Turbulent Nature of the Quasicontinuous Exhaust Regime for Fusion Plasmas

Paper Rehearsal

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The Quasicontinuous Exhaust regime (QCE)

- ELM-free H-mode with large λ_q,

  high n_{sep} in favor of detachment

- Experimental Observation:

  1. Separatrix spanning **Quasi-coherent mode** (QCM)

  2. Intermittent filaments **(plasma blobs)** in the SOL

- First-principles understanding

  $\rightarrow$ Turbulence simulations using GRILLIX
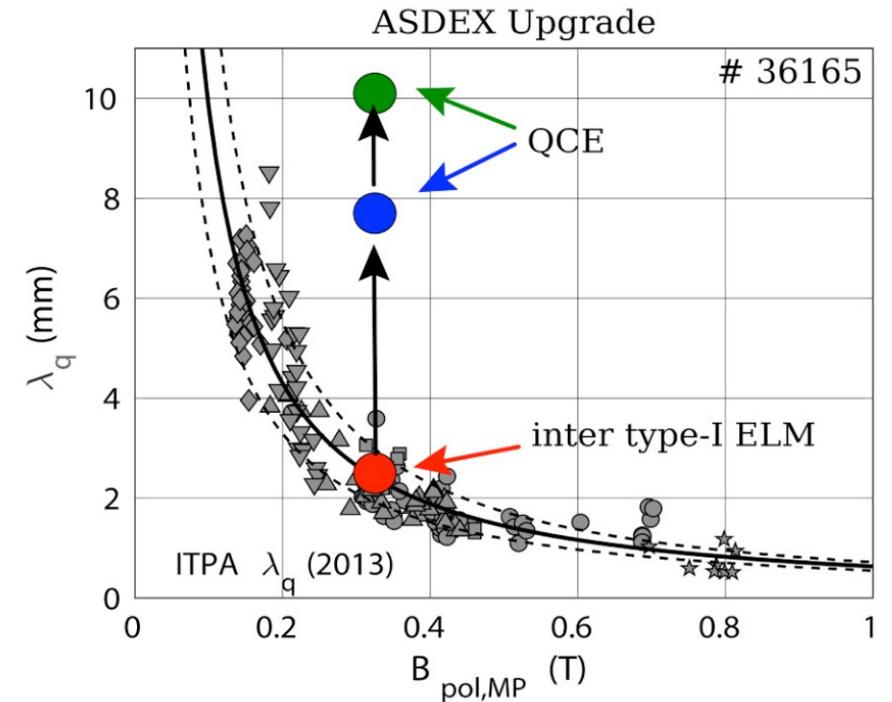
[M. Faitsch, Nuclear Materials and Energy, 2021]

GRILLIX: two-fluid turbulence codes for edge & SOL

Full-f, global

$n_0 + n_1, T_{e0} + T_{e1}, T_{i0} + T_{i1}$ evolve together ➡️ $n_1/n_0 \gtrsim 1$

→ coefficients (resistivity, viscosity, ionization rate ...)

Locally-field-aligned method

[A. Stegmeir, Comput. Phys. Comm. 2023]

Parallel: field aligned

Perpendicular: cartesian grid ➡️ $\Delta l_\perp \sim \rho_s$
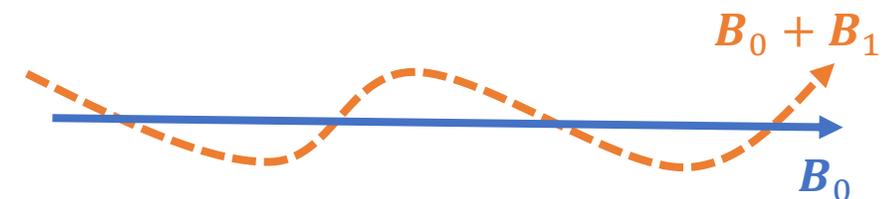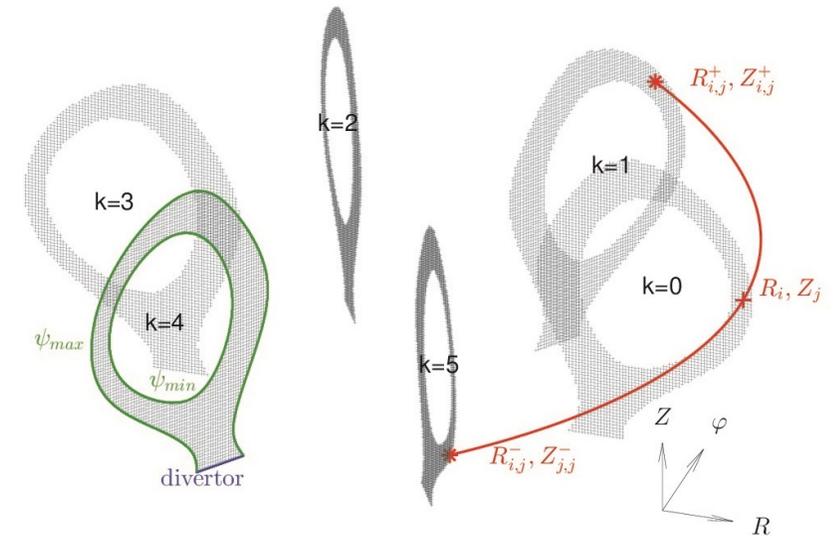
→ High resolution across the separatrix & X-point

