MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

ASDEX Upgrade

Experimental impurity transport studies for the plasma edge in different confinement regimes at ASDEX Upgrade

T. Gleiter, R. Dux, F. Sciortino, D. Fajardo, T. Hayward-Schneider,
R. M. McDermott, T. Odstrčil, E. Wolfrum, U. Stroth
and the ASDEX Upgrade Team

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

MOTIVATION

REQUIREMENTS FOR A REACTOR:

ENERGY CONFINEMENT	POWER EXHAUST

ENERGY CONFINEMENT

- High confinement operation regime
- Small impurity concentration in the core
  to avoid fuel dilution and energy loss by radiation

POWER EXHAUST

- ELM-free or -mitigated operation regime
  to avoid peak power loads
- Seed impurities at the edge
  for pedestal and divertor radiative cooling

Type-I ELMy H-mode

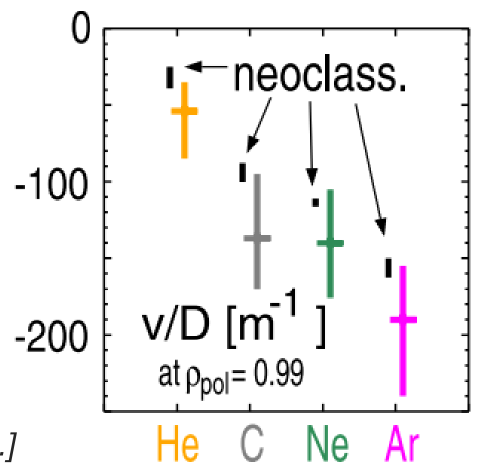
Inter-ELM impurity transport:

Suppressed turbulence /
transport at neoclassical, i.e., collisional level
at the edge transport barrier

→ *inward impurity transport at AUG*

→ *outward impurity transport expected for ITER*

[see **Ralph Dux** *et al. (2014). Plasma Phys. Control. Fusion, 56: 124003.]*



Thomas Pütterich *et al. (2011).*
J. Nucl. Mater., 415: 334-339.

ELM-free / -mitigated confinement regimes: QCE-regime, EDA-H mode, …

OUTLINE

EXPERIMENTAL SETUP: DISCHARGES & DIAGNOSTICS

ANALYSIS PRINCIPLE: IMPURITY TRANSPORT INFERENCES

TRANSPORT IN TYPE-I ELMY H-MODE VS. QCE-REGIME

SUMMARY

EXPERIMENTAL SETUP: DISCHARGES & DIAGNOSTICS

SET OF PERFORMED DISCHARGES

Various combinations of **confinement regimes** and **seed impurities** (in 2021 & 2022 campaigns):

	Neon	Argon	Nitrogen
Type-I ELMy H-mode	39086, 40219	40501	
QCE regime	39461, 40219, 40014	40501	
EDA-H regime	39463	40502	
I-mode	38711		
L-mode	40014		
RMP ELM-suppression		40570, 40805, 40807, 40808	
XPR regime	40758, 40760		40759

Up to now:
comparing neon transport
in type-I ELMy H-mode
and QCE-regime

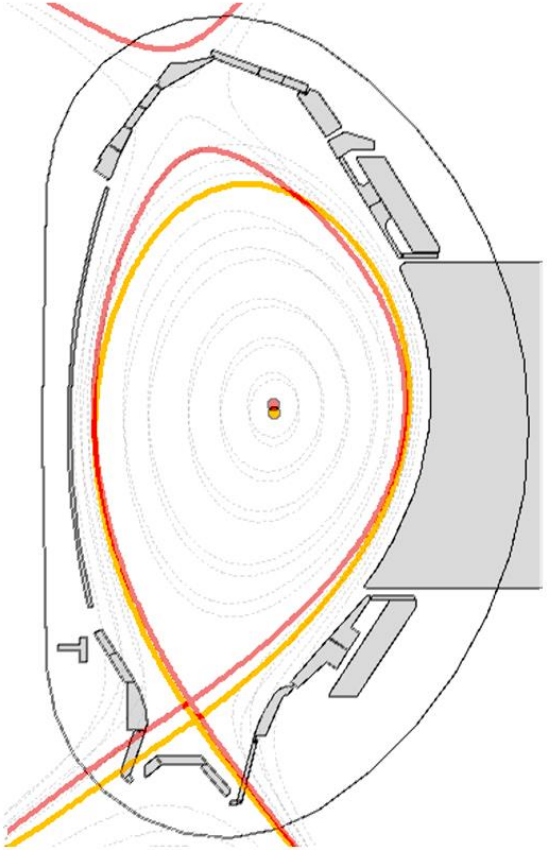
FOCUS: TYPE-I ELMy H-MODE VS. QCE REGIME

