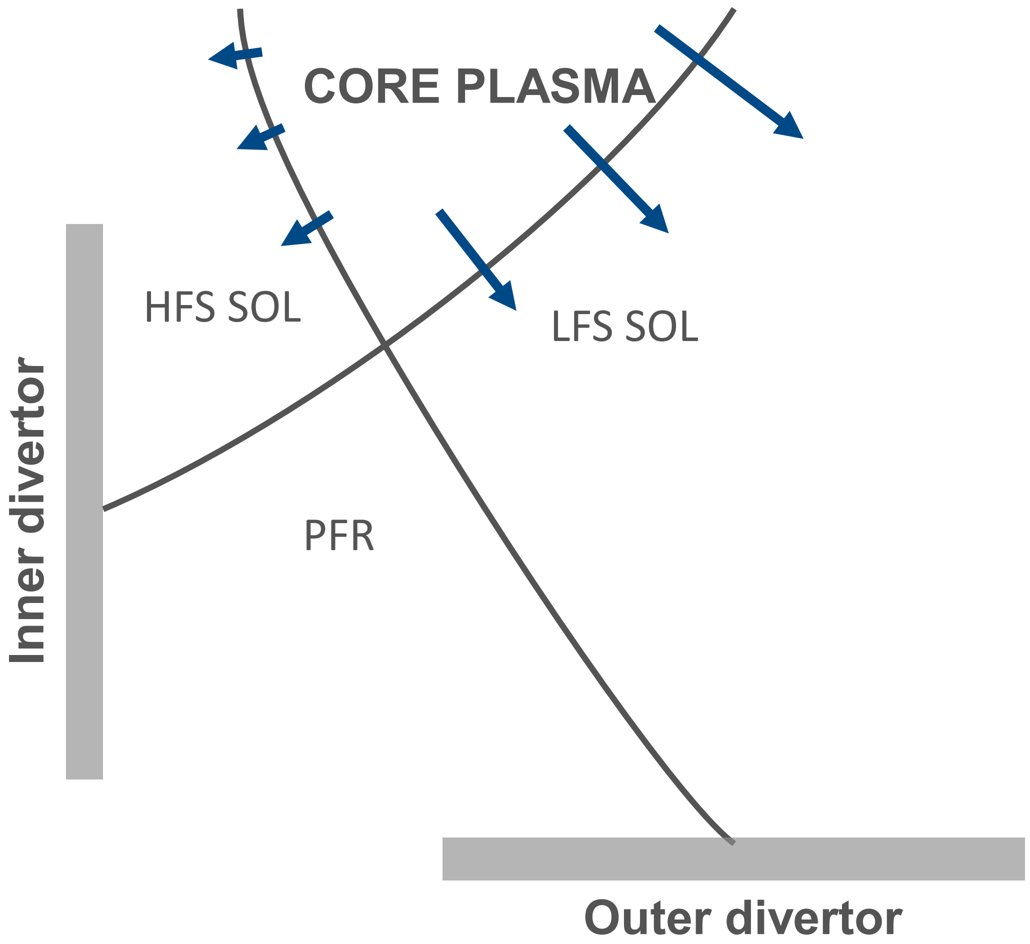
→ Pedestal turbulence moves heat towards the separatrix determining the pedestal characteristics

→ Edge/Scrape-off layer turbulence moves heat onto open fieldlines determining the SOL width

→ **Divertor turbulence re-distributes heat in the divertor legs impacting deposition on the divertor target**

**Well established physics basis**

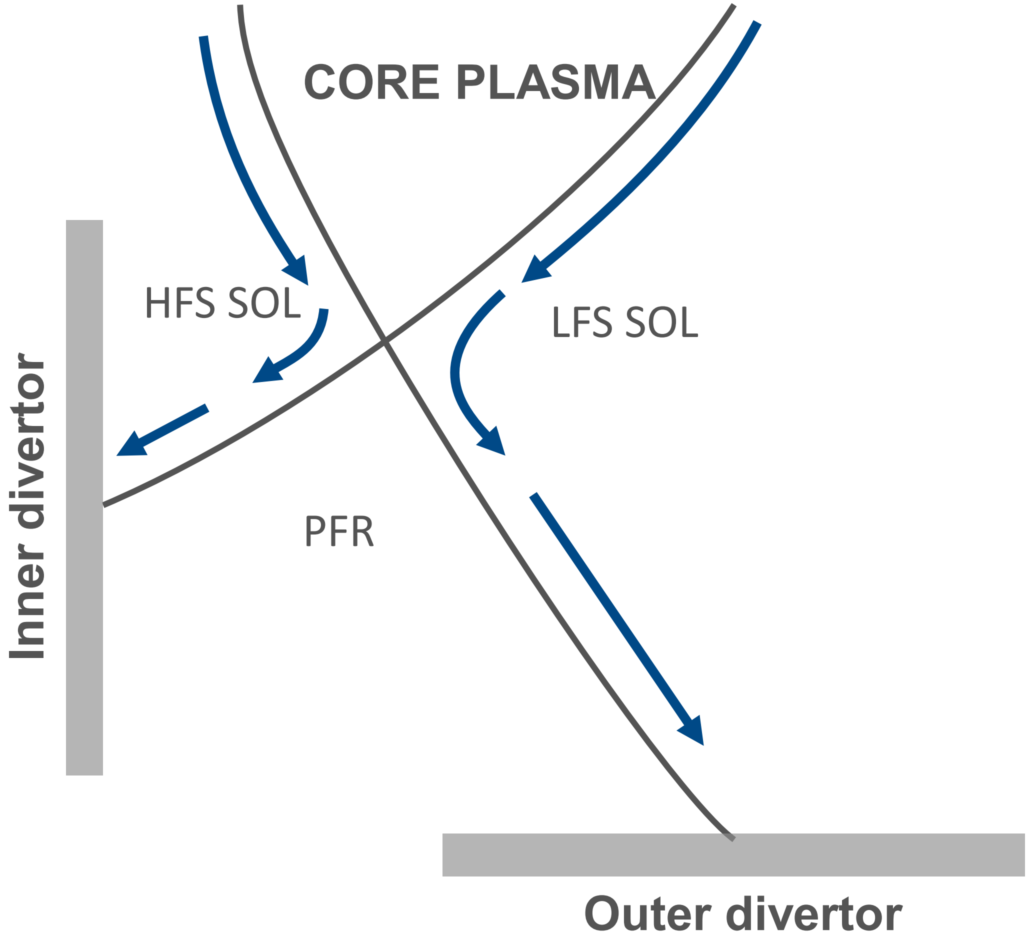
# Importance of divertor transport




**Transport processes that impact the divertor:**

- Cross-field transport from the core into the scrape-off layer

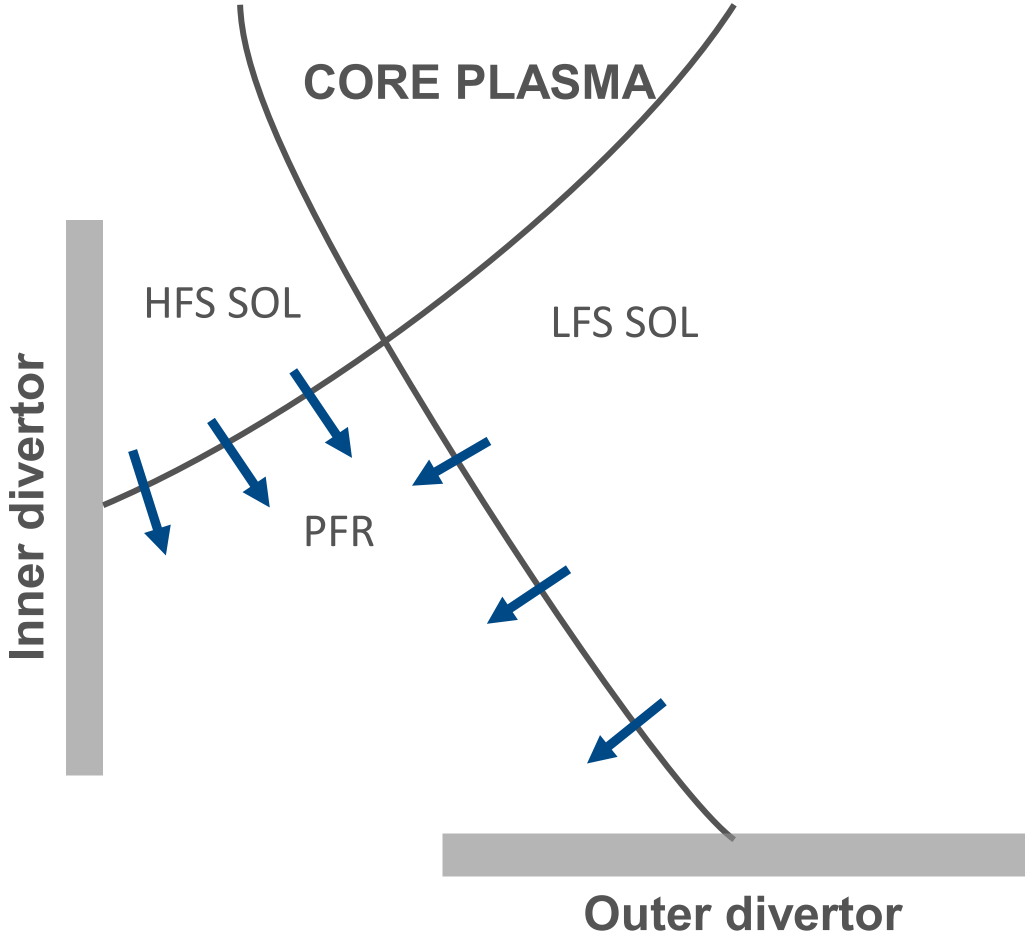
# Importance of divertor transport




**Transport processes that impact the divertor:**

- Cross-field transport from the core into the scrape-off layer
- Parallel transport towards the divertor plates

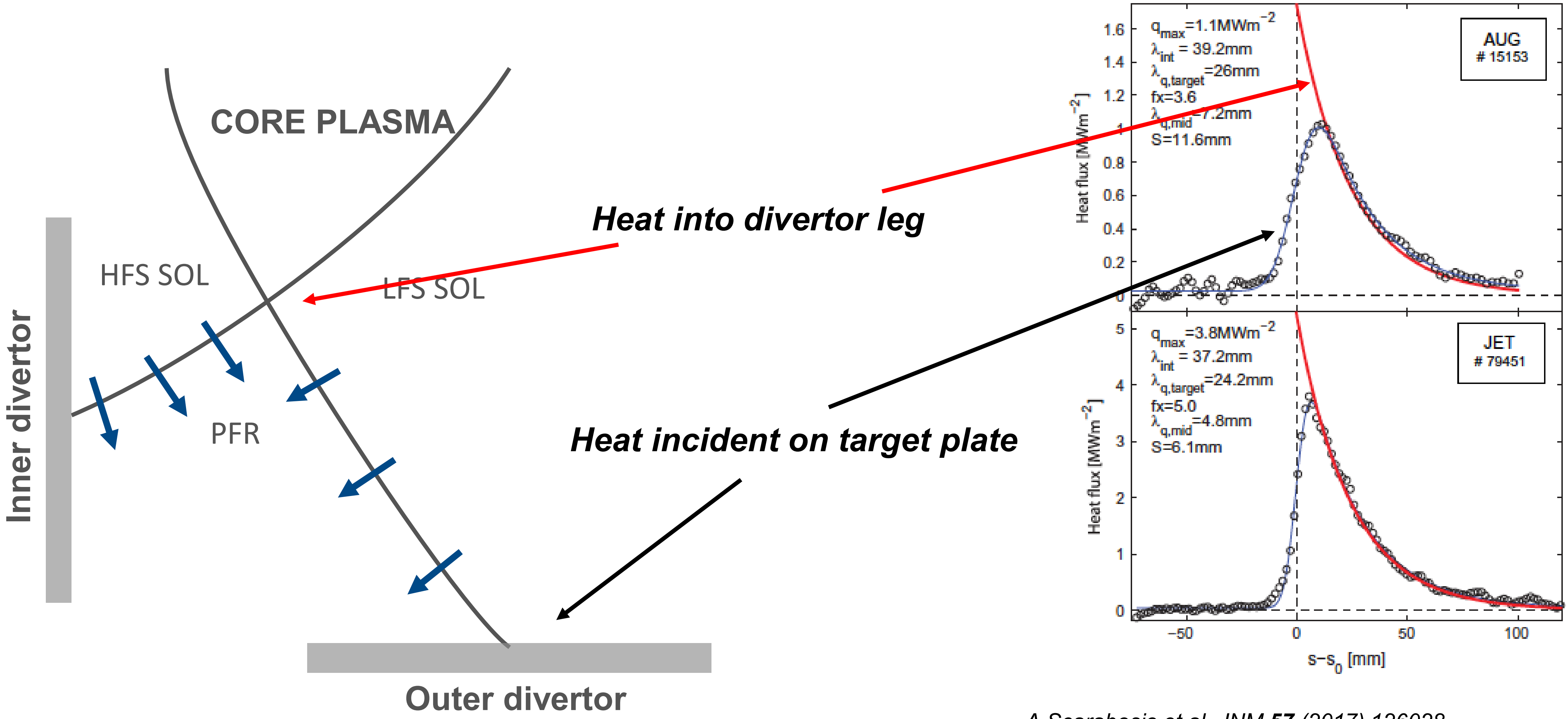
# Importance of divertor transport




**Transport processes that impact the divertor:**

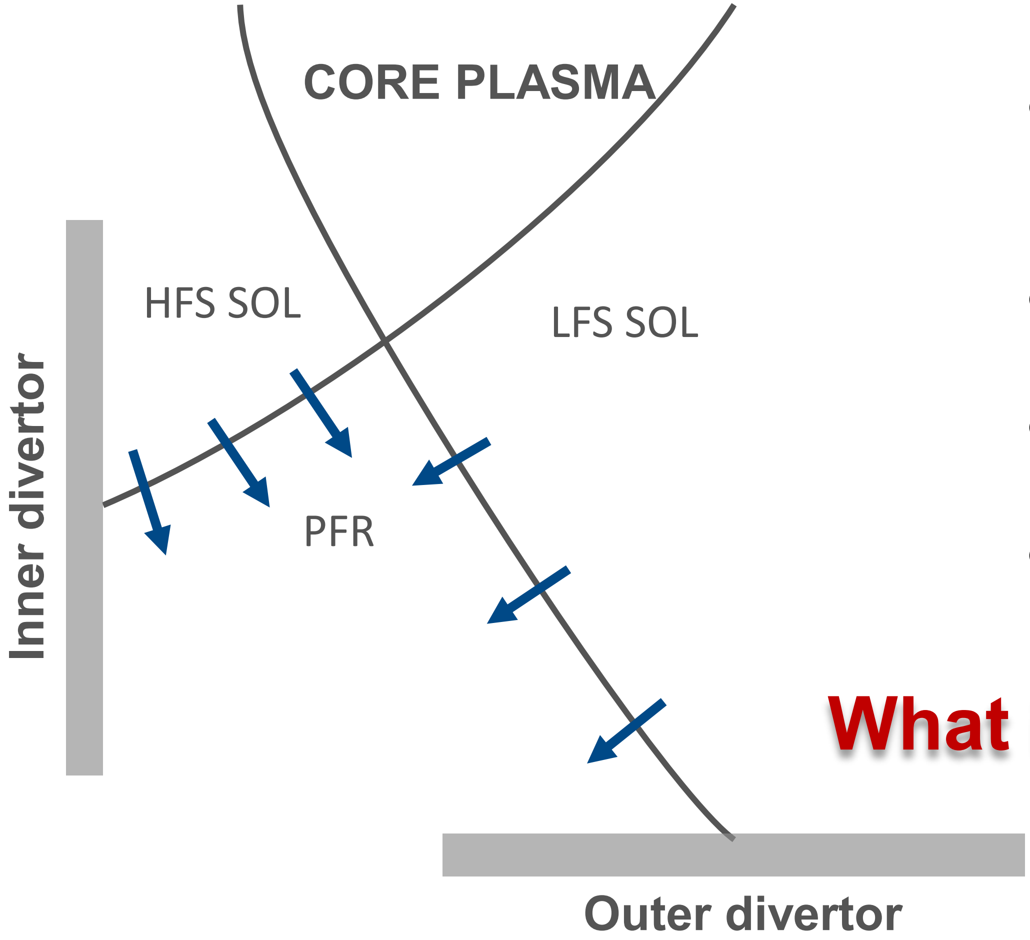
- Cross-field transport from the core into the scrape-off layer
- Parallel transport towards the divertor plates
- **Cross-field transport from the SOL into the PFR**

# Importance of divertor transport




*A.Scarabosio et al, JNM* ***57*** *(2017) 126028*

# Importance of divertor transport

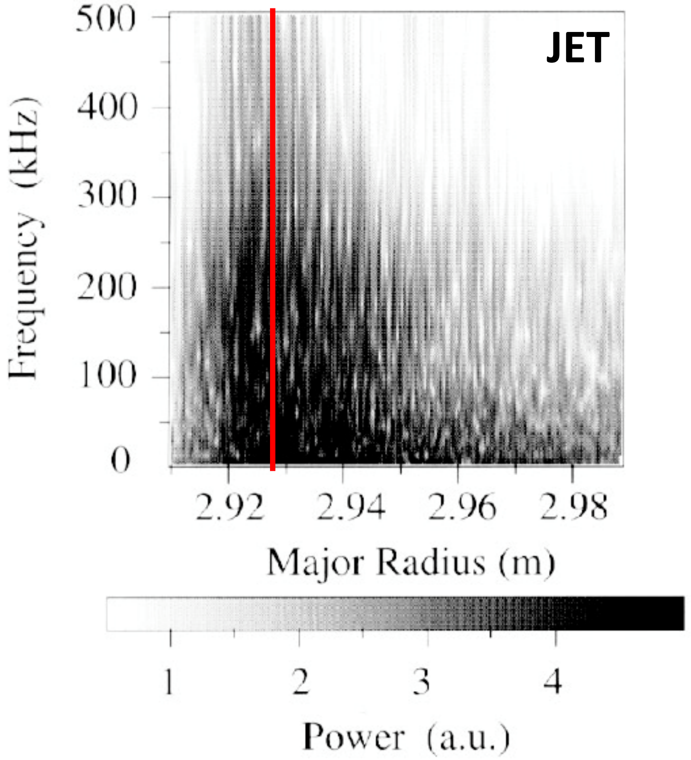



**Divertor transport affects:**

- The peak steady-state power hitting the divertor plate
- Detachment onset
- Helium pumping
- Peak ion temperature at the divertor