Electromagnetics

Turbulence-driven magnetic fluctuations ➡️ $\mathbf{B}_1 \neq 0$

[K. Zhang, Nucl. Fusion 2024]
[K. Zhang, Comput. Phys. Comm. 2024]

Phenomenology & Validation

Dynamics

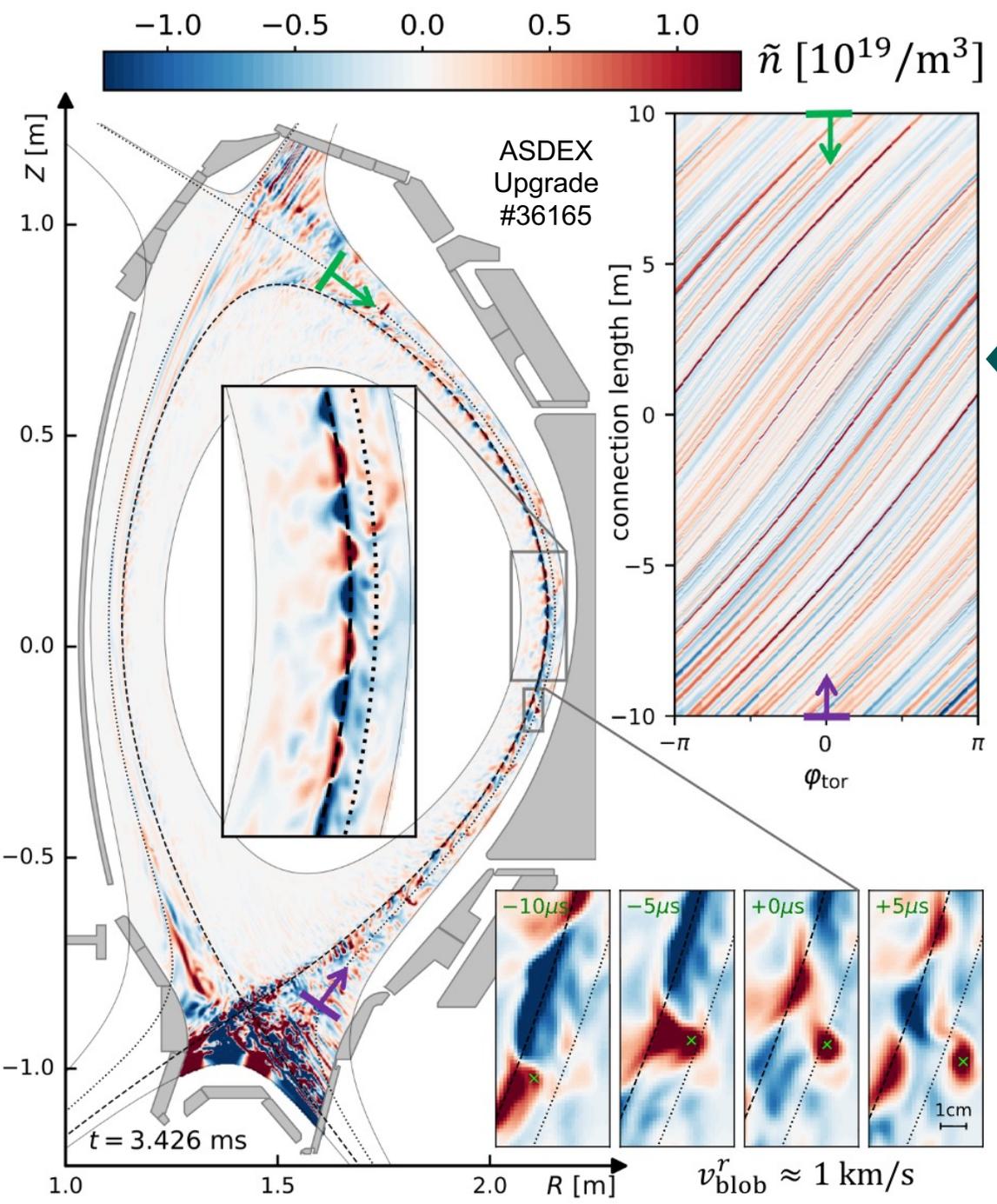- Quasi-coherent mode (QCM)

$$k_{\mathrm{pol}}\rho_s = 0.033$$

[J. Kalis, Nucl. Fusion, 2024]

- Blobs (filaments)

$$v_{\mathrm{blob}}^r \sim 1\mathrm{km/s}$$

[M. Griener, Nucl. Materials and Energy, 2020]