#39086 (4.30-7.47 s): type-I ELMy H-mode

- I_p = 1.0 MA
- $\delta_{up} = (R_{geo}-R_{up})/a = 0.03$
- D gas puff = $0.6\cdot10^{22}$ el/s

#39461 (3.95-6.81 s): QCE regime

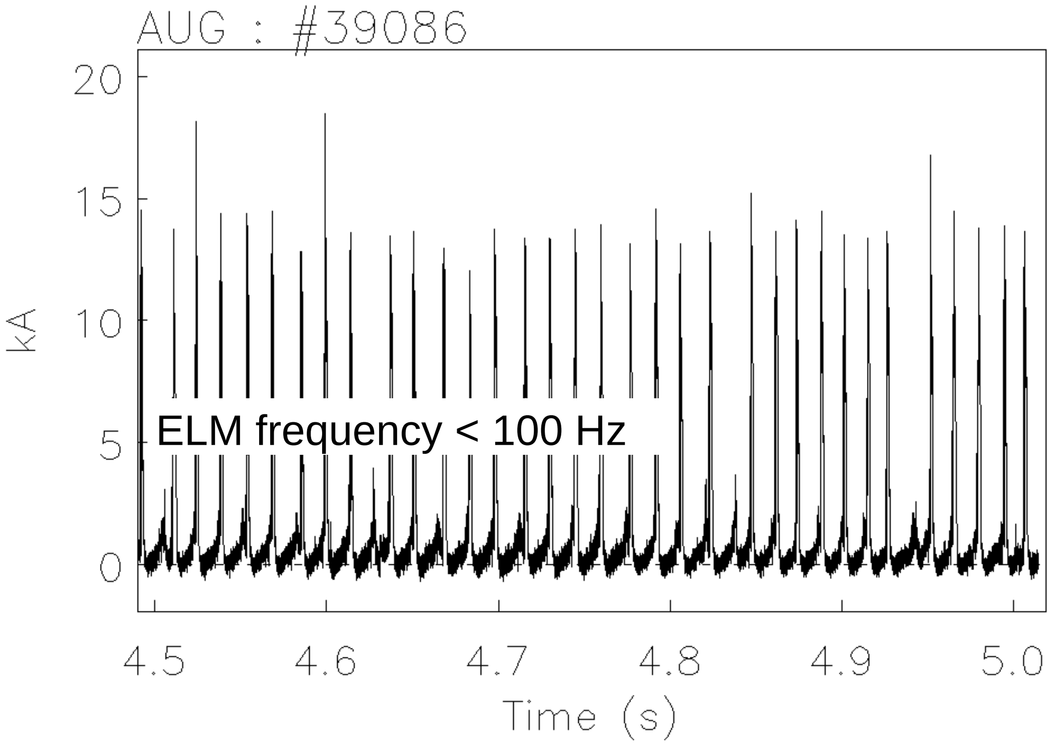
- I_p = 0.8 MA
- $\delta_{up} = (R_{geo}-R_{up})/a = 0.26$
- D gas puff = $2.4\cdot10^{22}$ el/s



FOCUS: TYPE-I ELMy H-MODE VS. QCE REGIME

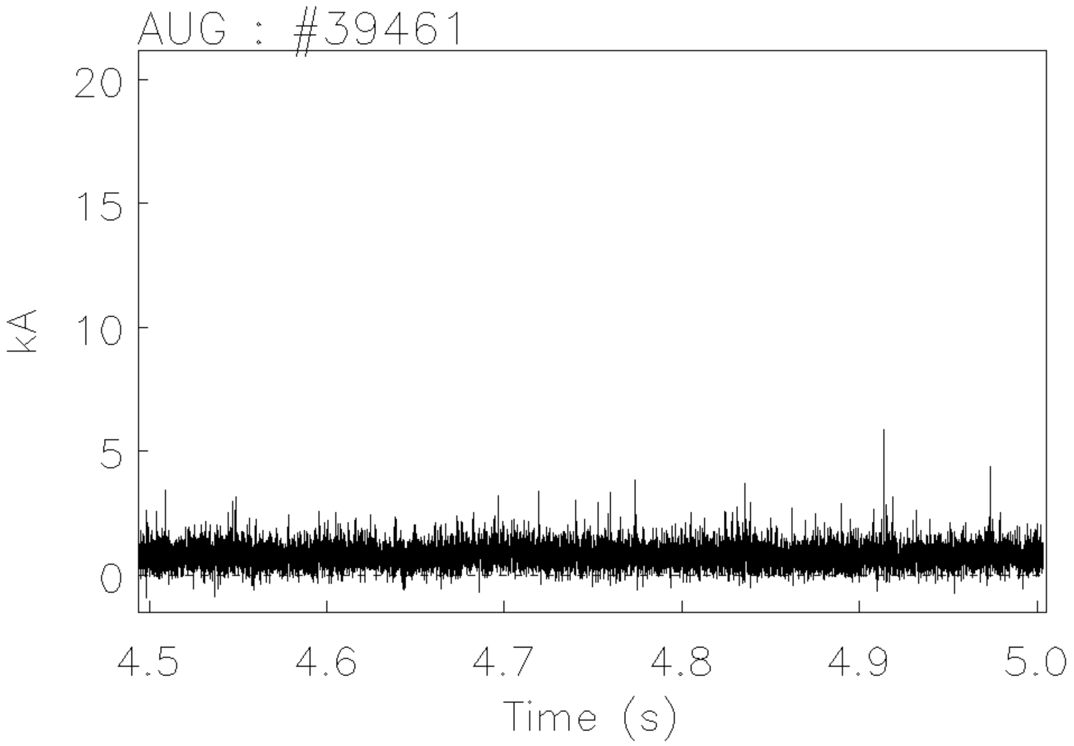
#39086 (4.30-7.47 s): type-I ELMy H-mode