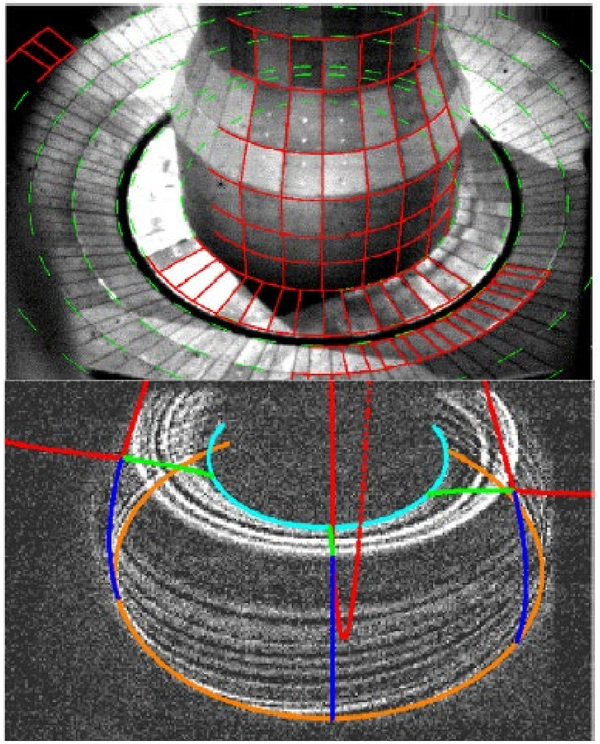
**What is the origin of divertor transport?**

# Overview of observations around the world



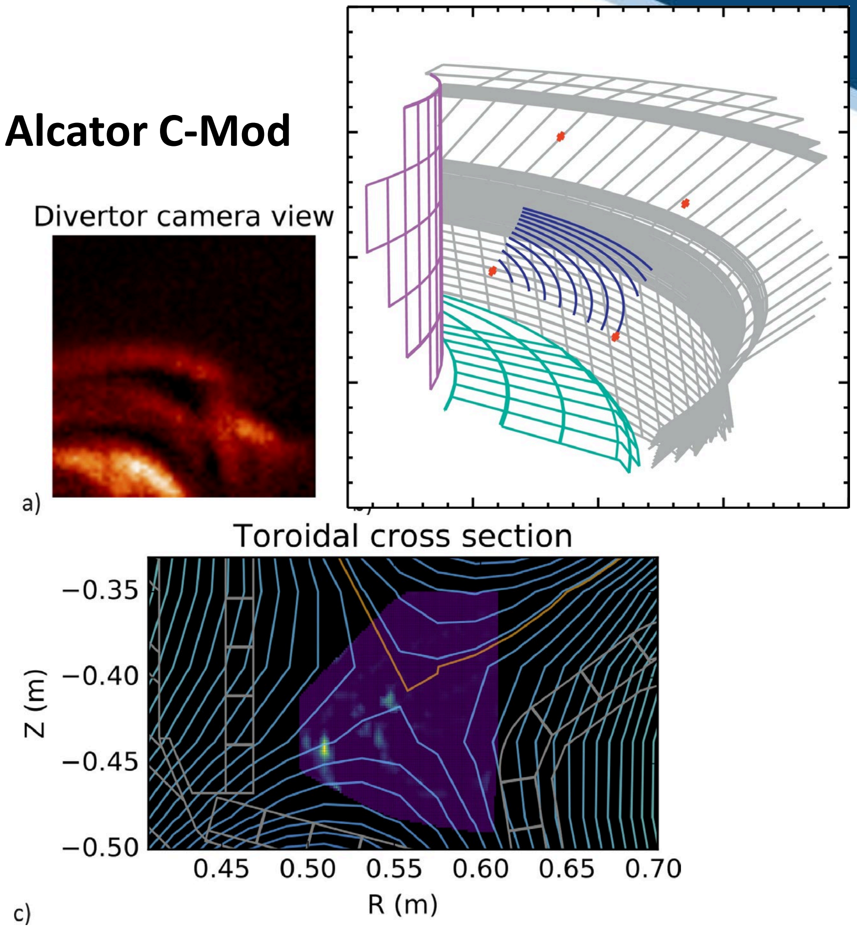

*I.Garca-Cortes et al, PPCF **38** (1996) 2051*

**NSTX-U**



*F.Scotti et al, NF **58** (2018) 126028*

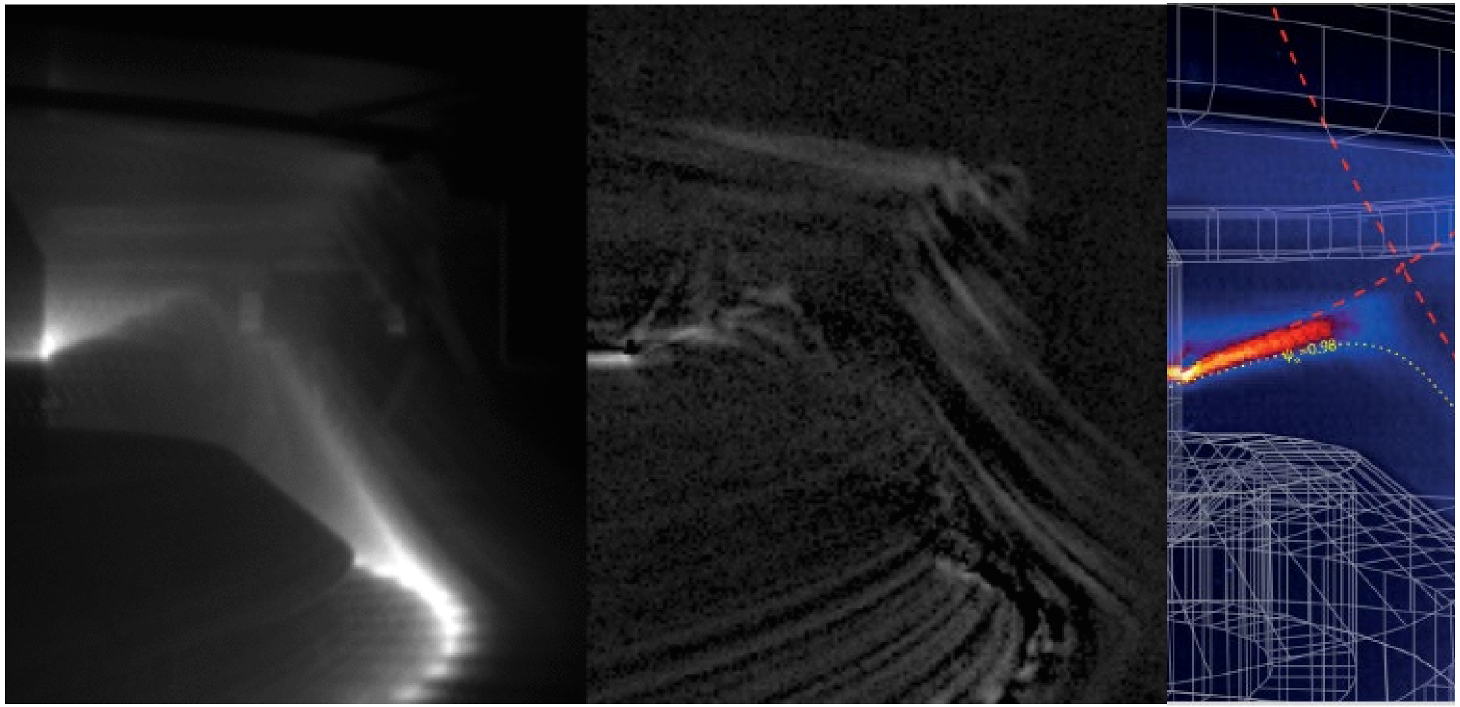
**Alcator C-Mod**



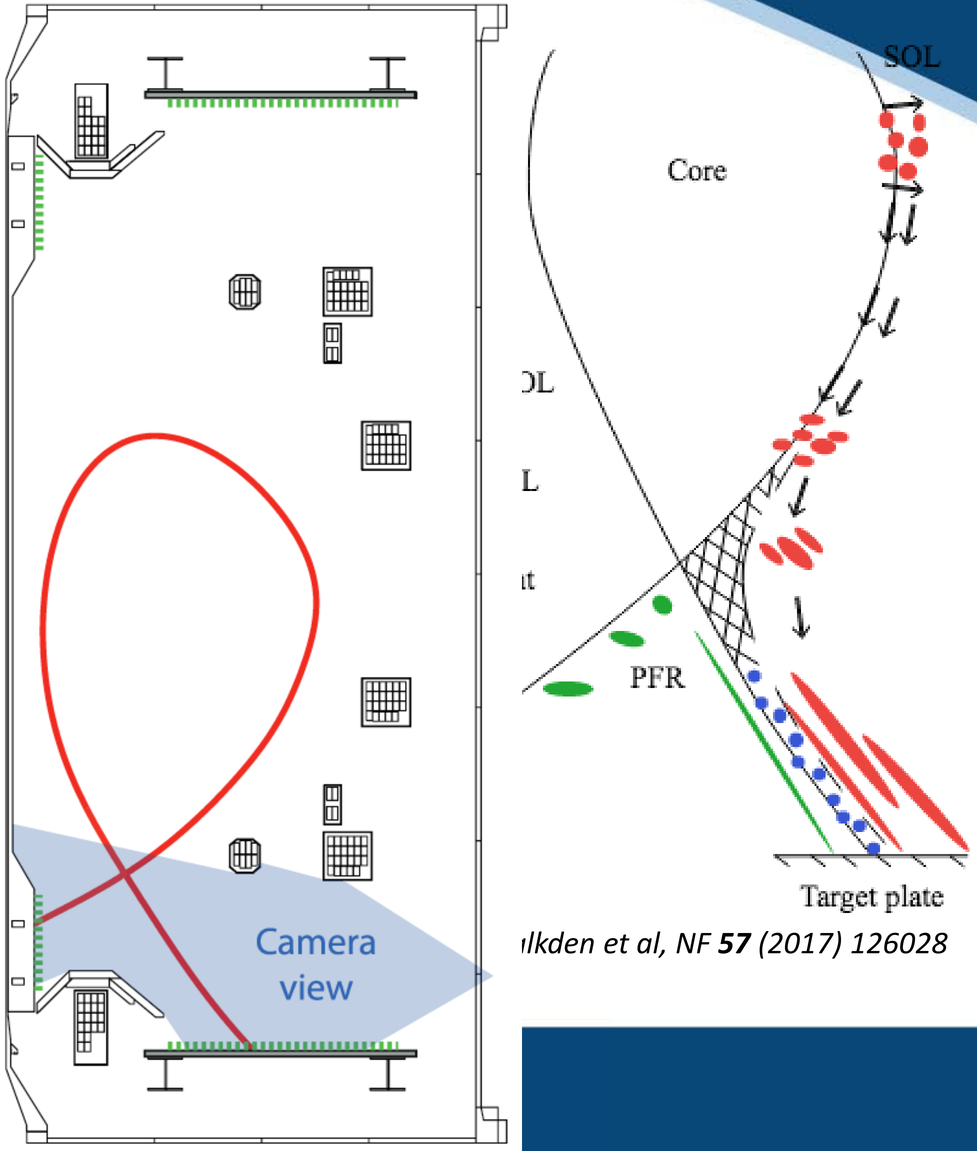

*S.Ballinger et al, NME **17** (2018) 269*

# Overview of observations around the world

**MAST**



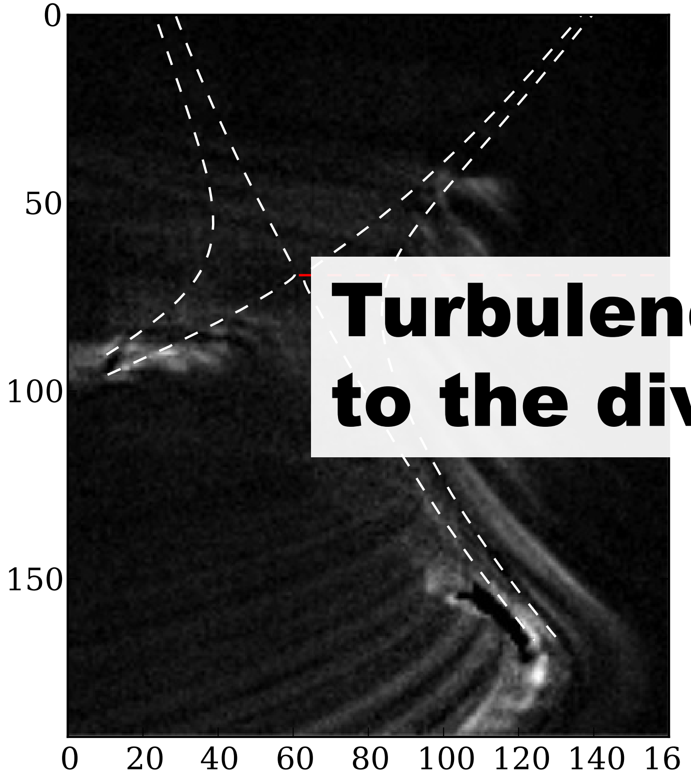
*J.Harrison et al, PoP **22** (2015) 092508*