$$L_\perp \sim 1\mathrm{cm} \qquad L_\parallel > 10\mathrm{m}$$

ASDEX Upgrade #36165

$\tilde{n}$ $[10^{19}/\mathrm{m}^3]$

$t = 3.426$ ms

$v_{\mathrm{blob}}^r \approx 1$ km/s

$-10\mu s$ $-5\mu s$ $+0\mu s$ $+5\mu s$

$\tilde{n}\ [10^{19}/\text{m}^3]$

ASDEX Upgrade #36165

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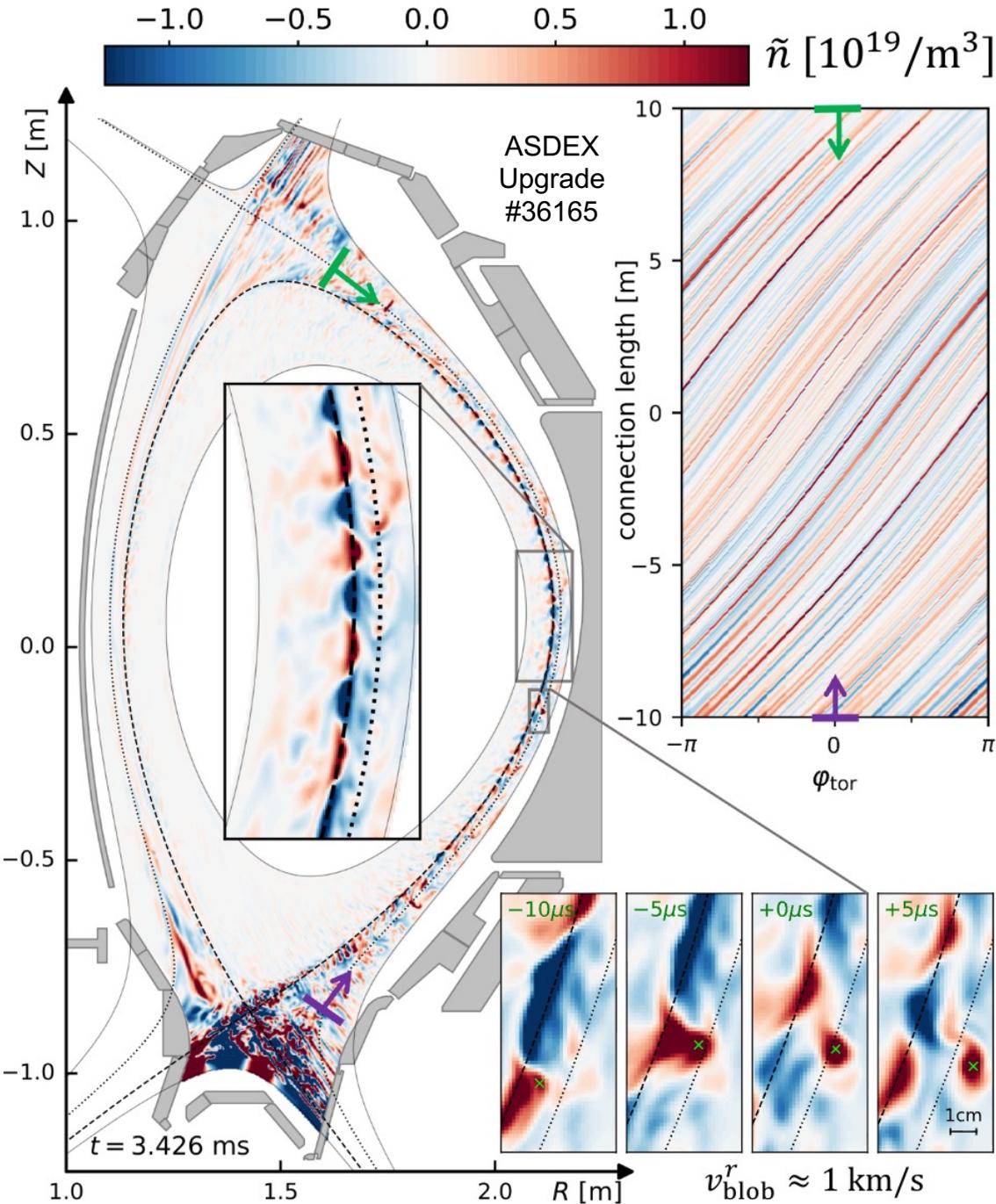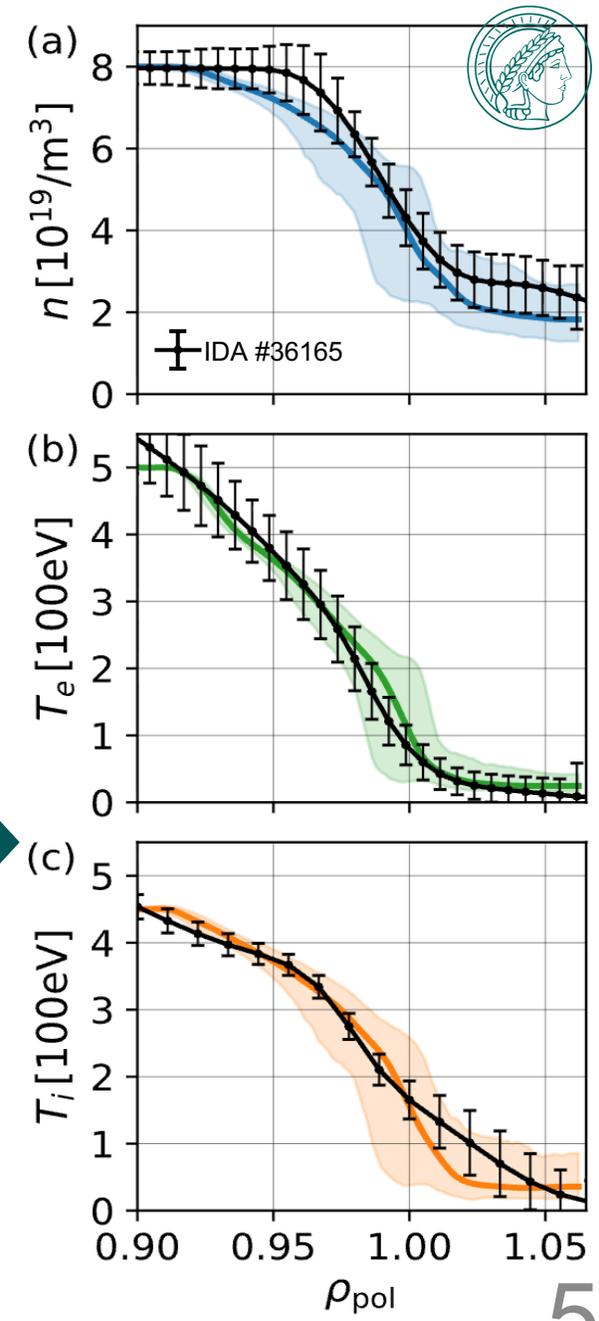$$k_{\text{pol}}\rho_s = 0.033$$
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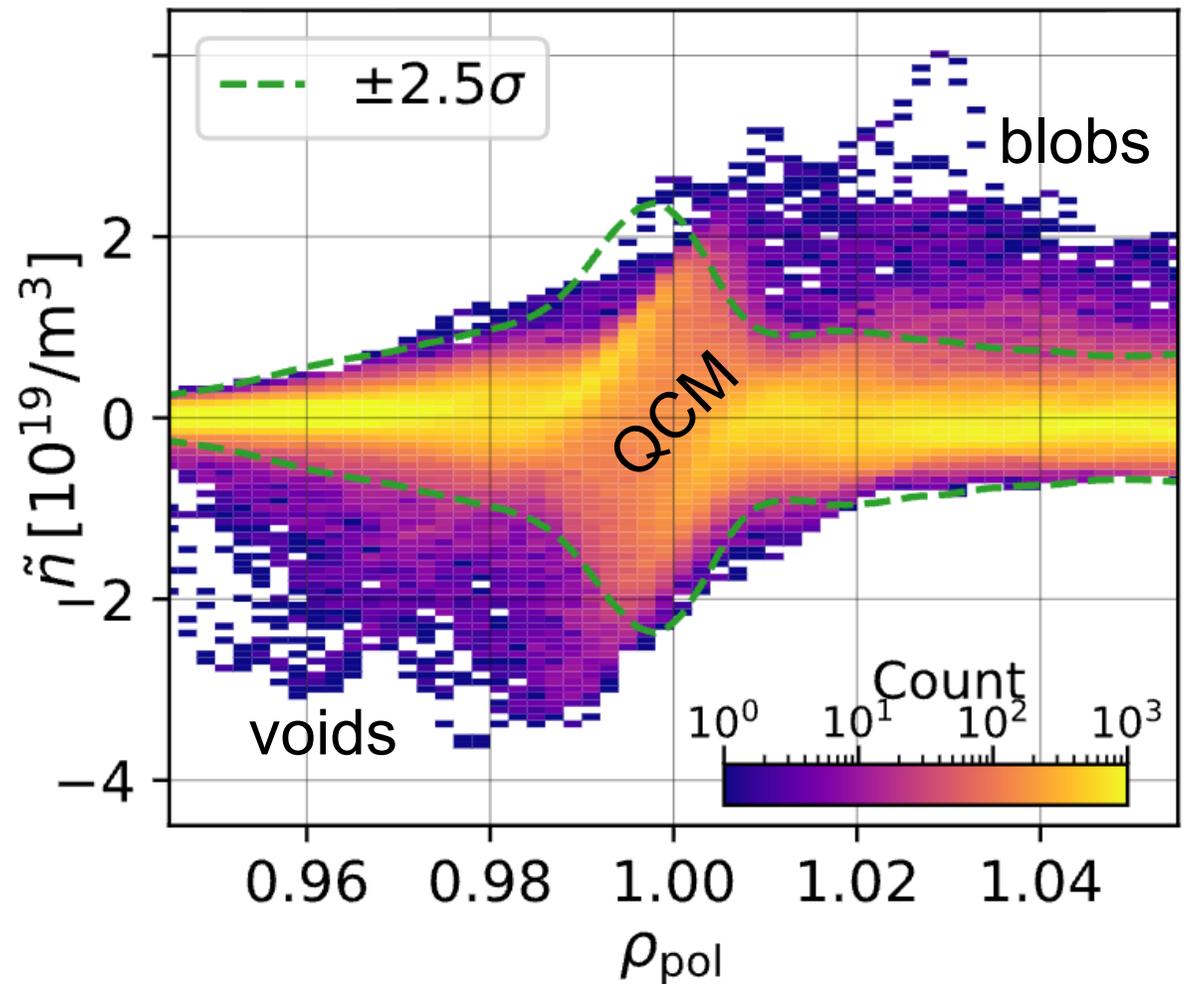
Plasma profiles