- I_p = 1.0 MA
- $\delta_{up} = (R_{geo}-R_{up})/a = 0.03$
- D gas puff = $0.6 \cdot 10^{22}$ el/s



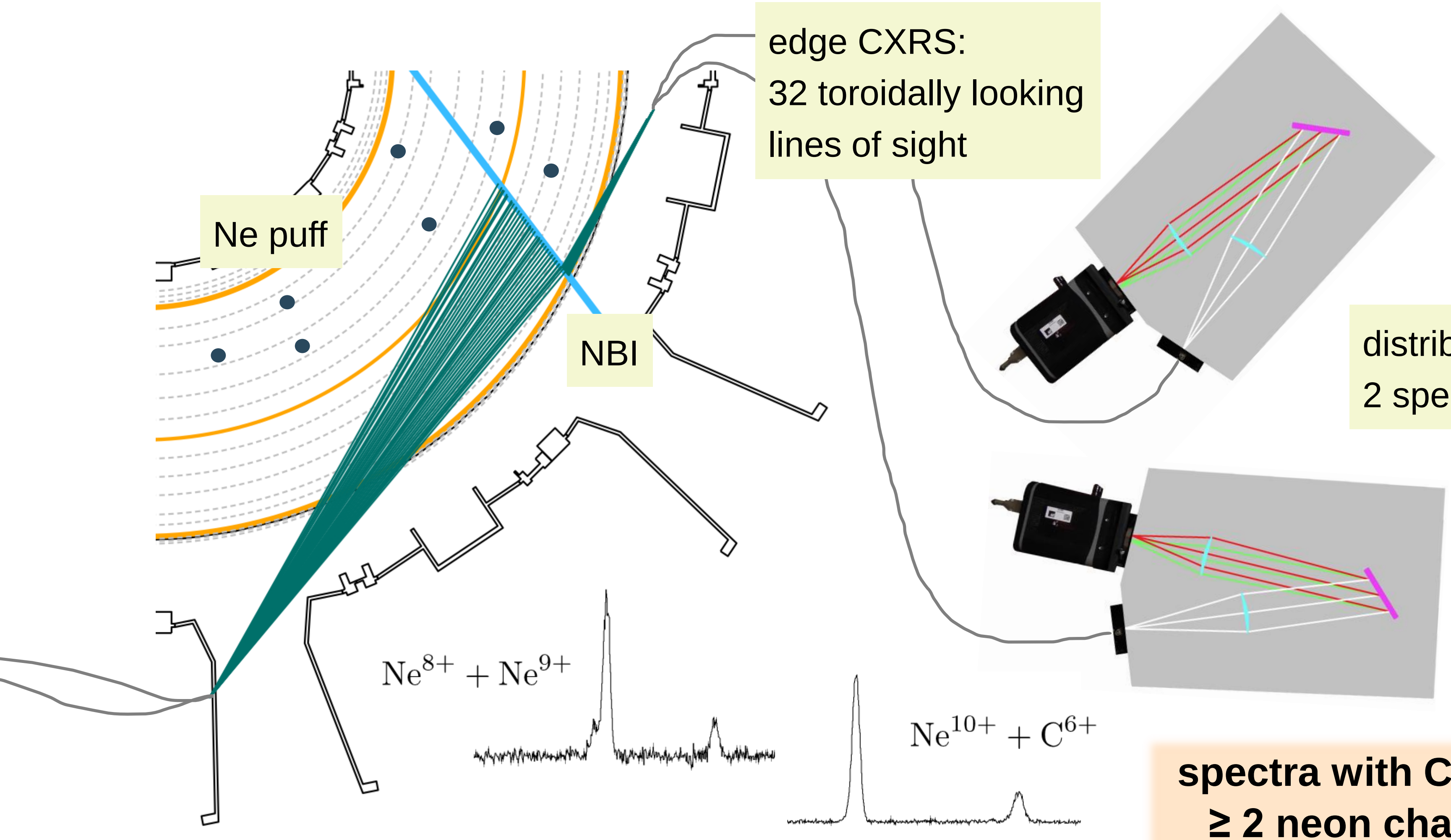
#39461 (3.95-6.81 s): QCE regime

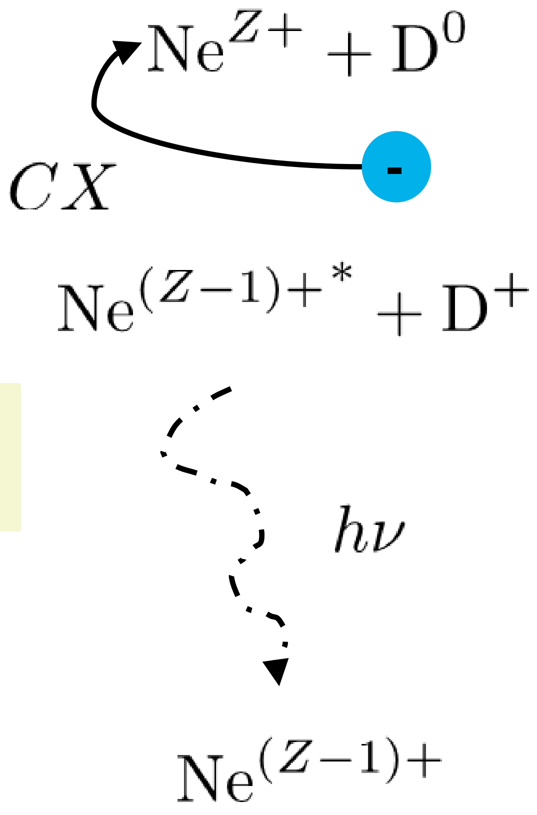
- I_p = 0.8 MA
- $\delta_{up} = (R_{geo}-R_{up})/a = 0.26$
- D gas puff = $2.4 \cdot 10^{22}$ el/s