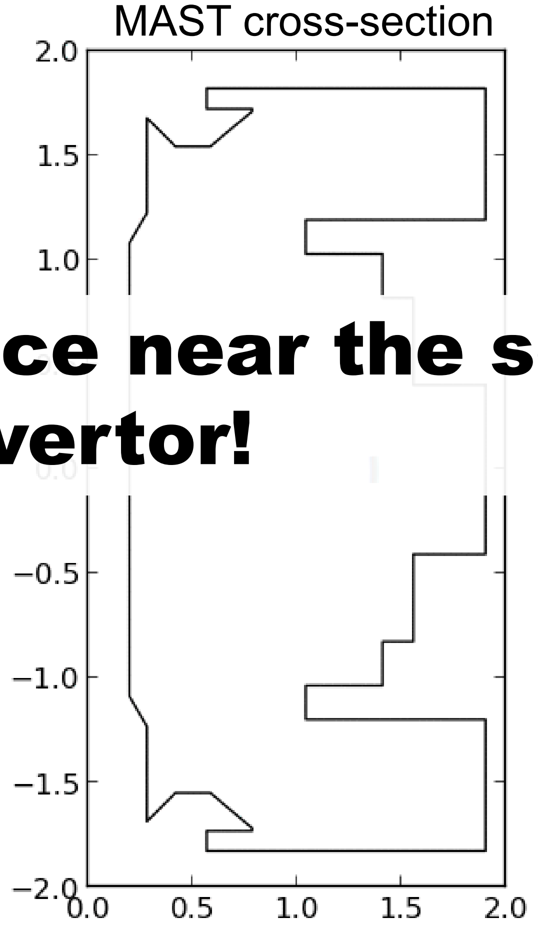


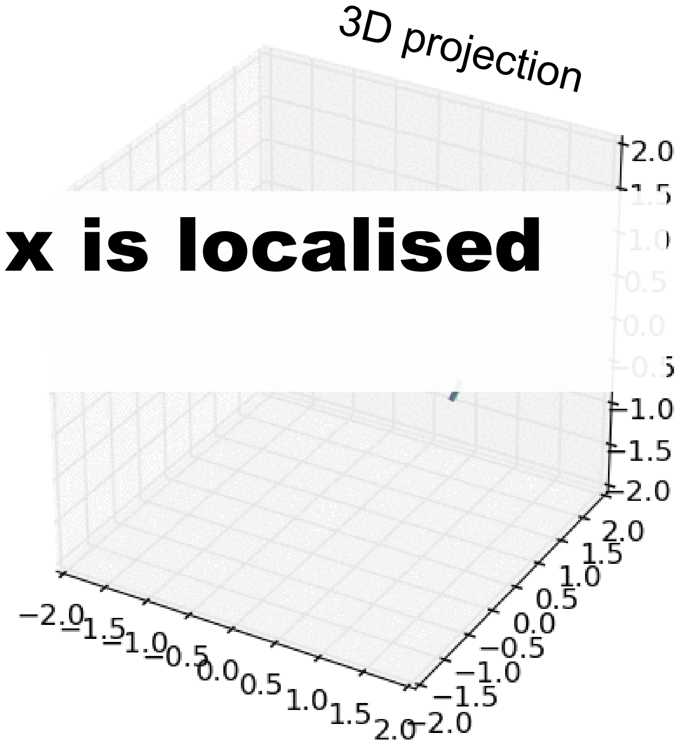

*lkden et al, NF **57** (2017) 126028*

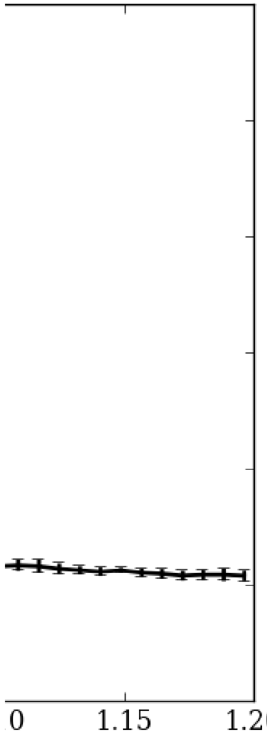
# Effect of the X-point

**Near the X-point, fluctuations from upstream are unable to enter the divertor**





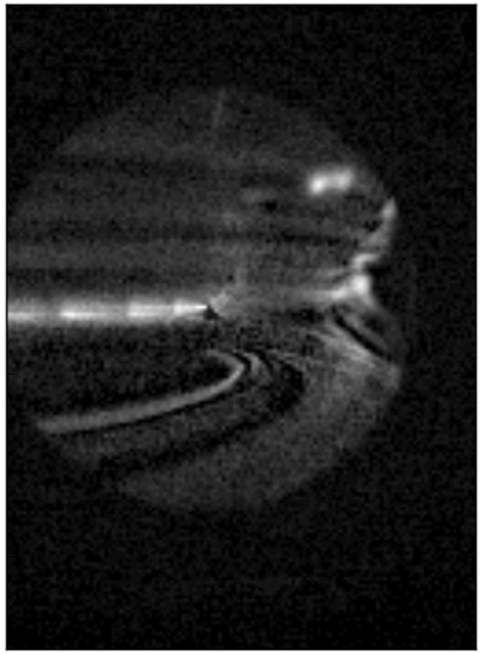



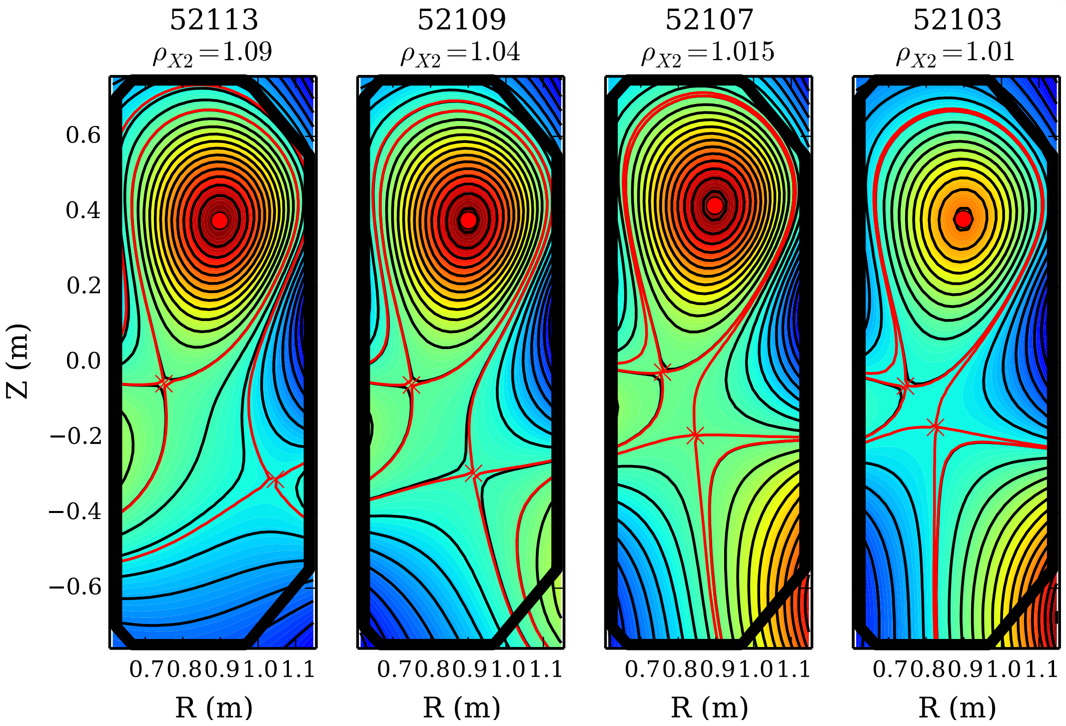
**Turbulence near the separatrix is localised to the divertor!**

*N.R.Walkden et al, NME **12** (2017) 175*

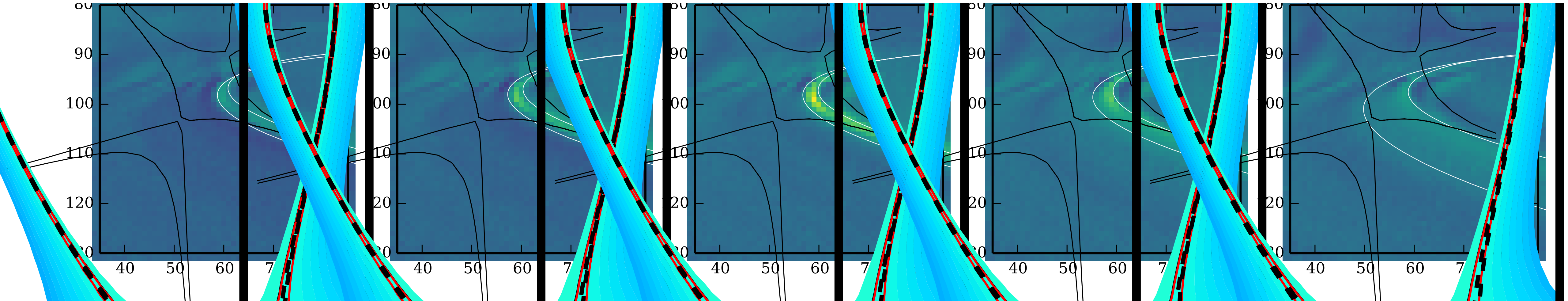
*N.R.Walkden et al, NF **57** (2017) 126028*

# Example from TCV snowflake plasmas






N.R.Walkden et al, *PPCF* ***60*** *(2018) 115008*



# Overview

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What is divertor turbulence, and why is it important?

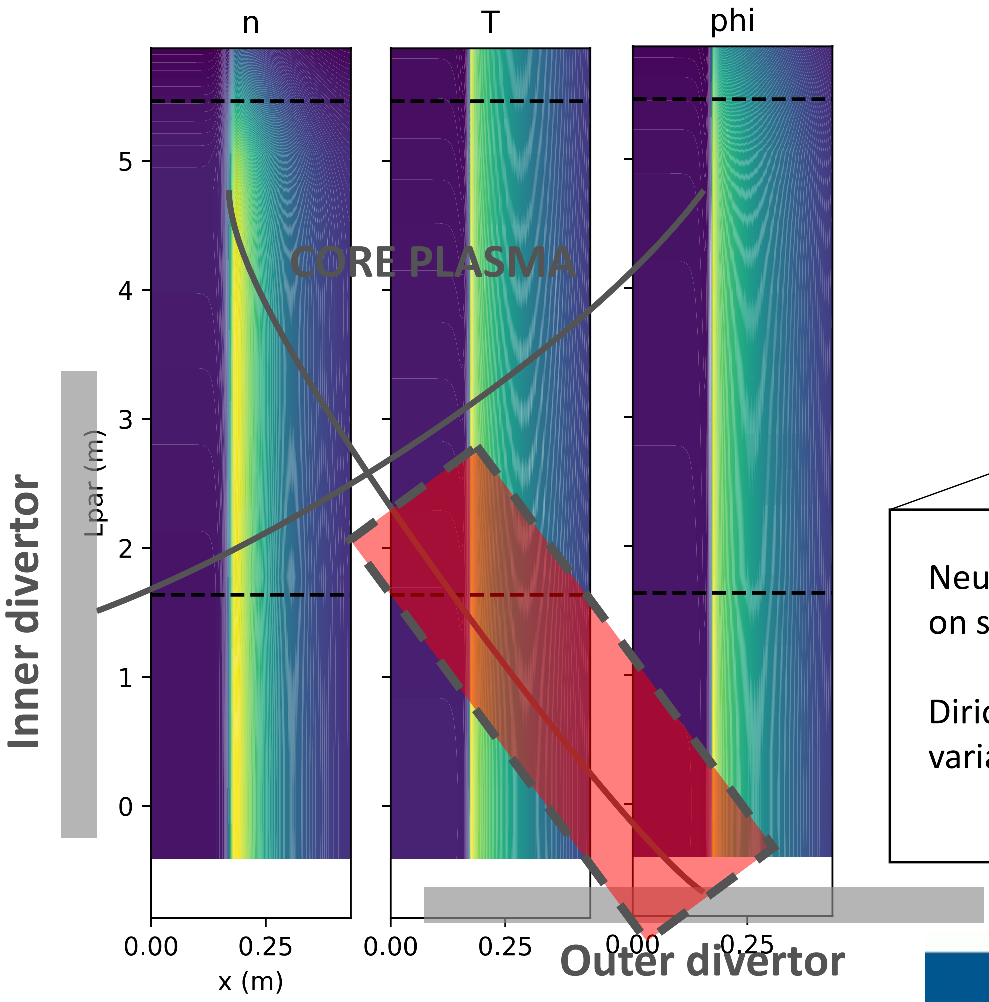
**Can we *understand* divertor turbulence?**

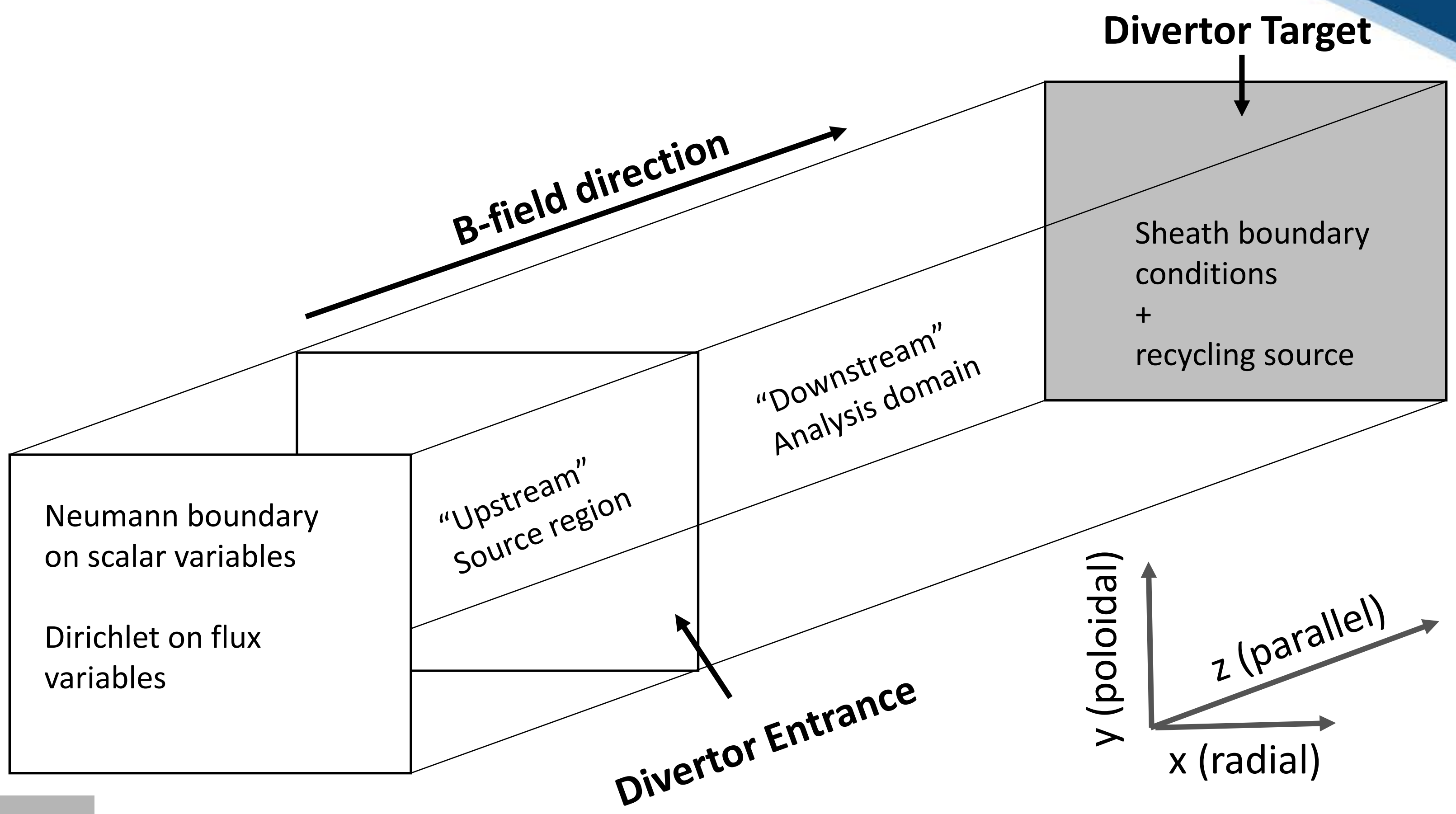
Summary

# STEP 1: ‘Mock-Divertor’ slab simulations

**For a first non-linear study, try to minimize the complexity to aid understanding**

**→ Simple slab representation of a single, isolated divertor leg**

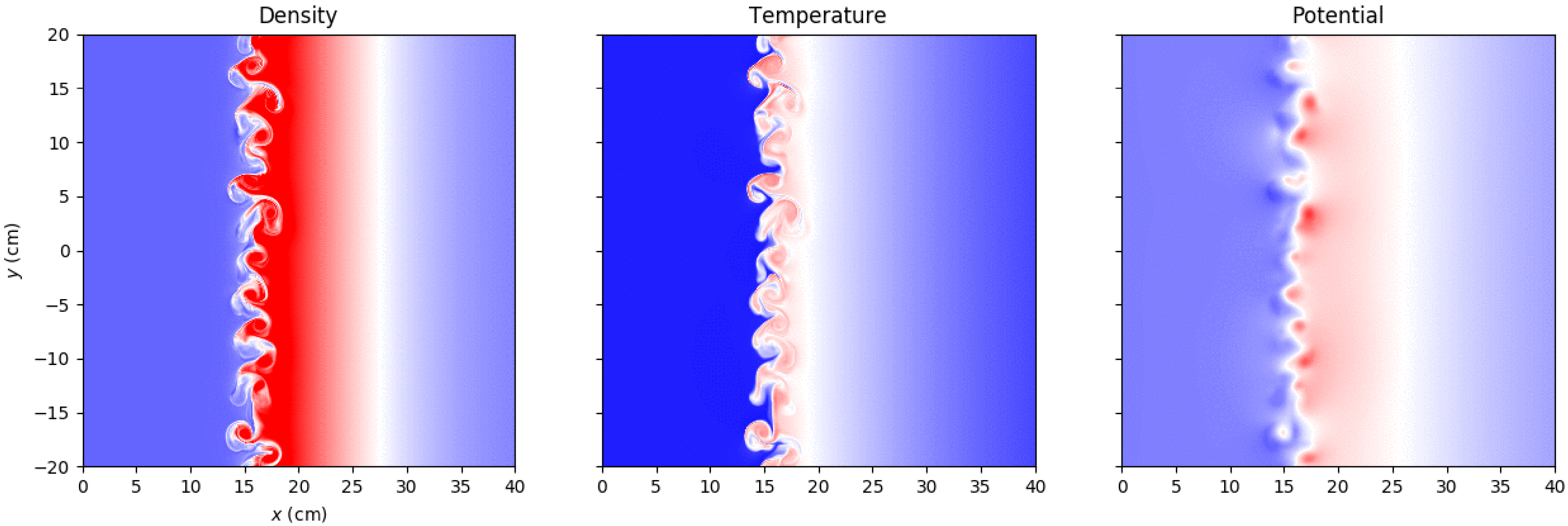



*N.R.Walkden et al, NME **18** (2019) 111*

# STEP 1: ‘Mock-Divertor’ slab simulations

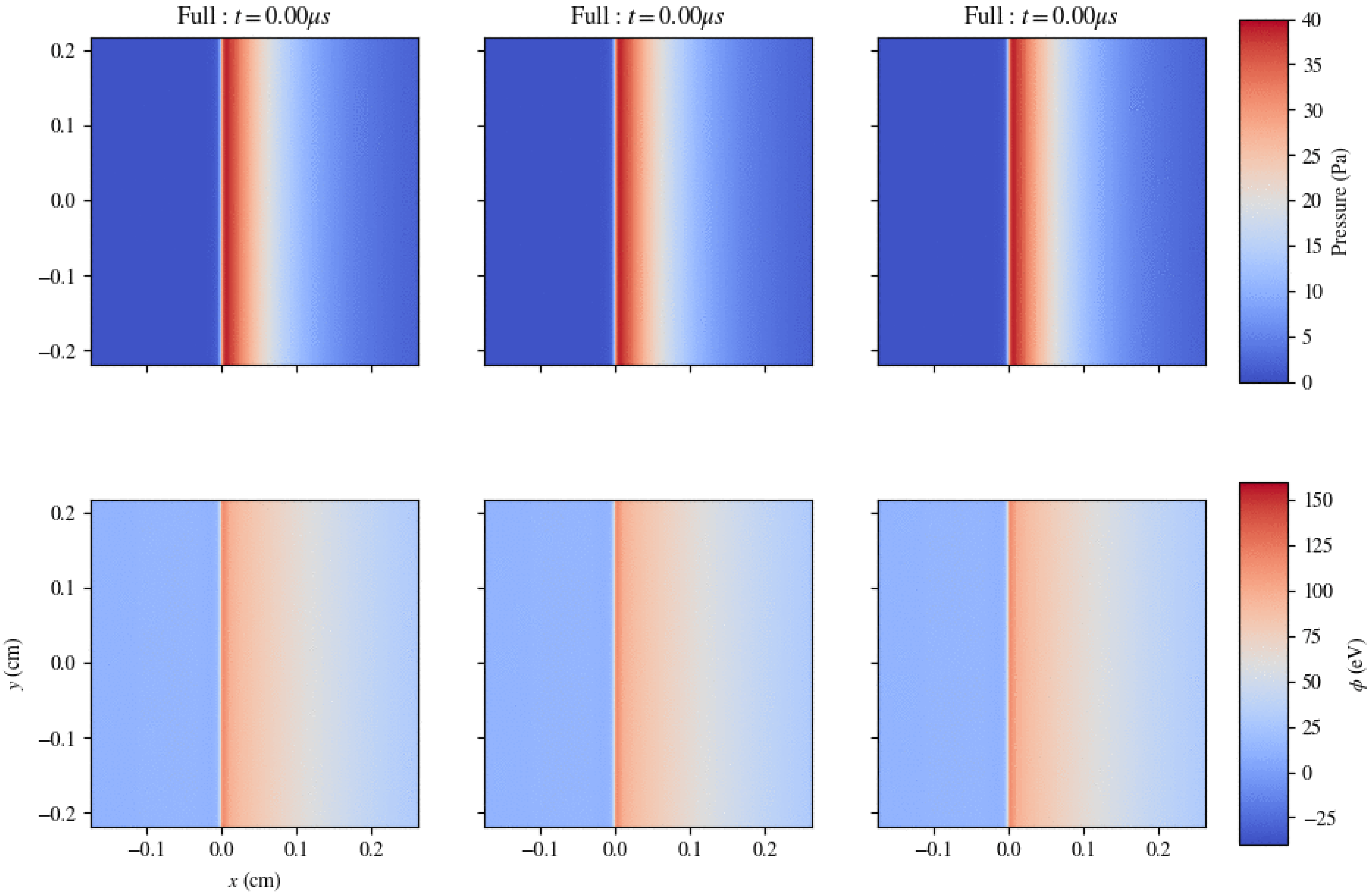
**Turbulence quickly develops in the vicinity of the separatrix**