Global, full-f, first-principles

- 3-moment neutral gas model with recycling boundary

- Landau fluid closure for $q_\parallel$
Neoclassical correction for $\eta_{\text{vis},\parallel}$

- **No free parameters**

(a) IDA #36165

(b)

(c)

5

Fluctuation statistics across the separatrix
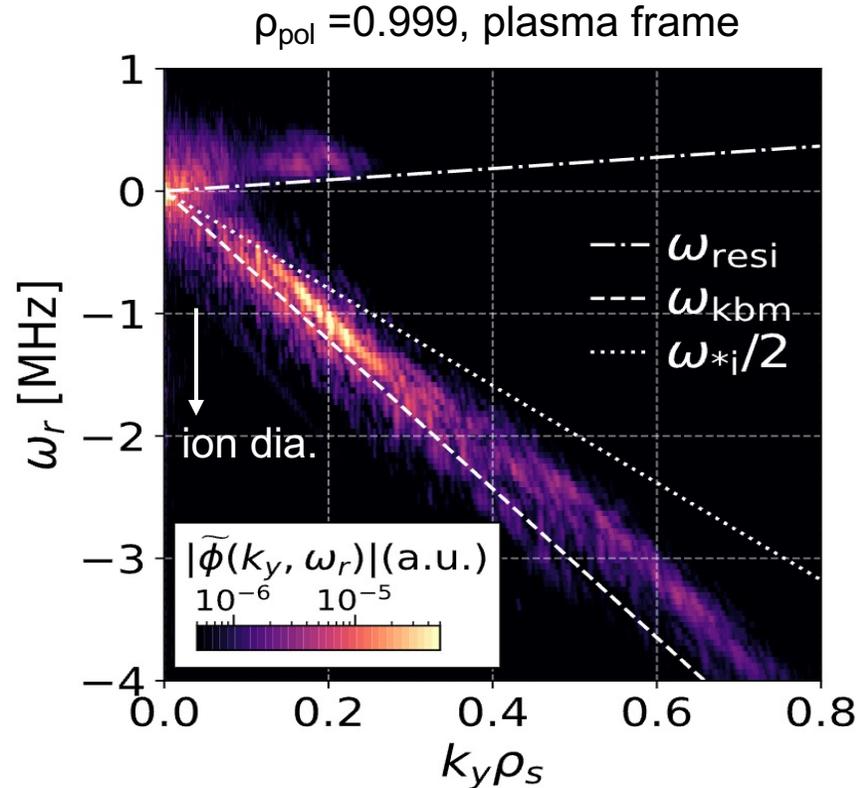
1. QCM: strong fluctuations within $\pm 2.5\sigma$ (continuous) at sep.

2. Voids $< -2.5\sigma$ (intermittent) inside sep.

3. Blobs $> 2.5\sigma$ (intermittent) outside sep.

Two separatrix-spanning modes underlying QCE

ρ_{pol} =0.999, plasma frame

- ω_{resi} (dash-dot)
- ω_{kbm} (dashed)
- $\omega_{*i}/2$ (dotted)

ion dia.

$|\widetilde{\phi}(k_y, \omega_r)|$(a.u.)

10^{-6} 10^{-5}

[J. R. Myra, Phys. Plasmas, 2005]

Kinetic ballooning mode (KBM)

'Winner' at outboard-mid plane

$$\omega_r \sim \omega_{kbm} \sim \frac{\omega_{*i}}{2}$$

$\alpha_{\phi,n} \approx \pi$

Resistive X-point mode (RXM)

'Loser' relegated near X-point

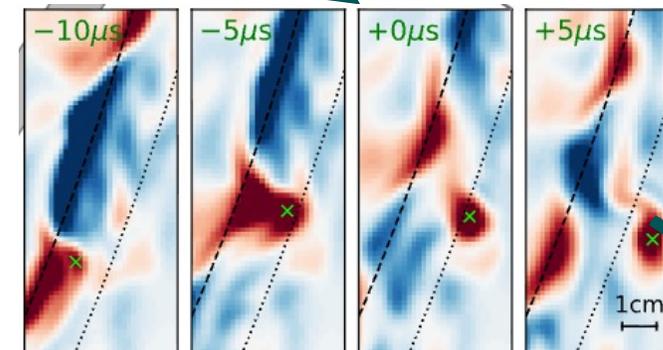$$\omega_r \sim \omega_{resi}$$

$\alpha_{\phi,n} \approx 0$

Quasi-coherent mode
in experiment

[J. Kalis, Nucl. Fusion 2024]
[G. Grenfell, Nucl. Fusion 2024]

$\alpha_{\phi,n} \approx \pi/2$

1. Separatrix: QCM is dominated by KBM
2. Near SOL: QCM undergoes $\alpha_{\phi,n} \rightarrow \pi/2$, where KBM & RXM's eigenfunctions merge, which ejects blobs.

Interchange for blobs [D. A. D'Ippolito, Phys. Plasmas, 2011]