TAILORED CXRS SETUP

CHARGE EXCHANGE RECOMBINATION SPECTROSCOPY

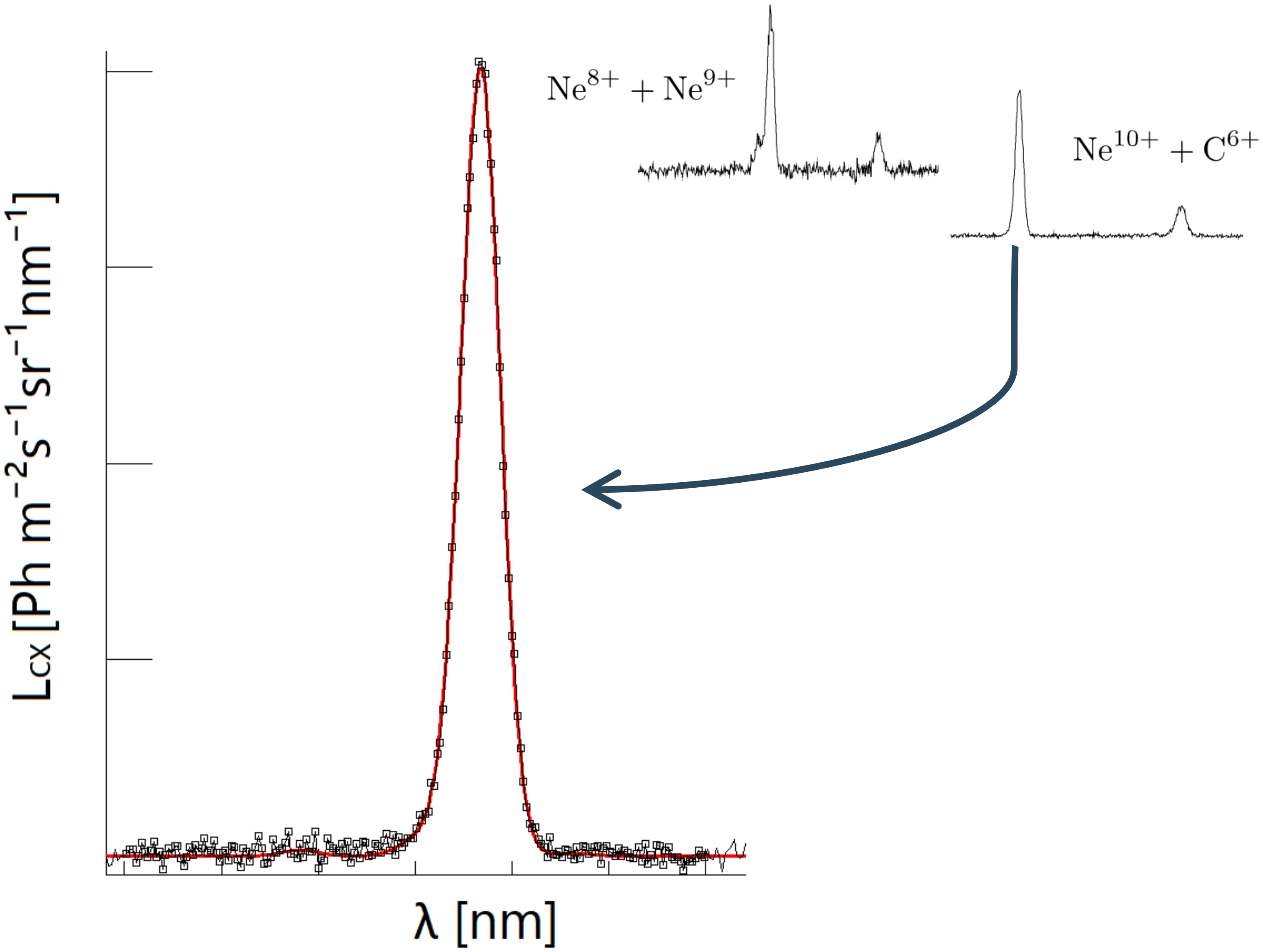




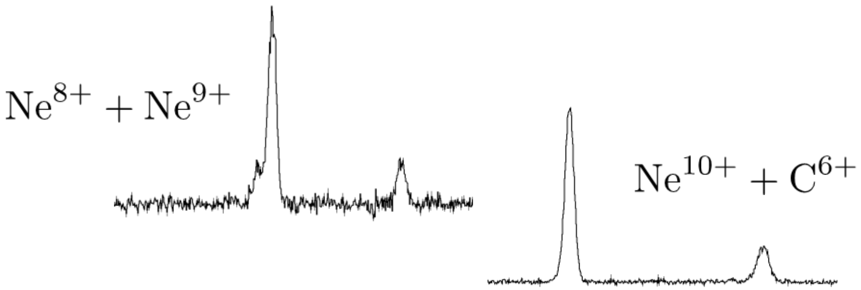
spectra with CX-lines from ≥ 2 neon charge stages along a radial profile!

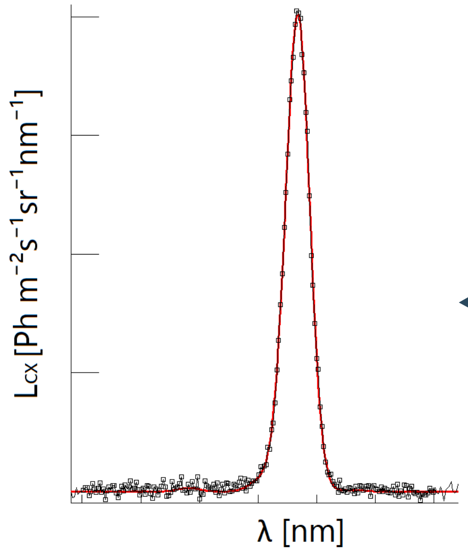
ANALYSIS PRINCIPLE: IMPURITY TRANSPORT INFERENCES

FROM SPECTROSCOPY TO IMPURITY TRANSPORT



FROM SPECTROSCOPY TO IMPURITY TRANSPORT





T_e

T_i

n_e

n_{D^+}

Z_{eff}

beam model &
beam attenuation code
(COLRAD)