*N.R.Walkden et al, NME **18** (2019) 111*

# STEP 1: ‘Mock-Divertor’ slab simulations




**By removing different driving terms we can isolate their effects**

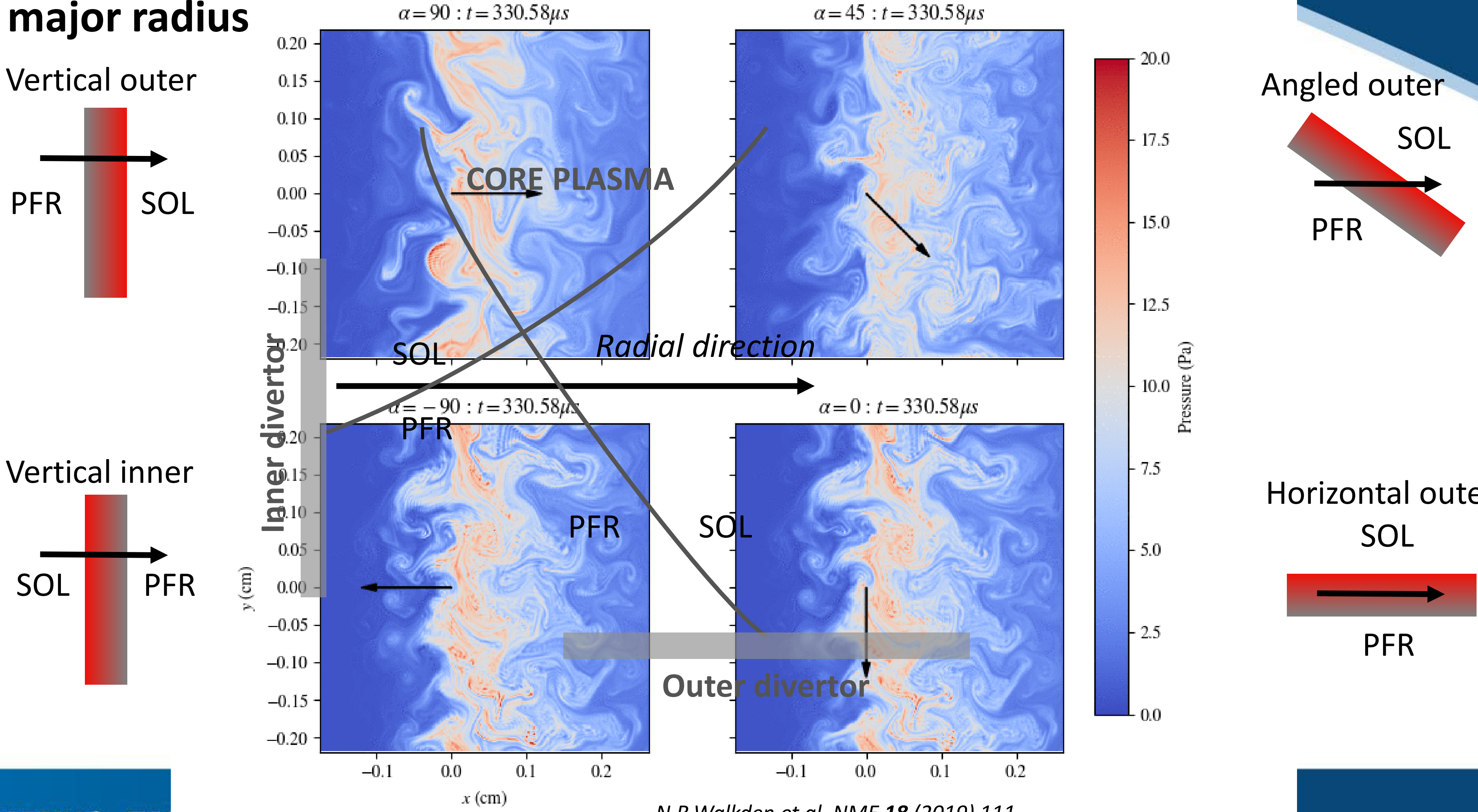
**→ K-H turbulence responsible for driving the system**

**→ Curvature effects seem to play a regulatory role on the turbulence**

*N.R.Walkden et al, NME **18** (2019) 111*

# STEP 1: 'Mock-Divertor' slab simulations

**In a tokamak magnetic curvature tends to force structures in the direction of the major radius**

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# STEP 1: ‘Mock-Divertor’ slab simulations

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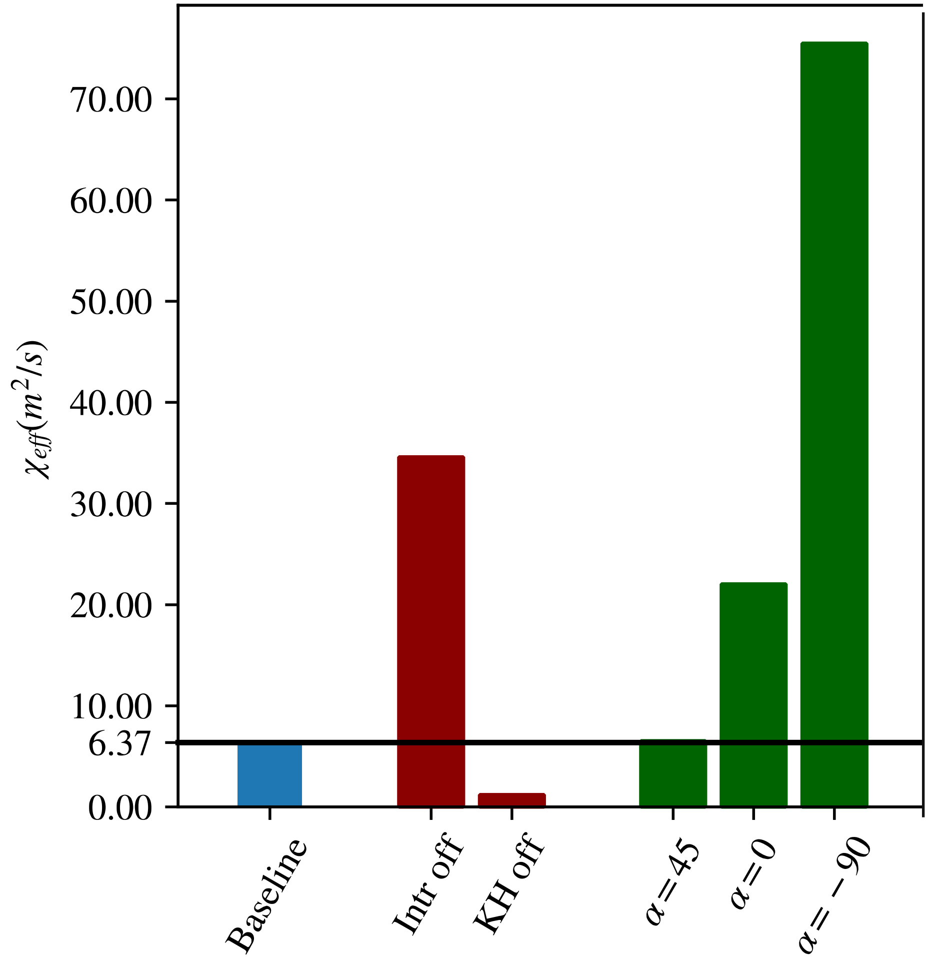
**In a tokamak magnetic curvature tends to force structures in the direction of the major radius**

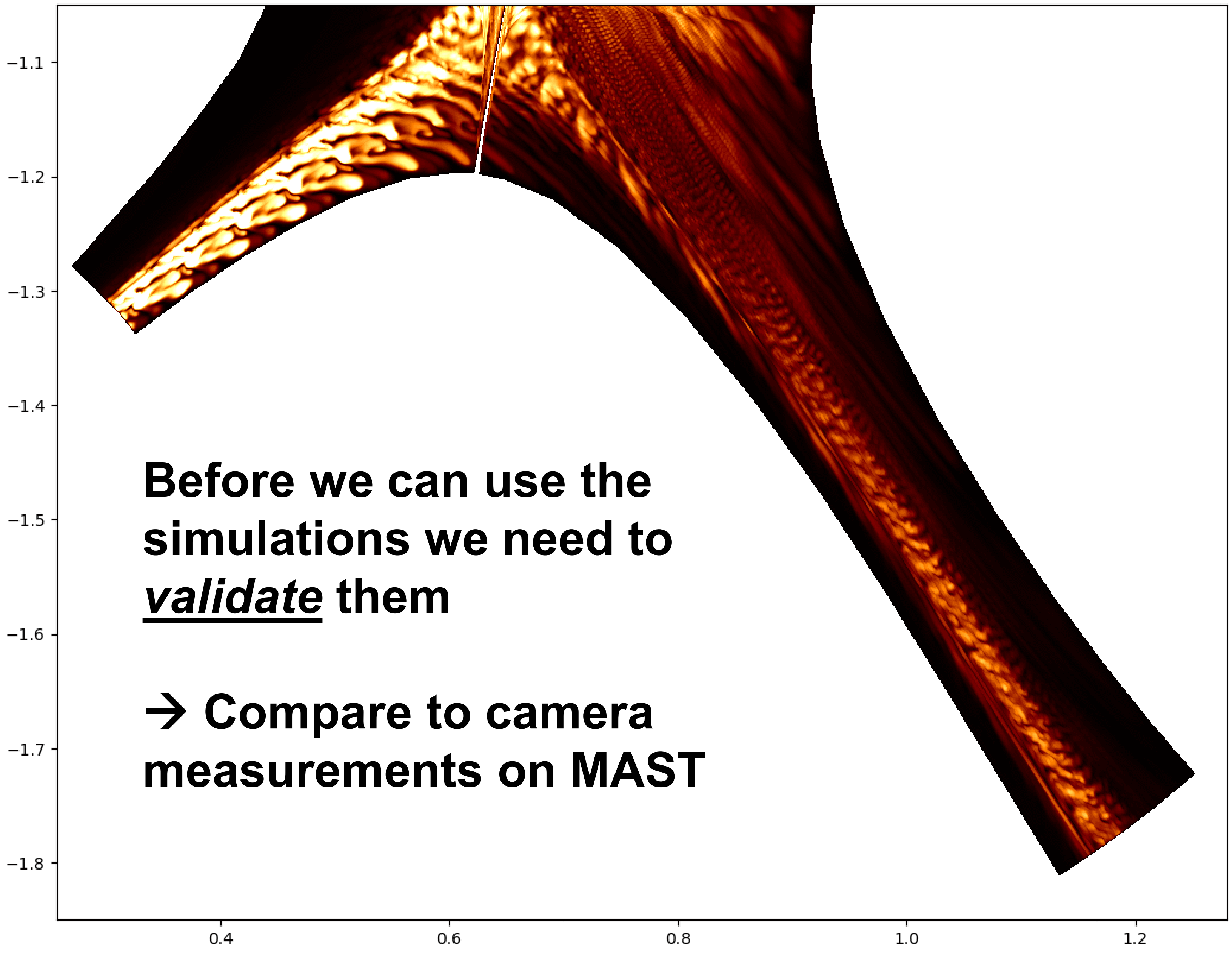



- → **The magnetic curvature is a principle actuator to vary the spreading parameter**
- → **Other factors appear to have a minimal effect**
- → **This is due to the balance between perpendicular and parallel transport**

N.R.Walkden et al, NME **18** (2019) 111

# STEP 2: Validate full geometry simulations





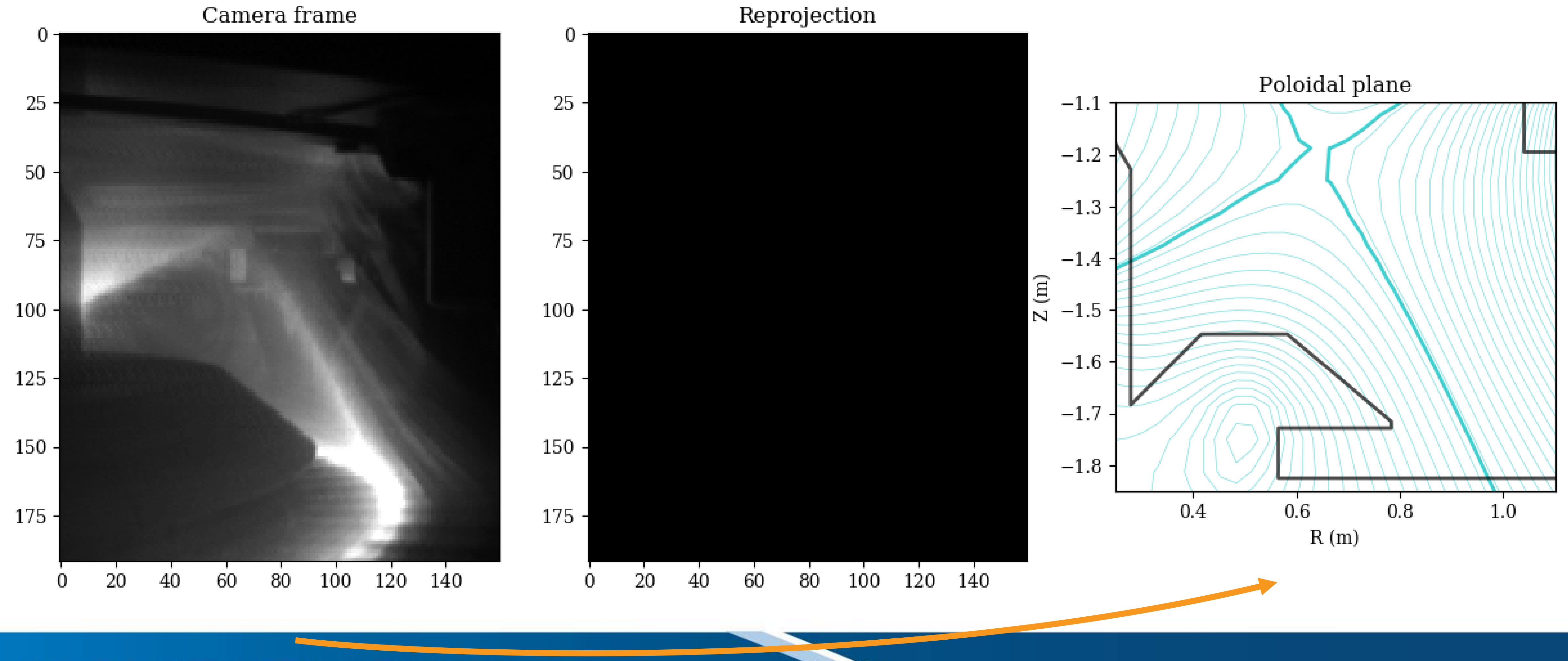

**Before we can use the simulations we need to *validate* them**

**→ Compare to camera measurements on MAST**

F.Riva *et al* Plasma Phys. Control. Fusion **61** (2019) 094013

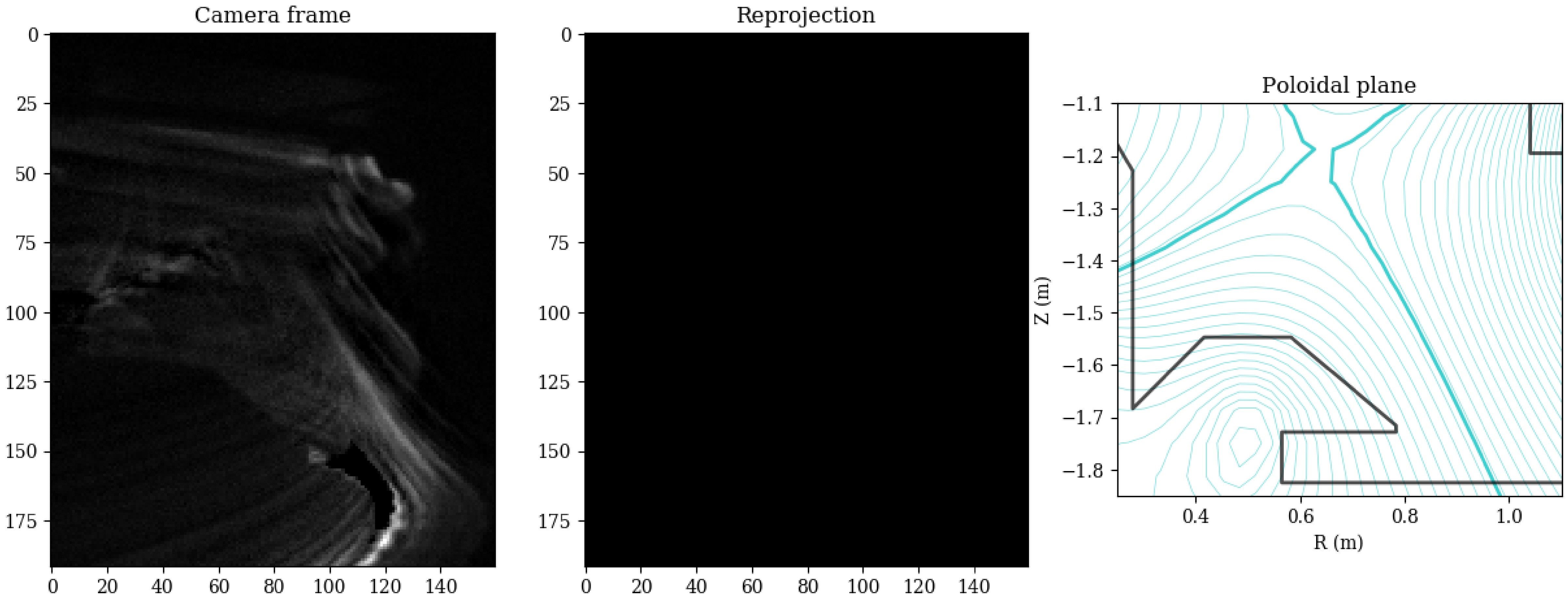
# STEP 2: Validate full geometry simulations