$-10\mu s$ $-5\mu s$ $+0\mu s$ $+5\mu s$

1cm

Blobs

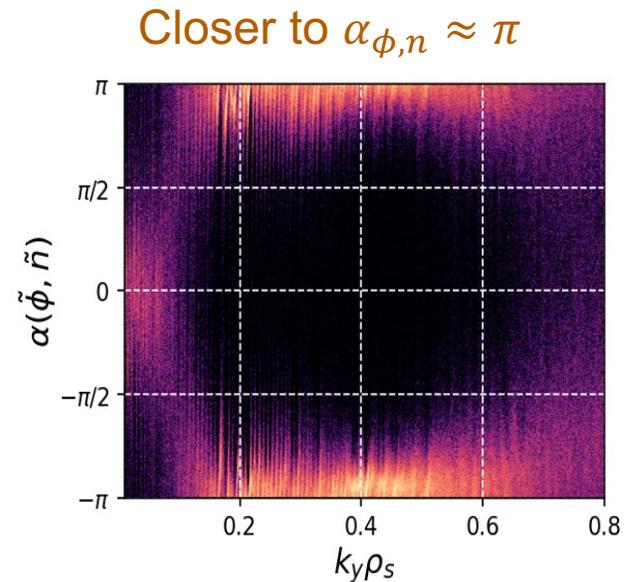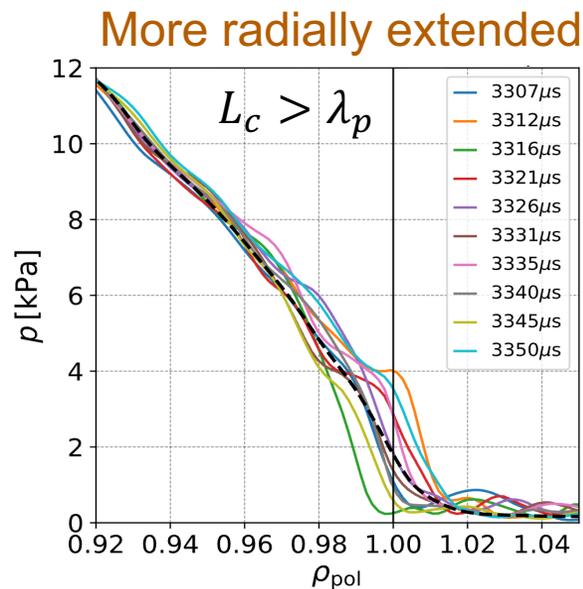# Mechanism for combining high-confinement & broad SOL fall-off
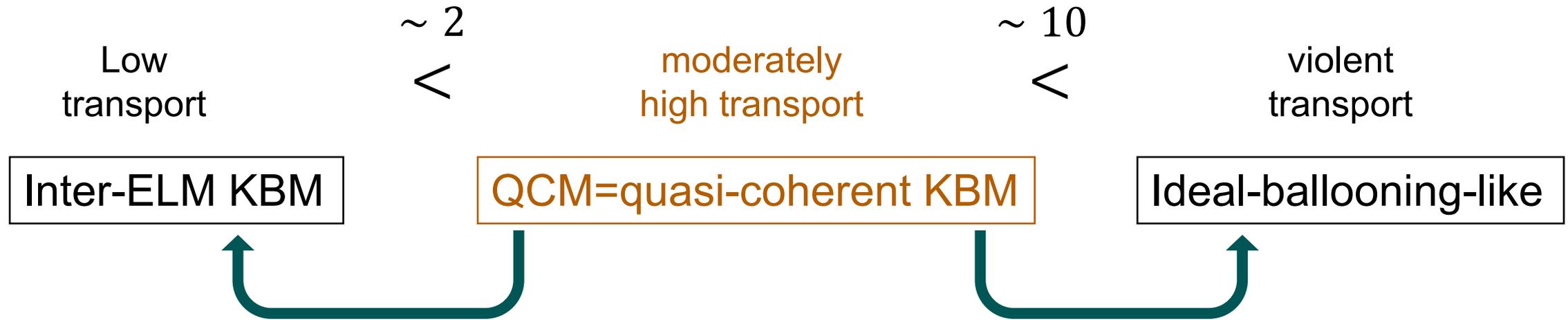
AUG [M. Faitsch, Nucl. Materials and Energy, 2021]

1. Observe **decoupled decay lengths** where

   $\alpha_{\phi,n} = \pi/2$ and QCM ejects blobs

2. Enhanced SOL transport is carried by

   intermittent fluctuations **(blobs)**

3. Pedestal-foot transport is dominated by **KBM**
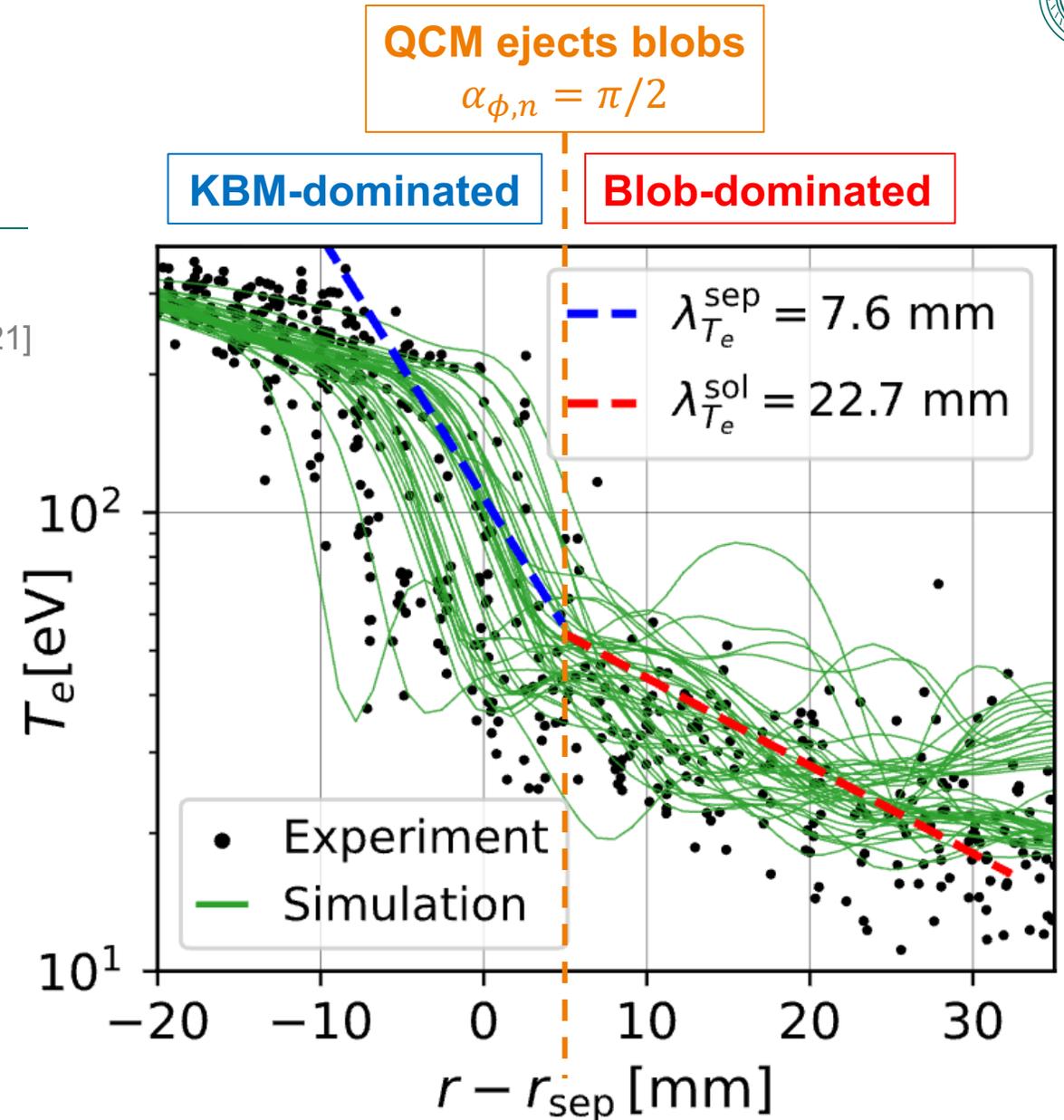
Transport properties at the pedestal foot