ADAS code

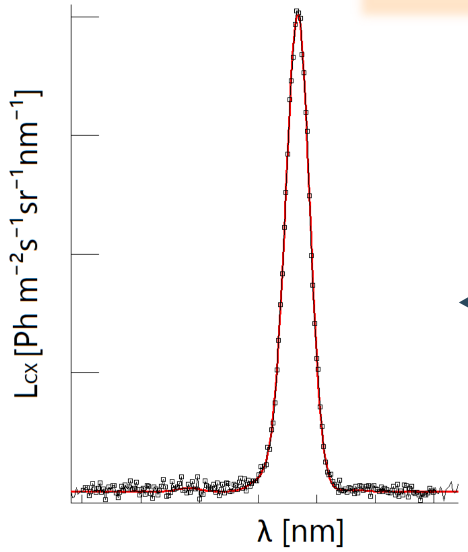
Forward model for line radiances:

$$L_{\mathrm{CX,\ LOS}} = \frac{h\nu}{4\pi} \sum_n \sum_j \int_{\mathrm{LOS}} n_{\mathrm{Ne}^{Z+}} \cdot n_{\mathrm{D}^0_{\mathrm{NBI},n,j}} \cdot \langle \sigma_{\mathrm{CX},n,j} v_j \rangle_{\mathrm{eff}}\, \mathrm{dl}$$

FROM SPECTROSCOPY TO IMPURITY TRANSPORT

Remember:

- **Radial resolution due to multiple LOS!**
- **Data for ≥ 2 charge stages!**



T_e T_i n_e n_{D^+} Z_{eff}

beam model & beam attenuation code (COLRAD)

ADAS code

Forward model for line radiances:

$$L_{CX,\ LOS} = \frac{h\nu}{4\pi} \sum_n \sum_j \int_{LOS} n_{Ne^{Z+}} \cdot n_{D^0_{NBI,n,j}} \cdot \langle \sigma_{CX,n,j} v_j \rangle_{eff} \, dl$$

FROM SPECTROSCOPY TO IMPURITY TRANSPORT

Continuity equation for each Z:

$$\frac{\partial n_{\mathrm{Ne}^{Z+}}}{\partial t} = Q_{\mathrm{Ne}^{Z+}} - \nabla \cdot \vec{\Gamma}_{\mathrm{Ne}^{Z+}}$$

ADAS atomic rates:

- ionization
- recombination
- thermal CX

T_e n_e

KN1D code

T_i

1.5 D approach

$$\frac{\partial n_{\mathrm{Ne}^{Z+}}}{\partial t} = Q_{\mathrm{Ne}^{Z+}} - \frac{1}{r}\frac{\partial}{\partial r}\left[r\Gamma_r\right]$$

diffusive-convective ansatz

$$\frac{\partial n_{\mathrm{Ne}^{Z+}}}{\partial t} = Q_{\mathrm{Ne}^{Z+}} - \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(-D\frac{\partial n_{\mathrm{Ne}^{Z+}}}{\partial r} + v n_{\mathrm{Ne}^{Z+}}\right)\right]$$

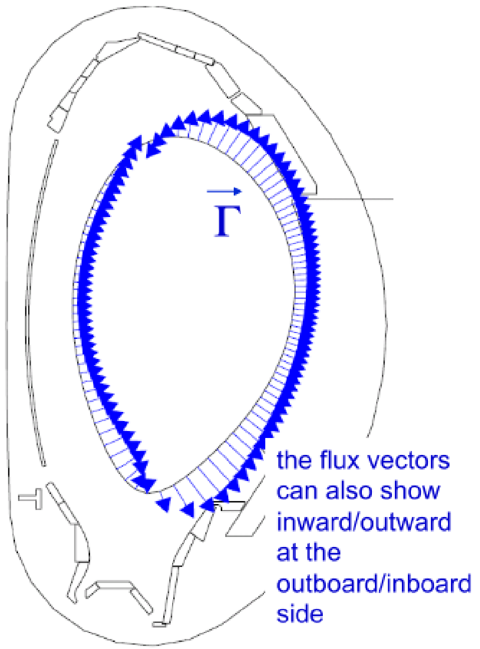
impurity transport solver:
STRAHL / Aurora

$n_{\mathrm{Ne}^{Z+}} \; \forall Z$

data for
≥ 2 charge stages

assume same D and v
for all present
charge stages

D and v of flux-surface averaged impurity transport can be inferred from radially resolved CXRS data of ≥ 2 impurity charge stages!