**Goal: Extract properties of fluctuating structures in real space from camera images**



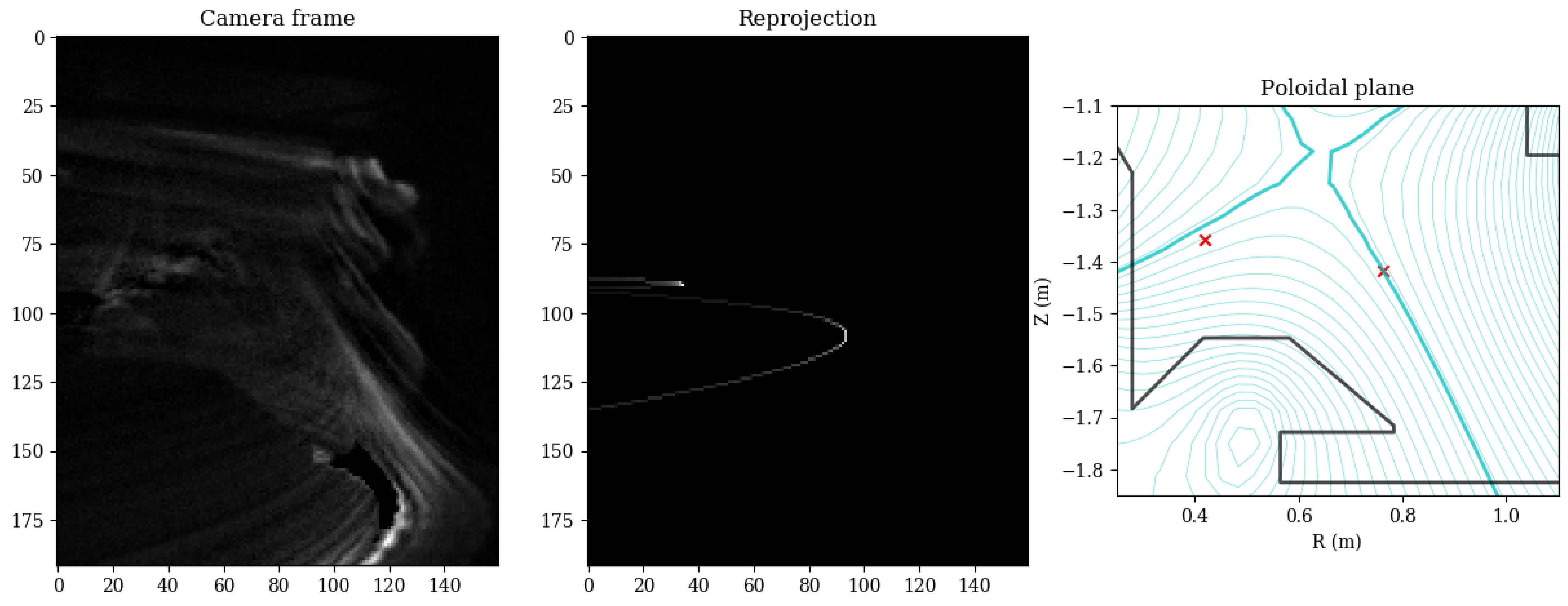
# STEP 2: Validate full geometry simulations

## Step 1: Background subtraction to isolate fluctuations



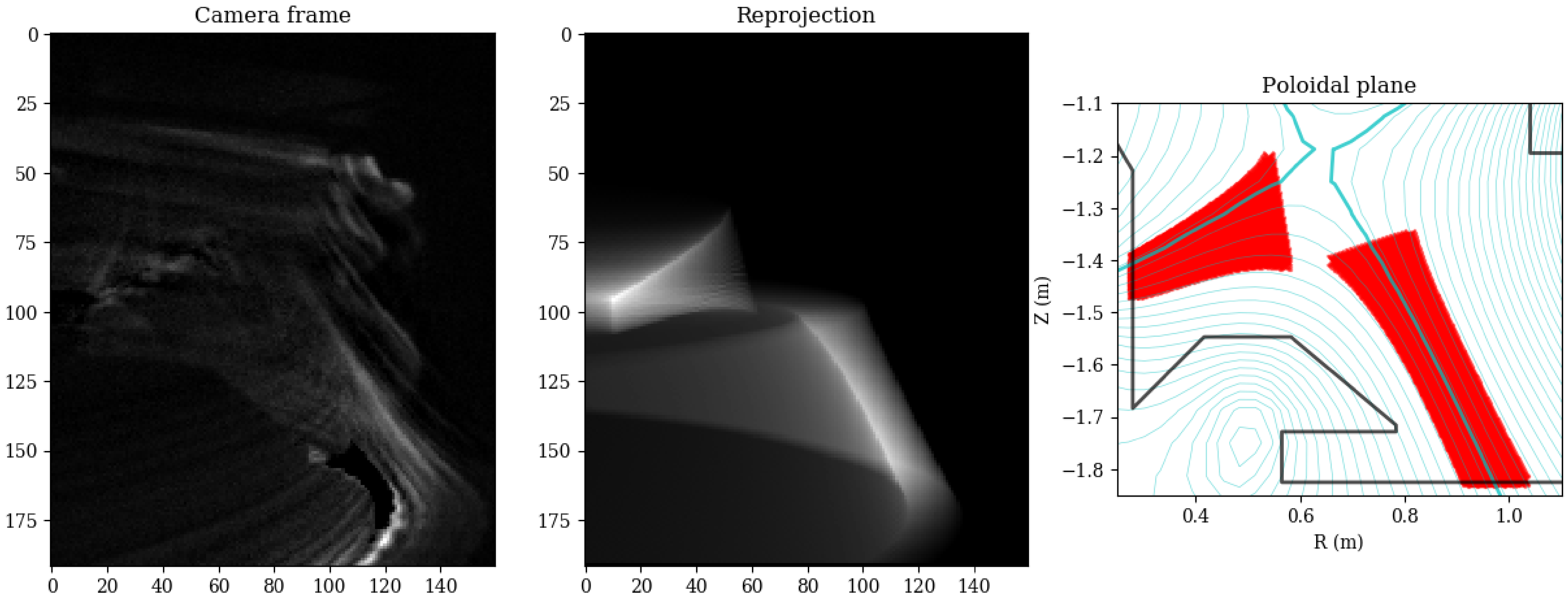
# STEP 2: Validate full geometry simulations

**Step 2: Project magnetic field lines onto camera image plane**



# STEP 2: Validate full geometry simulations

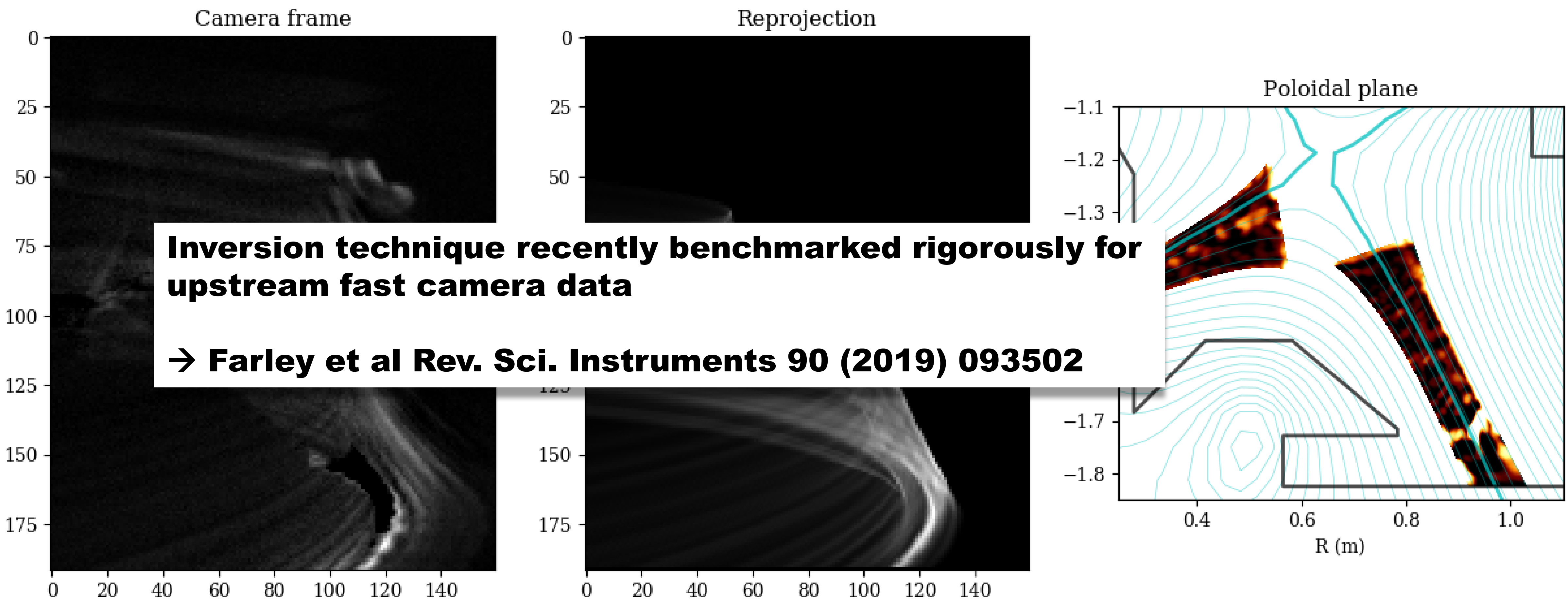
## Step 3: Create a basis-set of magnetic field lines



# STEP 2: Validate full geometry simulations



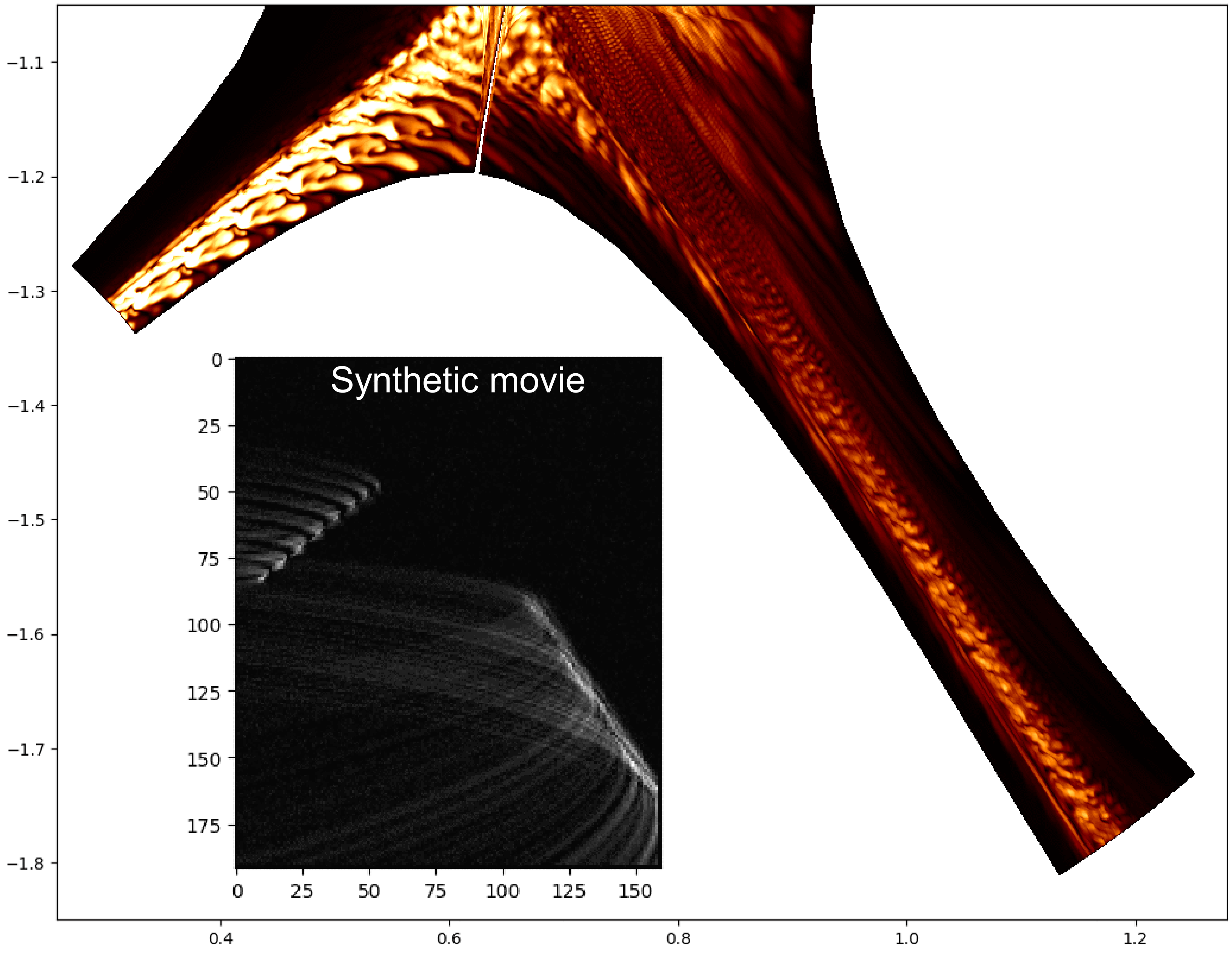
## Step 4: Find least-squares inversion of camera image onto basis-set




**Inversion technique recently benchmarked rigorously for upstream fast camera data**

**→ Farley et al Rev. Sci. Instruments 90 (2019) 093502**

# STEP 2: Validate full geometry simulations




F.Riva *et al* Plasma Phys. Control. Fusion **61** (2019) 094013

# STEP 2: Validate full geometry simulations

| Shot | Mode | $n_{e,sep}(10^{19}m^{-3})$ | $T_{e,sep}(eV)$ | $I_p(MA)$ | $B_{tor}(T)$ | $P_{NBI}(MW)$ |
|---|---|---|---|---|---|---|
| 29606 | L-mode | 0.72 | 18 | 0.63 | -0.59 | 0 |
| 29608 | L-mode | 0.97 | 17 | 0.63 | -0.57 | 0 |
| 29651 | L-mode | 0.85 | 24 | 0.62 | -0.55 | 1.27 |
| 29660 | L-mode (RMPs) | 0.94 | 25 | 0.63 | -0.54 | 1.22 |
| 29668 | L-mode | 1.05 | 27 | 0.63 | -0.56 | 0.61 |
| 29669 | L-mode | 1.25 | 19 | 0.42 | -0.51 | 0.62 |
| 29693 | L-mode | 0.97 | 32 | 0.42 | -0.48 | 1.23 |
| 29718 | L-mode | 1.00 | 38 | 0.63 | -0.54 | 1.61 |
| 29720 | L-mode | 1.37 | 29 | 0.42 | -0.47 | 1.61 |
| 29723 | H-mode (ELM-free) | 1.4 | 55 | 0.82 | -0.56 | 1.6 |
| STORM [16] | L-mode | 0.5 | 15 | 0.4 | -0.4 | 0 |