Experimentally, QCM avoids ELM, but can be very close to Ideal ballooning threshold

| Low transport | ~ 2 $<$ | moderately high transport | ~ 10 $<$ | violent transport |

| Inter-ELM KBM | QCM=quasi-coherent KBM | Ideal-ballooning-like |

More radially extended

$L_c > \lambda_p$

Closer to $\alpha_{\phi,n} \approx \pi$

$$E_r = \frac{\partial_r p_i}{en} + u_\varphi B_\theta - u_\theta B_\varphi$$

QCM resides inside a **broader** E_r well.

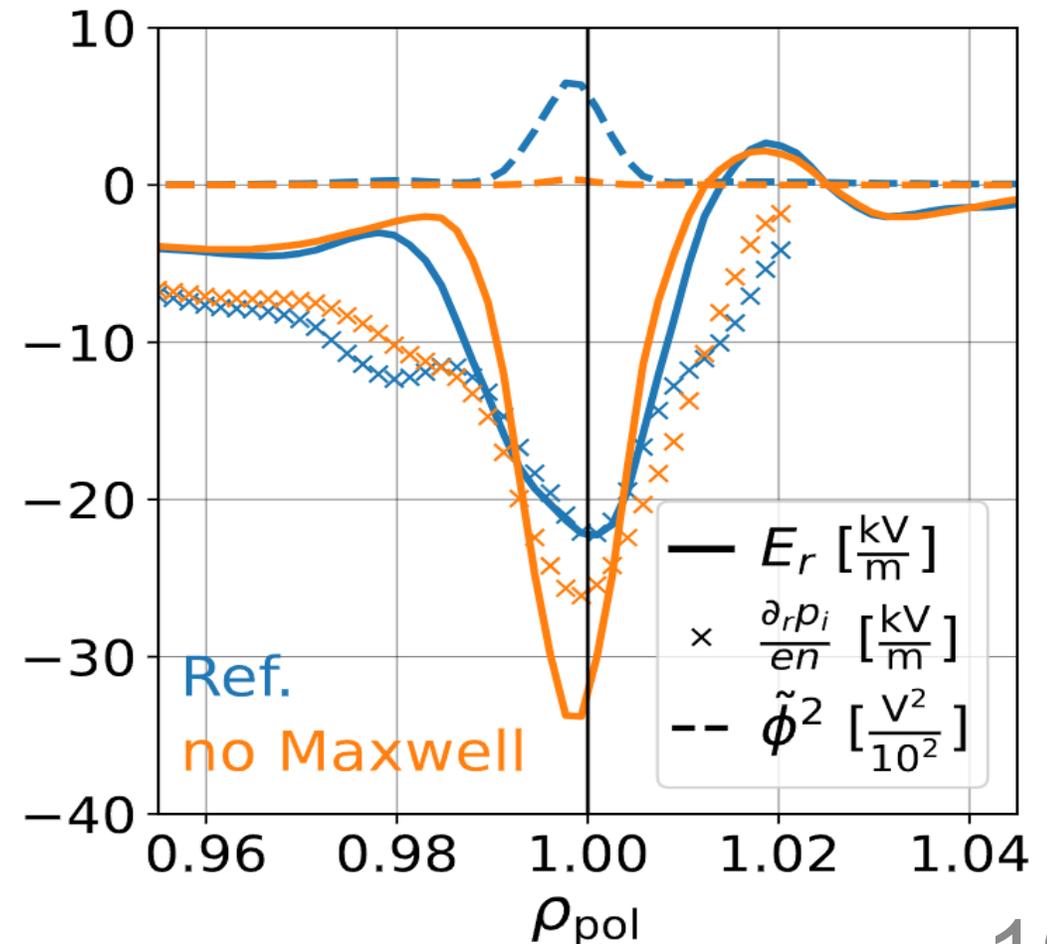AUG   [G. F. Harrer, Phys. Rev. Lett. 2022]

1. **High-n_{sep}** is a key lever for controlling QCM.