Graphic: Ralph Dux

BAYESIAN PROBABILITY ESTIMATION

Problems with minimizations:

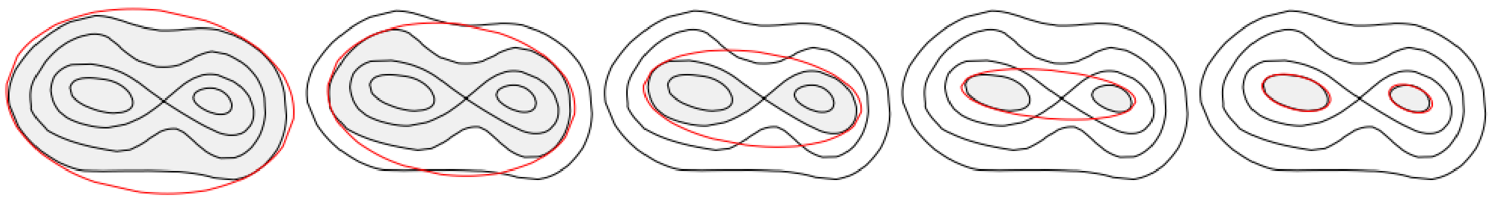
- ‘false’ (local) minima – depending on initial conditions
- deficient uncertainty quantification, e.g., only Gaussian errors
- neglect of prior knowledge about the parameter space

Better: Bayesian statistics – inference of parameters’ full probability distribution

$$p(\mathrm{P}|\mathrm{D},\mathrm{M}) \propto p(\mathrm{D}|\mathrm{P},\mathrm{M}) \cdot p(\mathrm{P}|\mathrm{M})$$

In practice: OMFIT ImpRad module

- employing the Nested Sampling algorithm MultiNest
- likelihood calculations with Aurora
- user specified prior probability distributions for all parameters



Farhan Feroz *et al. (2008). Mon. Not. R. Astron. Soc.*, 000: 1–14.

OMFIT: **Orso Meneghini** *et al. (2013). Plasma Fusion Res.*, 8:2403009-2403009.

Aurora: **Francesco Sciortino** *et al. (2021). Plasma Phys. Control. Fusion*, 63:112001.

BAYESIAN PROBABILITY ESTIMATION