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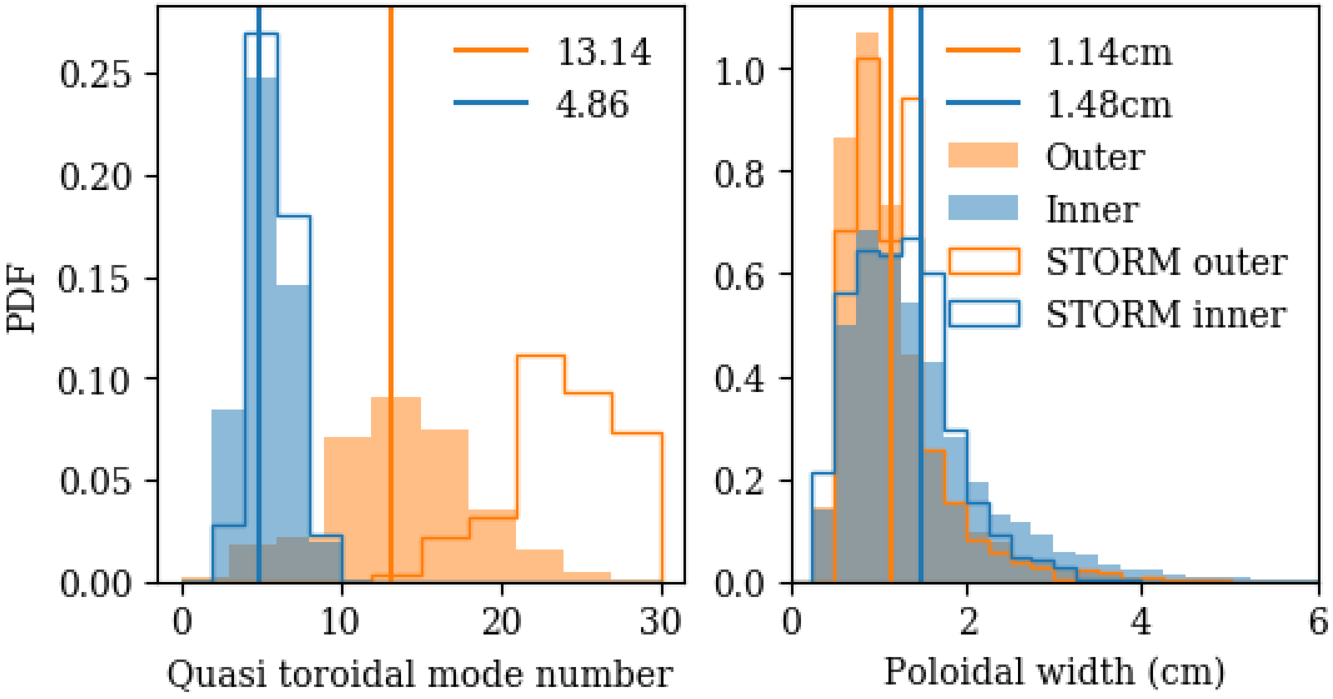
# STEP 2: Validate full geometry simulations

## **Measurements are made cumulatively across the shot database**

- Inner and outer leg decoupled
- Similar poloidal sizes in both legs
- Strong collapse across database indicating insensitivity to operational parameters
- Excellent agreement from simulation, though over-estimation of outer-leg mode number



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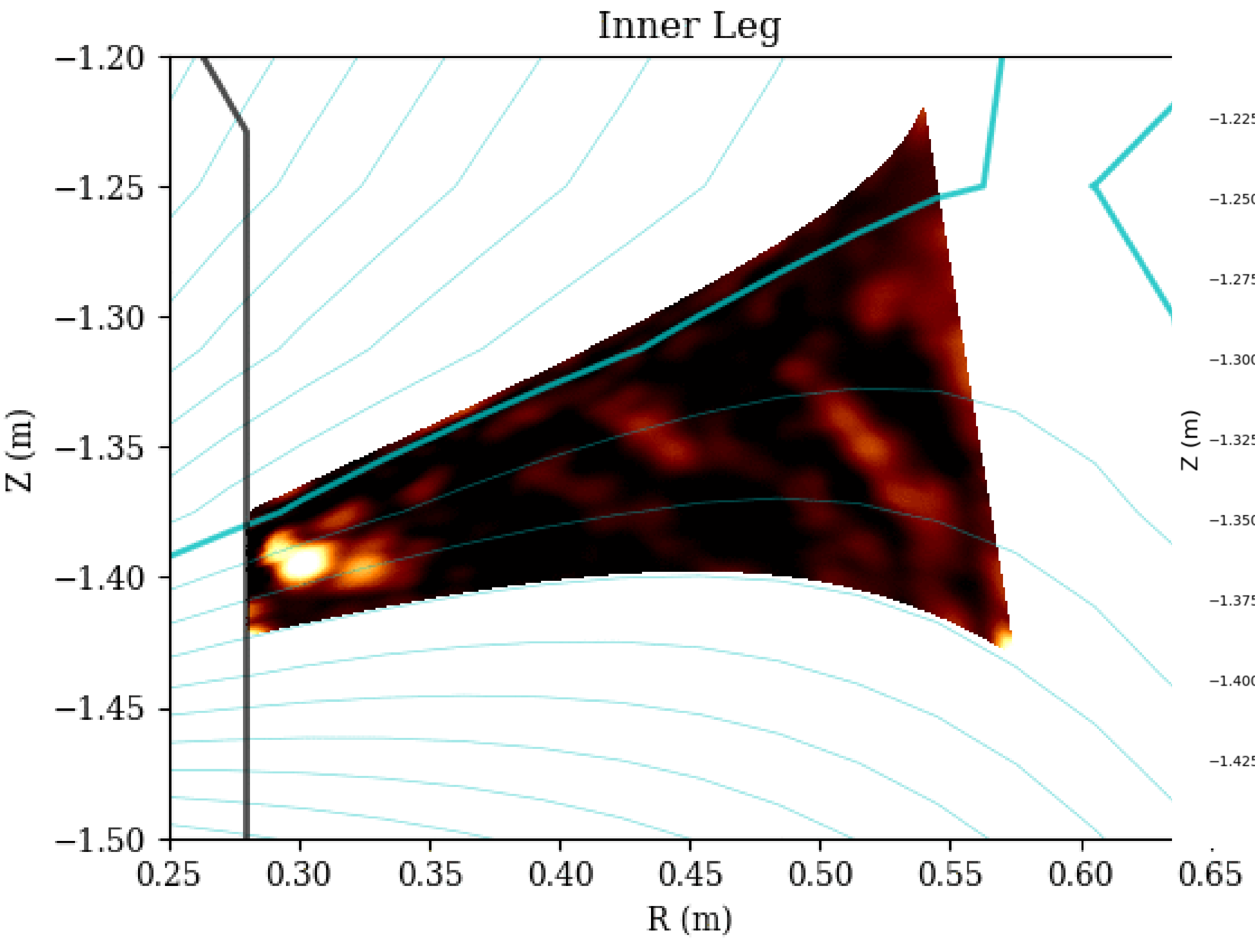
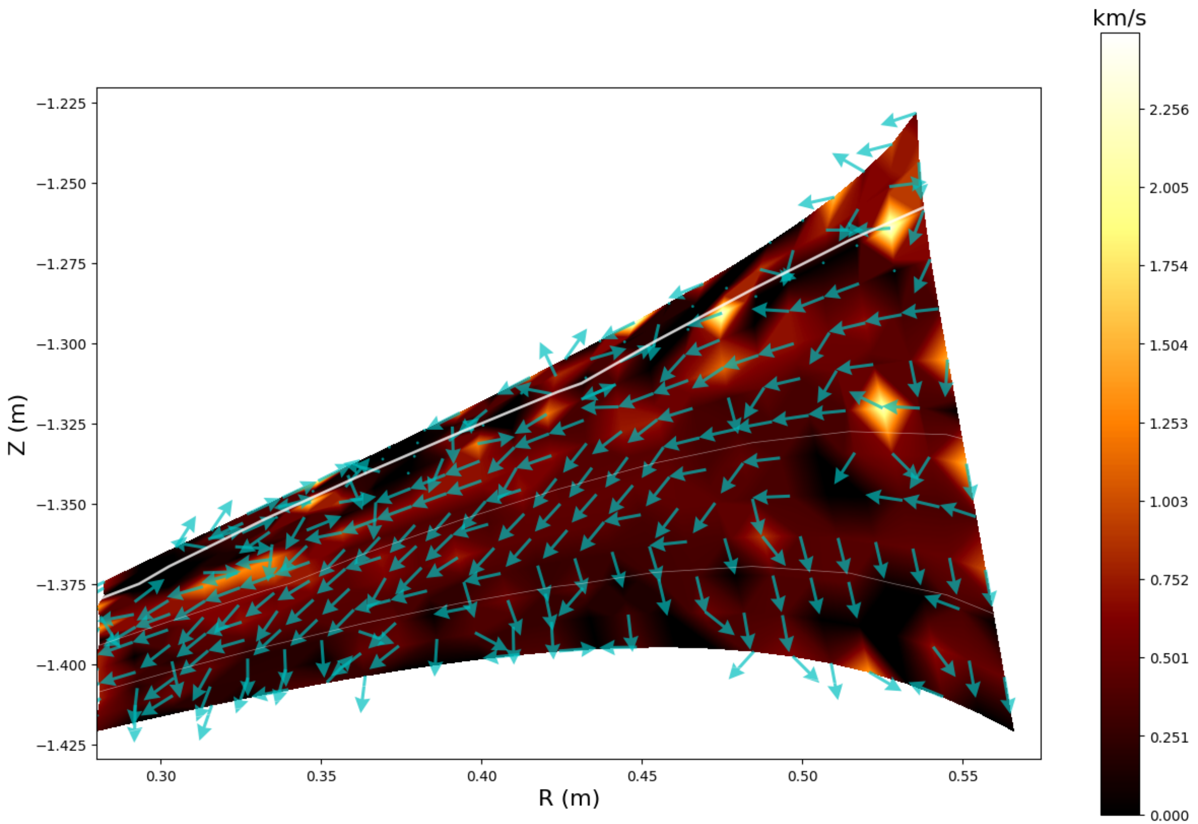
# STEP 2: Validate full geometry simulations

**Two-point correlation technique used to map flow in inner divertor leg**

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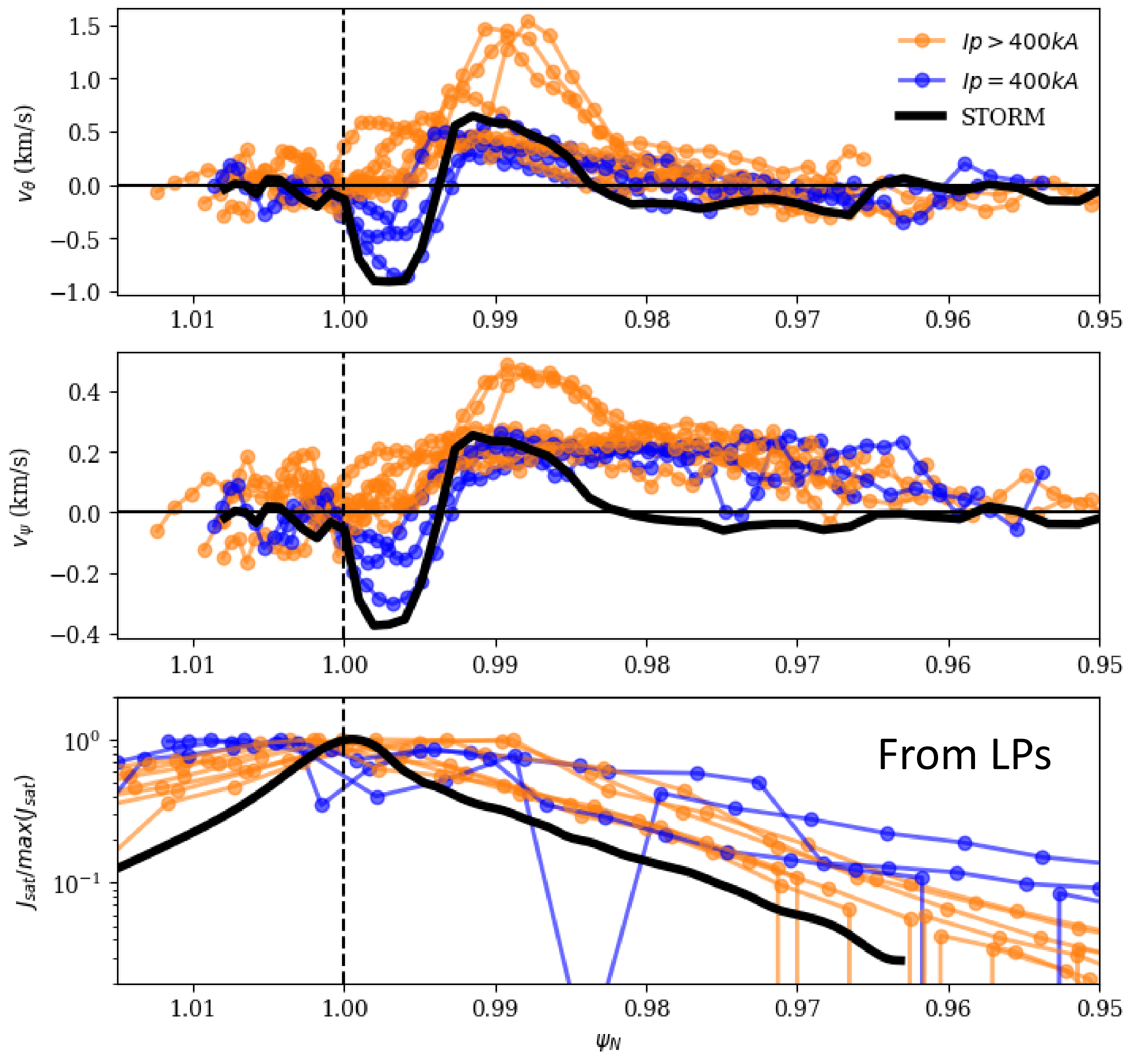
# STEP 2: Validate full geometry simulations

**Two-point correlation technique used to map flow in inner divertor leg**

- Broadly similar flow profiles, though some variation, particularly in poloidal flow
- Radial flow ~ 200m/s in PFR concomitant with radial decay of Jsat at inner target
- Flow measurements from simulation match data extremely well, though radial velocity drops faster and profile decays quicker

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# STEP 3: Diagnose the turbulence

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**Impressive agreement between simulation and experiment means that simulations can be used to diagnose the turbulence**

Vorticity eqn in STORM:

$$\frac{\partial \Omega}{\partial t} + U\mathbf{b} \cdot \nabla \Omega = -\mathbf{b} \times \nabla \phi \cdot \nabla \Omega + \frac{1}{n} \nabla \times \left( \frac{\mathbf{b}}{B} \right) \cdot \nabla P$$

$$+ \frac{1}{n} \nabla \cdot \left( \mathbf{b} J_{||} \right) + \mu_{\Omega_0} \nabla_{\perp}^2 \Omega$$

# STEP 3: Diagnose the turbulence

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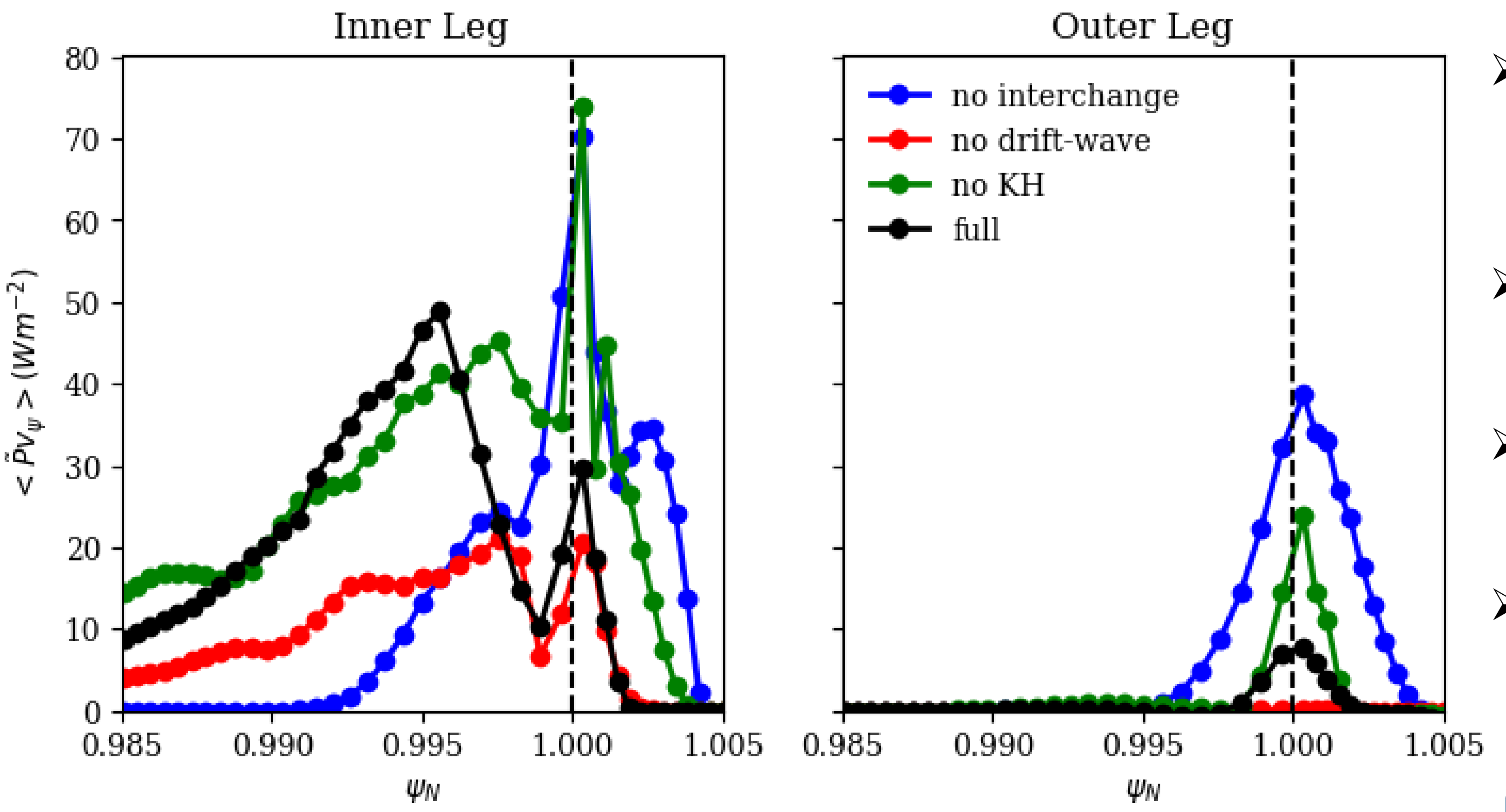
- $-\mathbf{b}\times\nabla\phi\cdot\nabla\Omega$: Shear-flow turbulence via Kelvin-Helmholtz instability
- $\frac{1}{n}\nabla\times\left(\frac{\mathbf{b}}{B}\right)\cdot\nabla P$: Curvature driven turbulence via interchange instability
- $\frac{1}{n}\nabla\cdot\left(\mathbf{b}J_{||}\right)$: Drift-wave turbulence