AUG   [M. Faitsch, Nucl. Fusion, 2023]
C-Mod [M.A. Miller, Nucl. Fusion, 2025]

2. **Maxwell stress** depletes zonal flow. Without it, E_r & $\partial_r p_i$ evolve deeper, QCM vanishes.

$$\frac{\partial}{\partial t}\frac{\partial \langle nu^\vartheta \rangle}{\partial \varrho} = \underbrace{-\frac{\partial^2}{\partial \varrho^2}\langle nu^\varrho u^\vartheta \rangle}_{\text{Reynolds stress}} + \underbrace{\frac{\hat{\Omega}_i}{e}\frac{\mu_0}{B_{ax}^2}\frac{\partial}{\partial \varrho^2}\langle B_1^\varrho B_1^\vartheta \rangle}_{\text{Maxwell stress}} + \text{others}$$

Ref.

no Maxwell

Legend:
— E_r [$\frac{kV}{m}$]
× $\frac{\partial_r p_i}{en}$ [$\frac{kV}{m}$]
-- $\tilde{\phi}^2$ [$\frac{V^2}{10^2}$]

ρ_{pol}
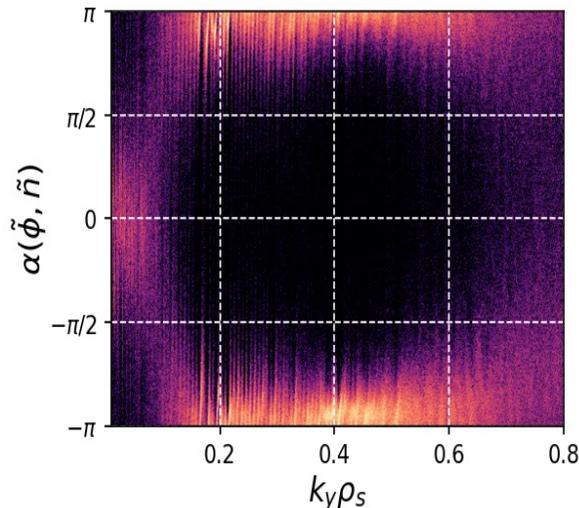
10

Mechanism for preventing violent transport

- **Finite Larmor radius effects**, sustaining $\alpha_{\phi,n} \sim \pi$

Linear KBM

$$\frac{d}{d\theta}\left(1 + (s\theta - \alpha_m \sin\theta)^2\right)\frac{d}{d\theta}\frac{\tilde{A}_\parallel}{K_\parallel} = \left[C_0 + C_2 \omega^2 + C_1 \omega + \frac{C_{-1}}{\omega - \omega_0}\right]\frac{\tilde{A}_\parallel}{K_\parallel}$$
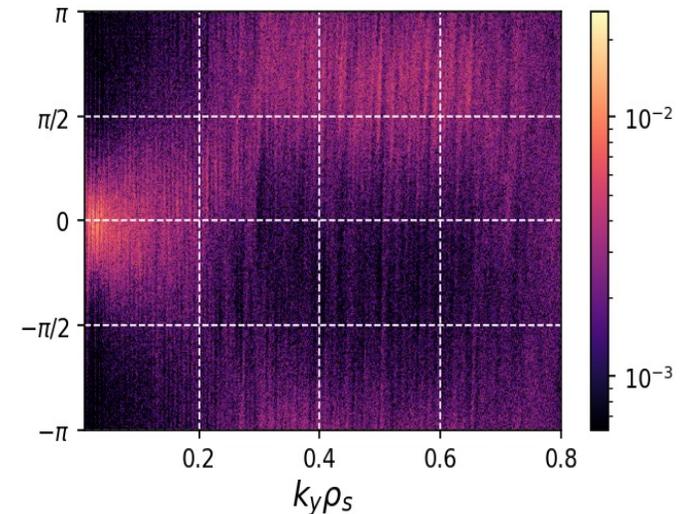
ballooning angle

magnetic shear

$\propto \frac{\partial \beta}{\partial r}$

Ideal Ballooning Mode
$\alpha_{\phi,n} = \pi/2$

Finite Larmor radius
$\alpha_{\phi,n} = \pi/2 \rightarrow \pi$

Magnetic Drift Resonance
reduce unstable threshold

Turbulence

Reduce FLR

Consequences
Heat flux $\times 10$
Pedestal drops

Conclusions

- Validation against a wide set of experiment metrics:
  mean profiles, fluctuation spectra, mode structure

- Two separatrix-spanning modes
  Kinetic ballooning mode, KBM (outboard midplane)
  Resistive X-point mode, RXM (X-point)

- Quasi-coherent mode: a self-organized mesoscopic KBM,
  with Finite Lamour radius effects and Maxwell stress regulating its transport
- Blobs: ejected by interchange dynamics during the interaction between RXM and KBM
- The blob-dominated SOL temperature fall-off is well decoupled from
  the pedestal-foot gradient set by the QCM.