Problems with minimizations:

- ‘false’ (local) minima – depending on initial conditions
- deficient uncertainty quantification, e.g., only Gaussian errors
- neglect of prior knowledge about the parameter space

Better: Bayesian statistics – inference of parameters’ full probability distribution

$$p(\mathrm{P}|\mathrm{D},\mathrm{M}) \propto p(\mathrm{D}|\mathrm{P},\mathrm{M}) \cdot p(\mathrm{P}|\mathrm{M})$$

In practice: OMFIT ImpRad module

- employing the Nested Sampling algorithm MultiNest
- likelihood calculations with Aurora
- user specified prior probability distributions for all parameters

Parameter space:

- *D and v at spline knot positions (cubic spline parameterization) (+ spline knot positions)*
- *1 scaling parameter for the thermal neutral D density profile (shape from KN1D)*
- *2 fudge factors for edge CXRS diagnostics*
- *other parameters thinkable…*

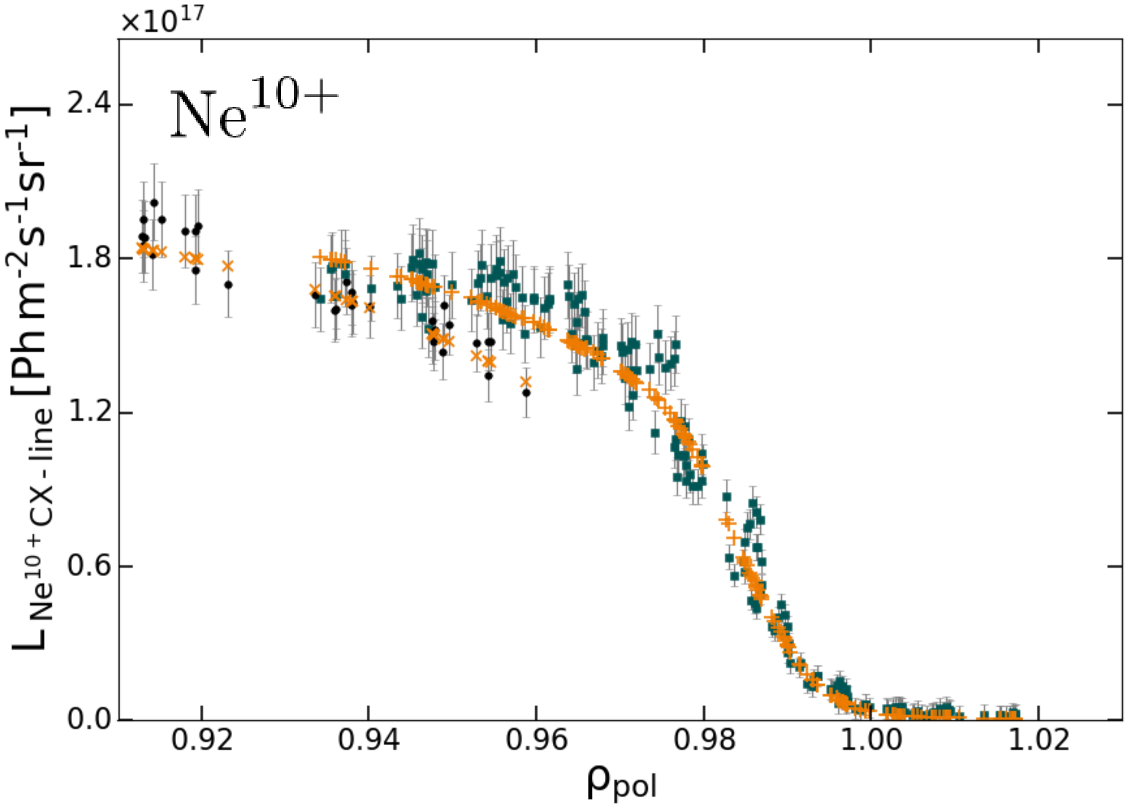
OMFIT: **Orso Meneghini** *et al. (2013). Plasma Fusion Res.*, 8:2403009-2403009.