# STEP 3: Diagnose the turbulence

**Impressive agreement between simulation and experiment means that simulations can be used to diagnose the turbulence**

Removing these turbulence drives shows how each contributes to the total radial fluxes




- Generally higher and more radially extended fluxes in inner leg than outer
- Shear-flow (KH) effects are stabilizing in both divertor legs
- Inner-leg turbulence is drift-interchange
- Outer-leg turbulence is drift-wave with curvature playing a stabilizing role

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# Overview

**What is divertor turbulence, and why is it important?**

**Can we *understand* divertor turbulence?**

**Summary**

# Summary

1. Radial transport in the divertor is a complex non-linear turbulent phenomenon

2. Divertor turbulence is relatively insensitive to parameters of the plasma

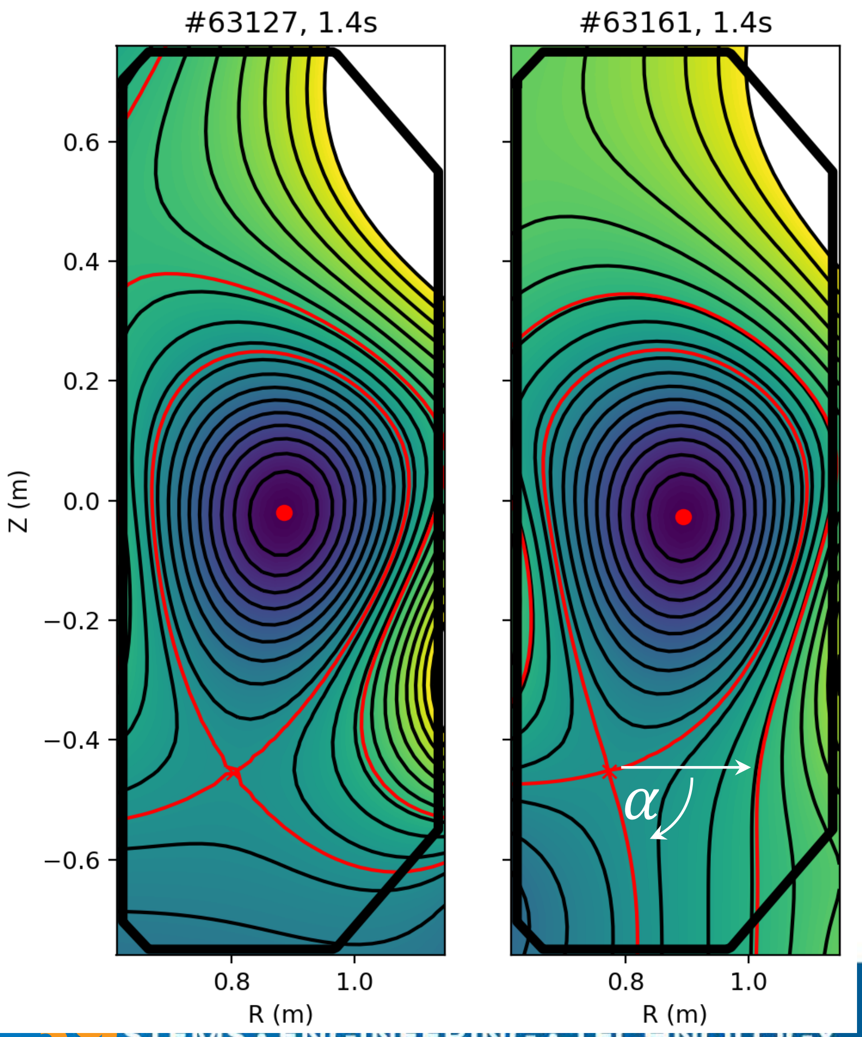
3. Turbulence in the two divertor legs differs significantly
    - On the inner divertor leg turbulence is mainly interchange
    - On the outer leg, turbulence is mainly drift-wave

4. The magnetic curvature plays a vital role in divertor turbulence
    - It drives transport into the PFR in the inner leg
    - It suppresses transport into the PFR in the outer leg

**This is just the start, there is a lot of learning to go!**

# STEP 4: Test the conclusions via experiment

**Aim: Test in impact of the magnetic curvature by varying the poloidal divertor leg angle**

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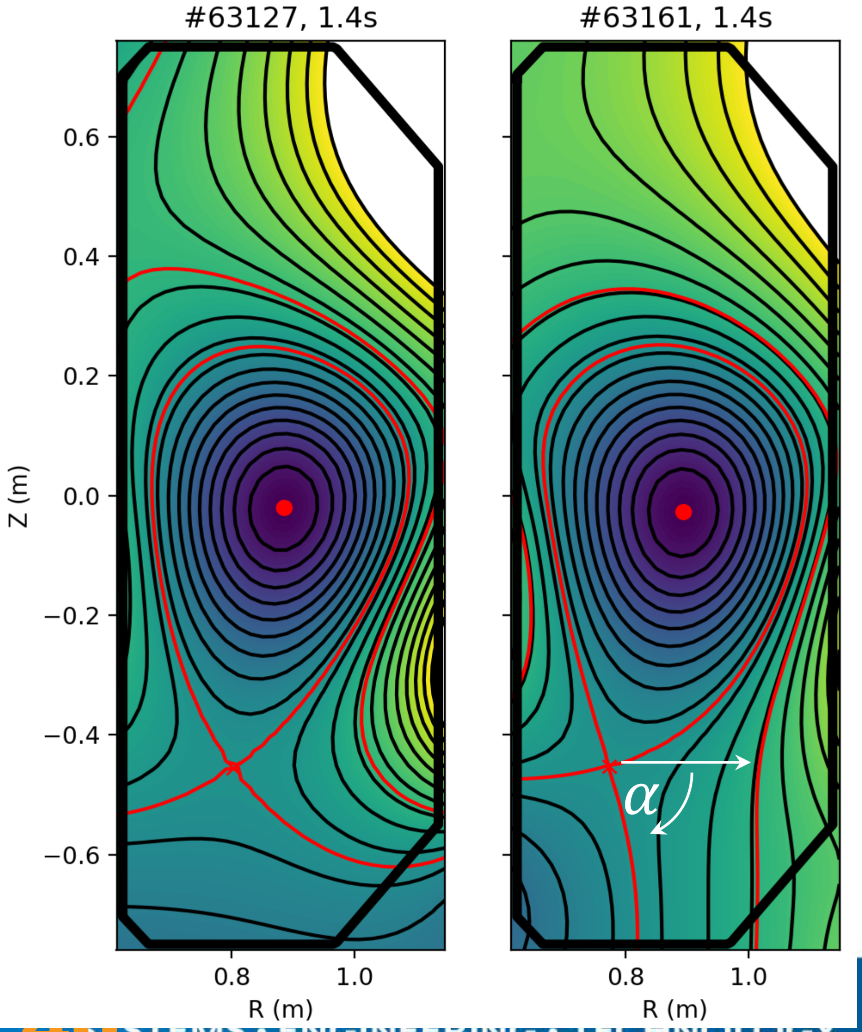



$$\alpha \approx -\arctan\left(\frac{Z_{SP} - Z_X}{R_{SP} - R_X}\right)$$

| **Shot** | 63127/28 | 63161/62 |
|---|---|---|
| **$\alpha$ (deg)** | 32 | 80 |

# STEP 4: Test the conclusions via experiment

**Clear change in profiles at the outer target**

The horizontal leg shows

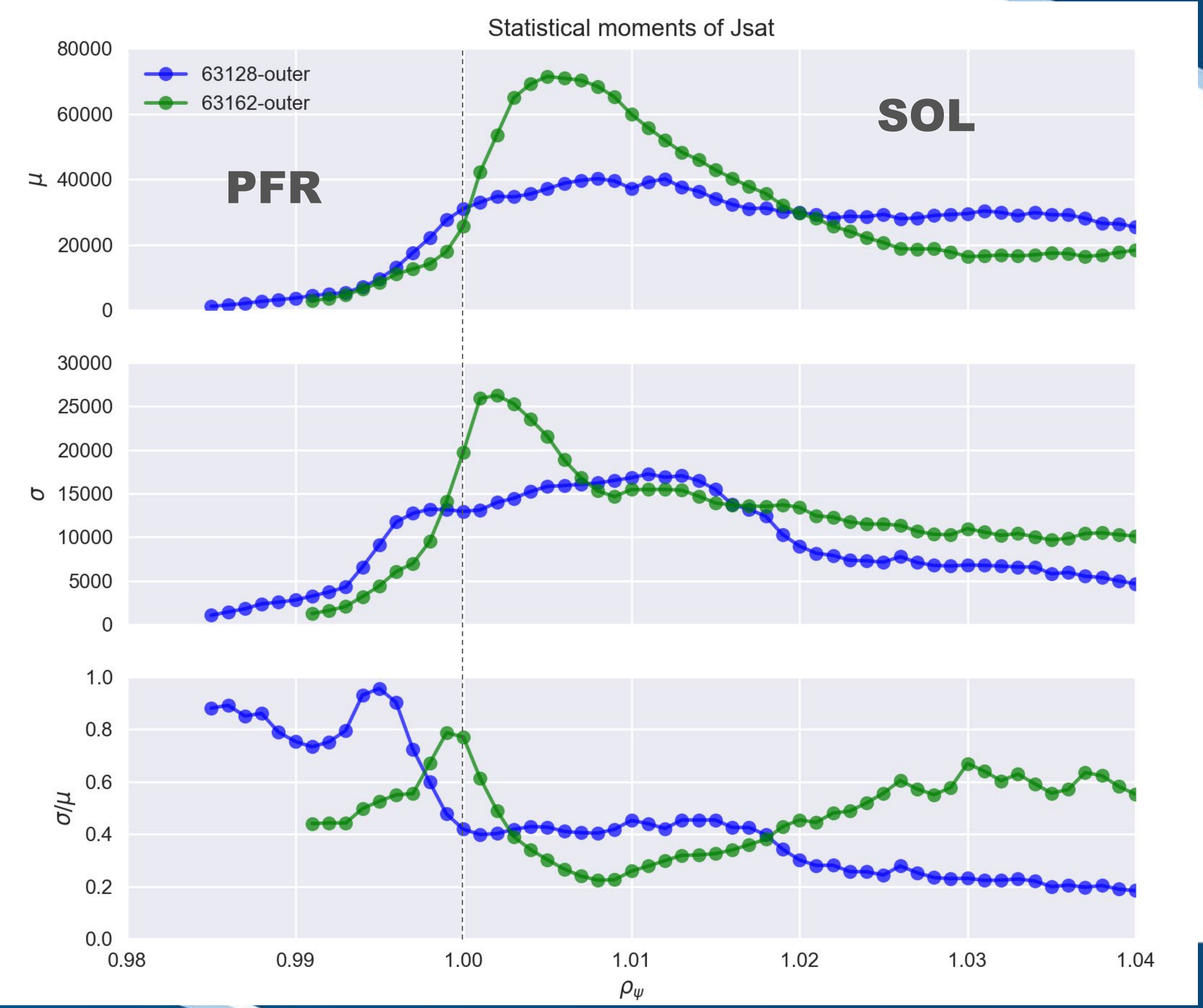
→ Increased spreading into the PFR

→ Generally flatter profile

→ Higher standard deviation in the PFR

→ 50% higher fluctuation level in the PFR

→ Peak in fluctuation level further into PFR





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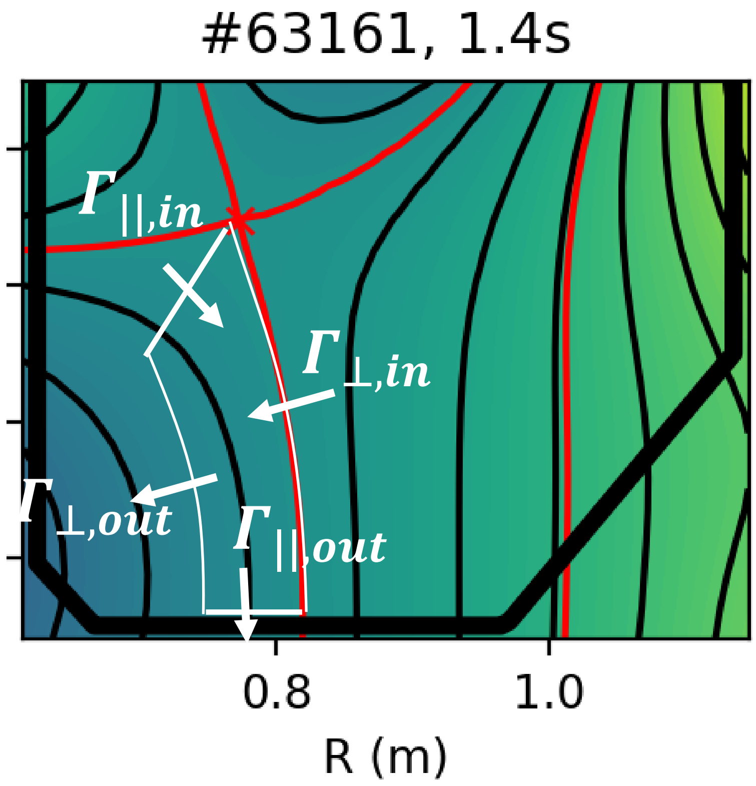
STEP 4: Test the conclusions via experiment

**Treating the PFR as a closed system with no sources we can estimate a poloidally averaged radial transport flux**



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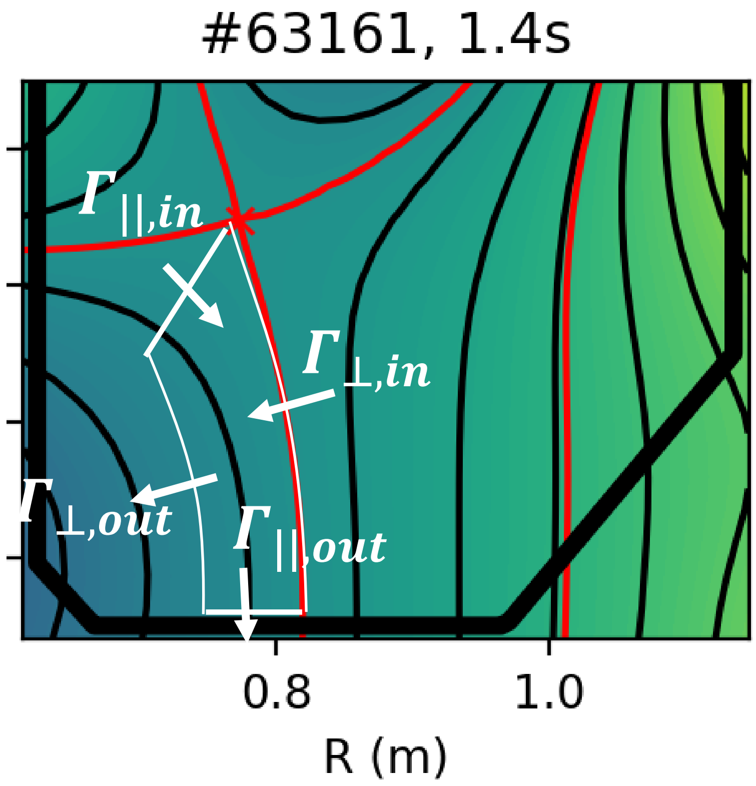


Assume:

- Stagnation near the X-point → $\boldsymbol{\Gamma_{||,in} = 0}$
- Outer PFR sufficiently far from separatrix →$\boldsymbol{\Gamma_{\perp,out} = 0}$


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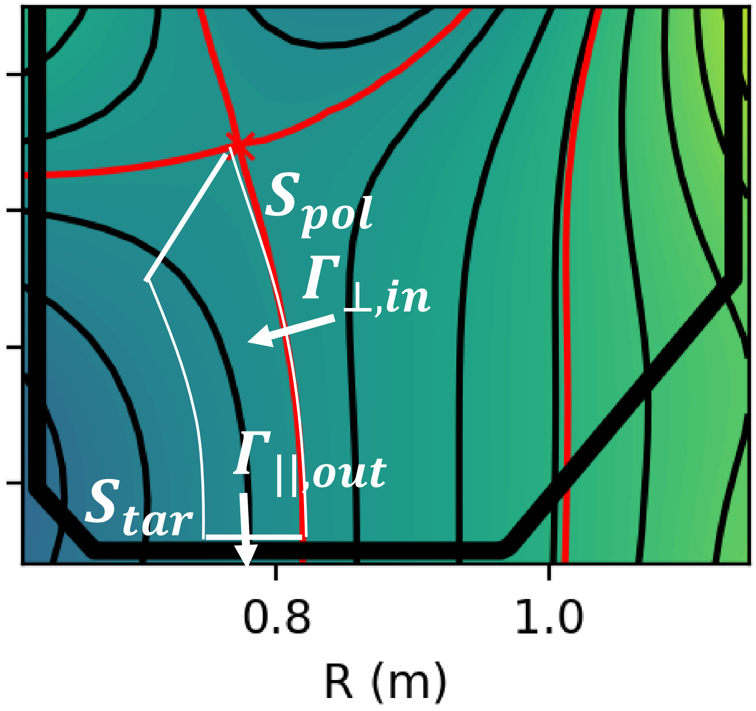


Assume:

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- Outer PFR sufficiently far from separatrix →$\boldsymbol{\Gamma_{\perp,out} = 0}$

$$2\pi \int \Gamma_{\perp} R(S_{pol}) dS_{pol} = 2\pi \int \Gamma_{||} \frac{B_{pol}(S_{tar})}{B(S_{tar})} R(S_{tar}) dS_{tar}$$

$$\langle \Gamma_{\perp} \rangle \approx \frac{\int \Gamma_{||} \frac{B_{pol}(S_{tar})}{B(S_{tar})} R(S_{tar}) dS_{tar}}{\int R(S_{pol}) dS_{pol}}$$

STEP 4: Test the conclusions via experiment

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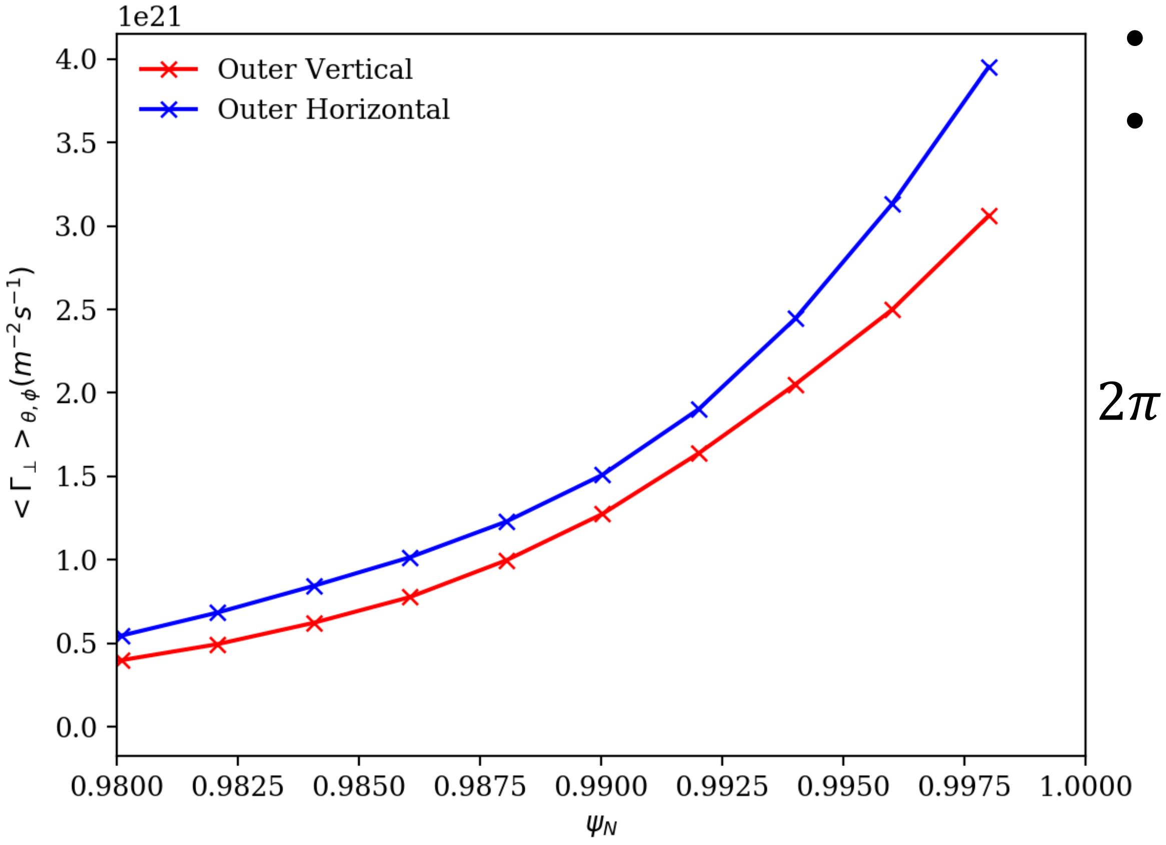


Assume:

- Stagnation near the X-point → $\boldsymbol{\Gamma}_{||,in} = \mathbf{0}$
- Outer PFR sufficiently far from separatrix →$\boldsymbol{\Gamma}_{\perp,out} = \mathbf{0}$

$$2\pi \int \Gamma_\perp R(S_{pol})dS_{pol} = 2\pi \int \Gamma_{||} \frac{B_{pol}(S_{tar})}{B(S_{tar})} R(S_{tar})dS_{tar}$$

$$\langle\Gamma_\perp\rangle \approx \frac{\int \Gamma_{||} \frac{B_{pol}(S_{tar})}{B(S_{tar})} R(S_{tar})dS_{tar}}{\int R(S_{pol})dS_{pol}}$$


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# STEP 4: Test the conclusions via experiment

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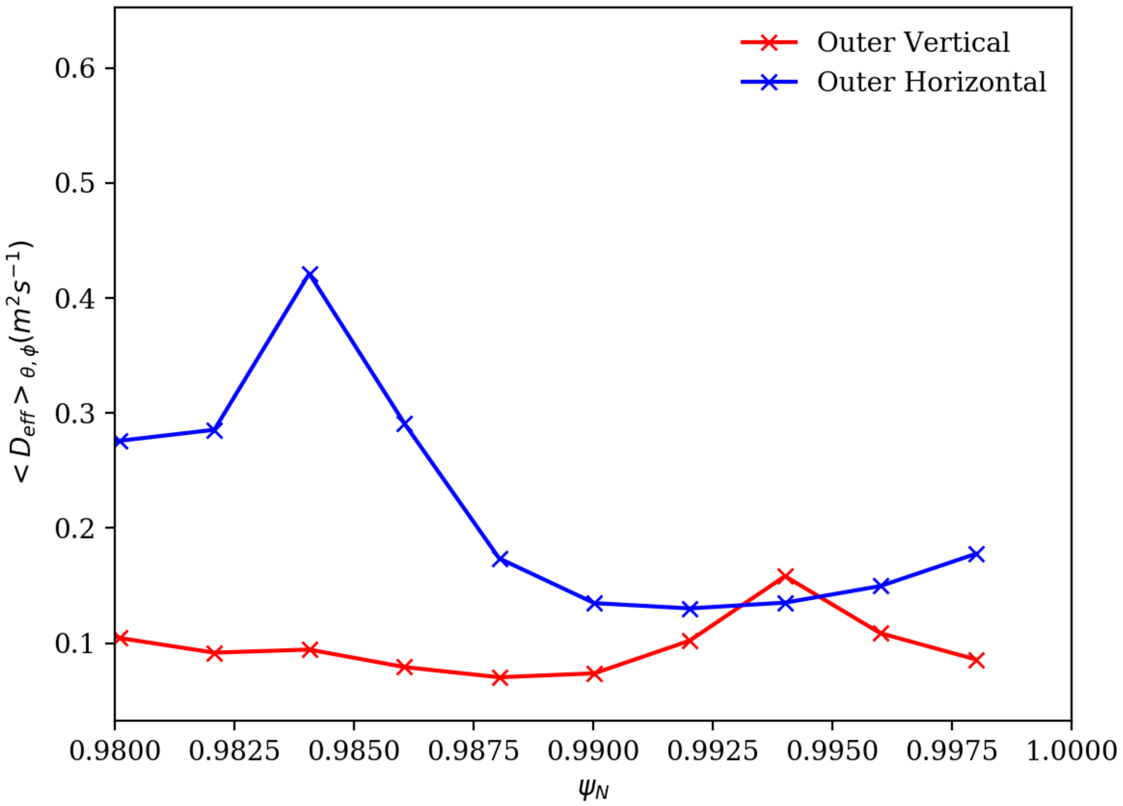
A KBR COMPANY

## Treating the PFR as a closed system with no sources we can estimate a poloidally averaged radial transport flux




Assume:

- Stagnation near the X-point → $\boldsymbol{\Gamma}_{||,in} = 0$
- Outer PFR sufficiently far from separatrix →$\boldsymbol{\Gamma}_{\perp,out} = 0$
- Density profile can be inferred from Jsat profile scaled by peak target density
- Transport can be expressed as a diffusion or convection

$$\langle D_\perp \rangle \approx \frac{\int \Gamma_{||} \frac{B_{pol}(S_{tar})}{B(S_{tar})} R(S_{tar}) dS_{tar}}{\frac{\partial n}{\partial \psi} \int B_{pol}^{-1}(S_{pol}) dS_{pol}}$$

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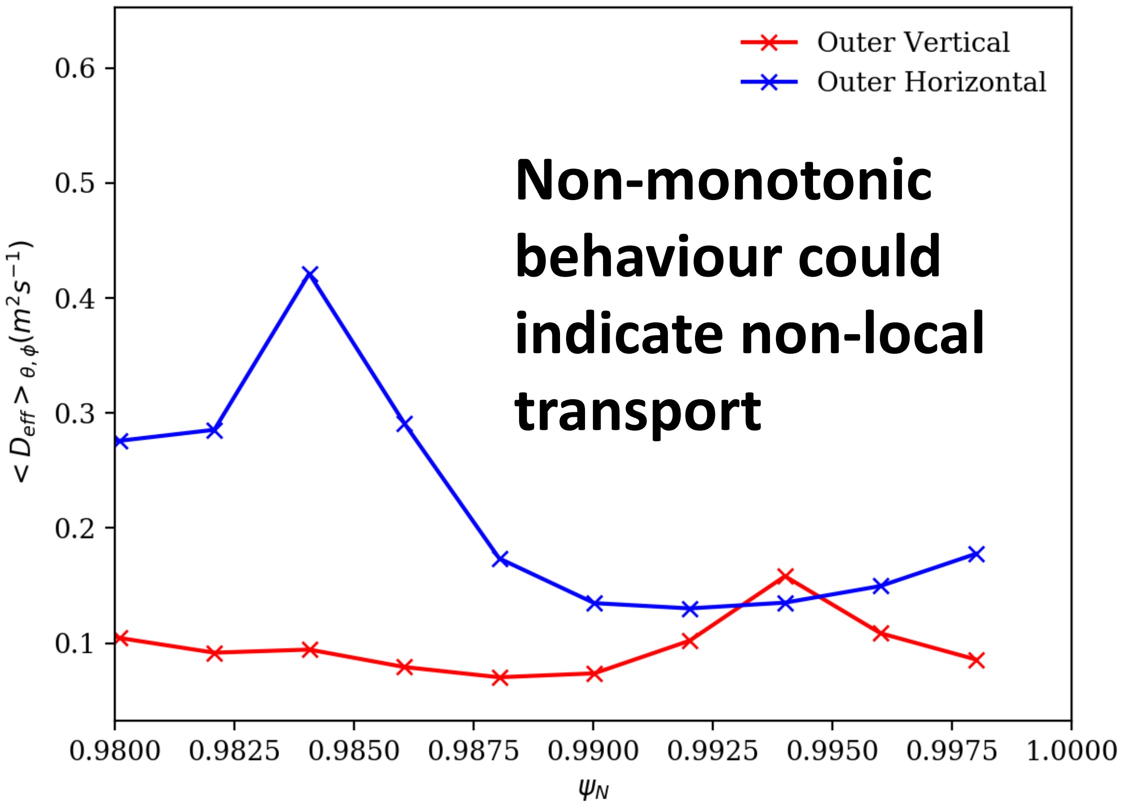


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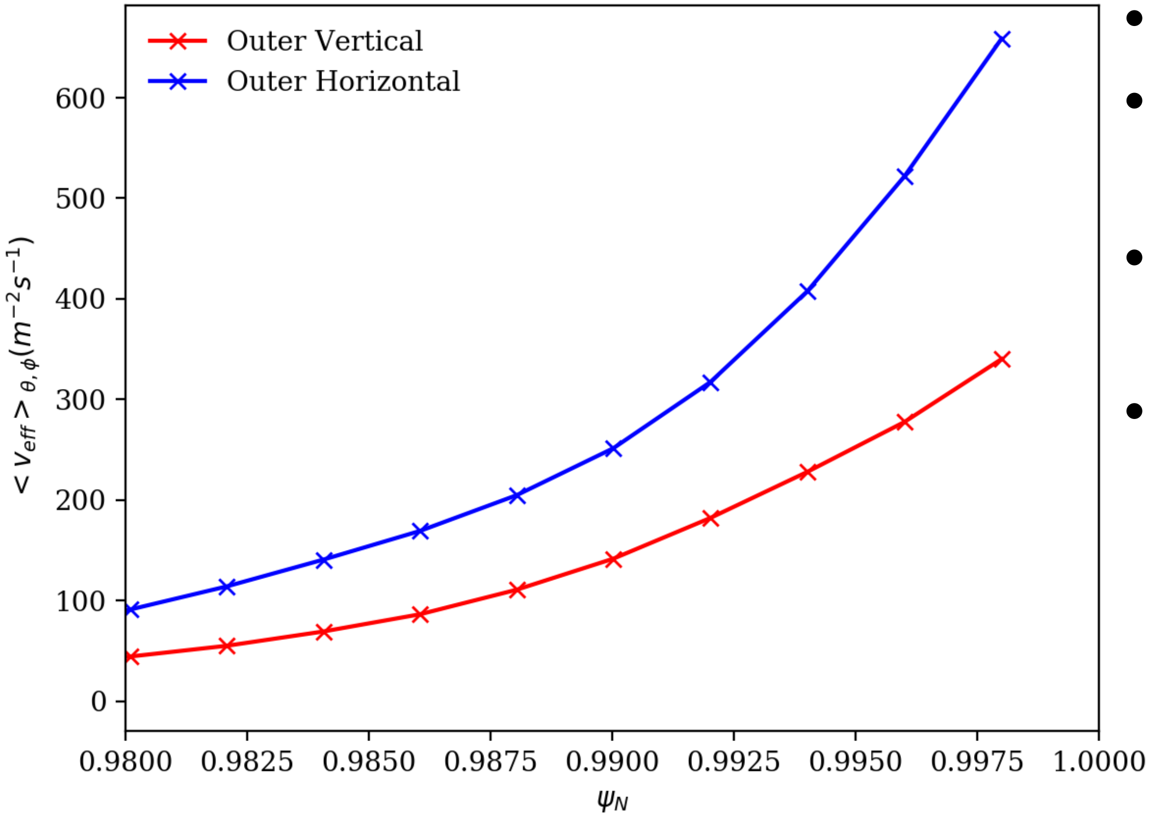


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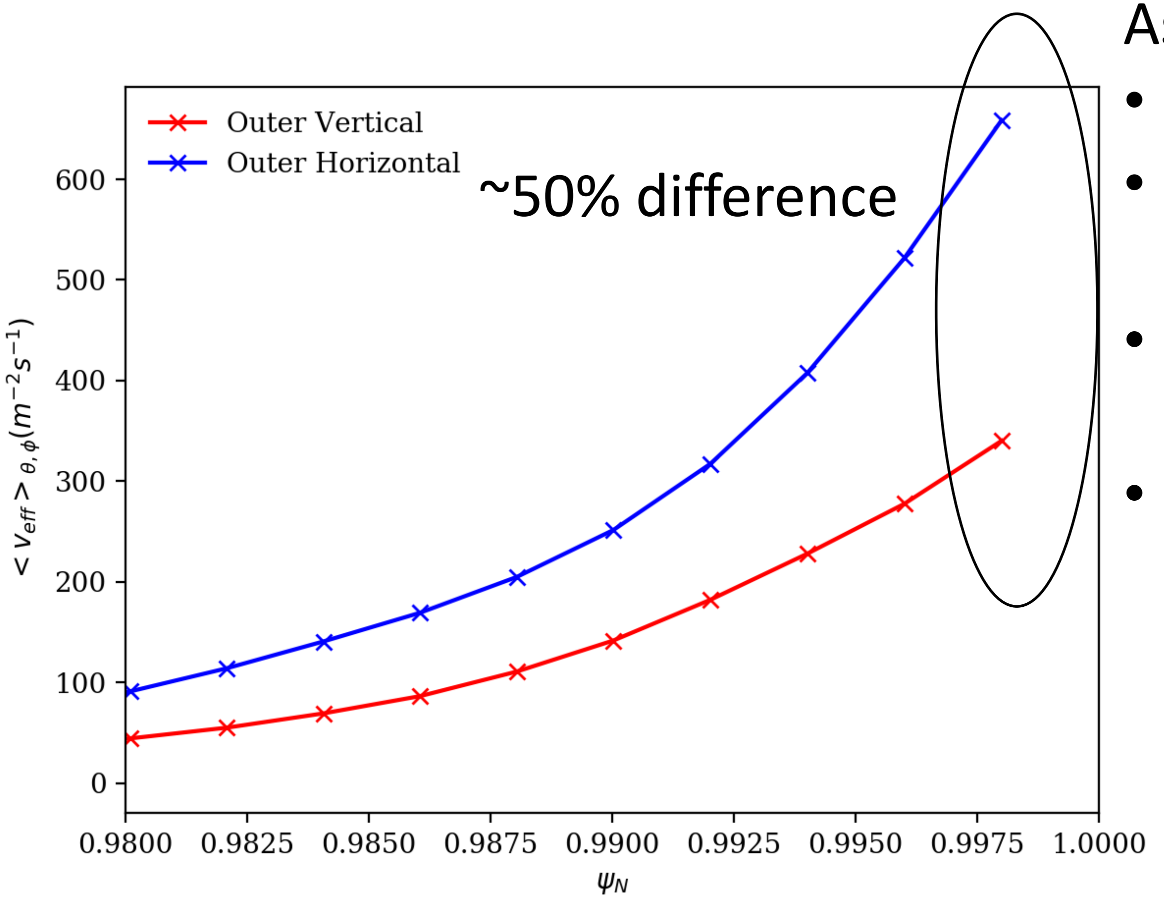


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