Aurora: **Francesco Sciortino** *et al. (2021). Plasma Phys. Control. Fusion*, 63:112001.

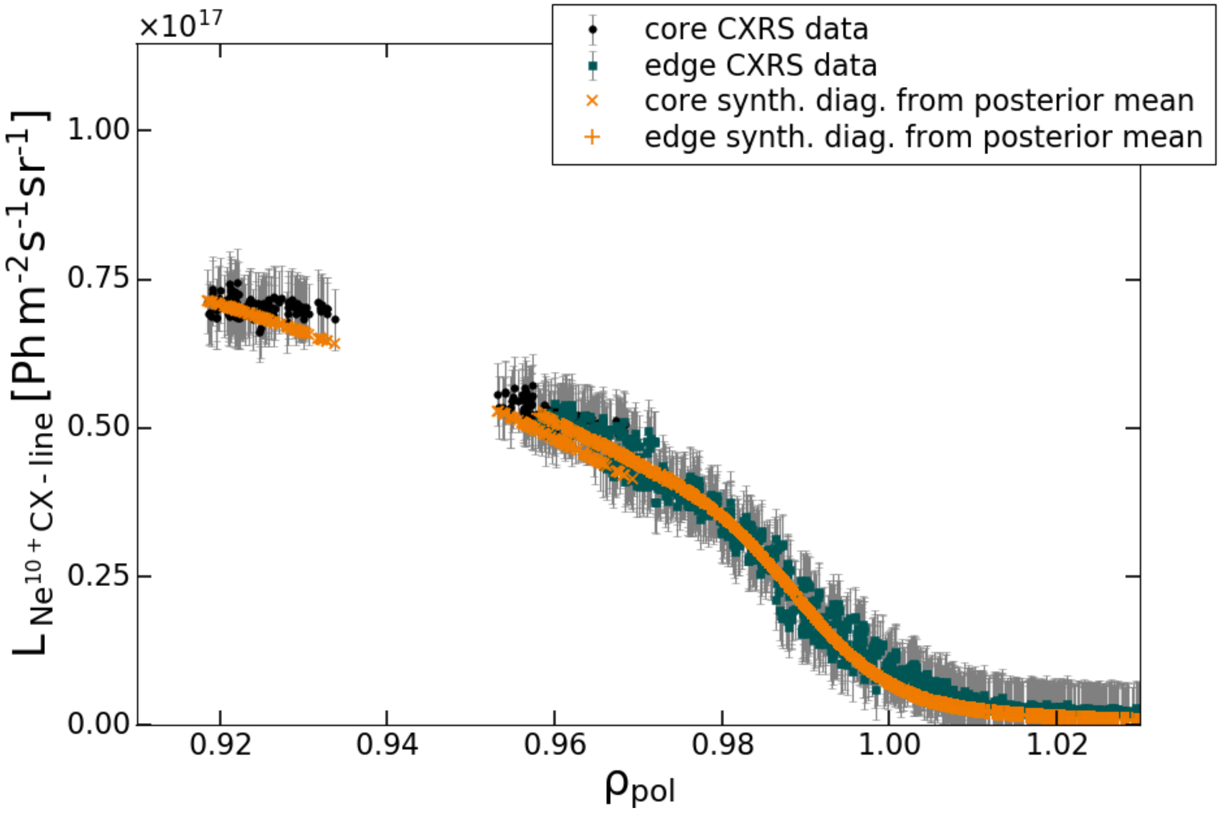
TRANSPORT IN TYPE-I ELMY H-MODE VS. QCE-REGIME

DATA AGREEMENT

#39086: type-I ELMy H-mode



#39461: QCE regime

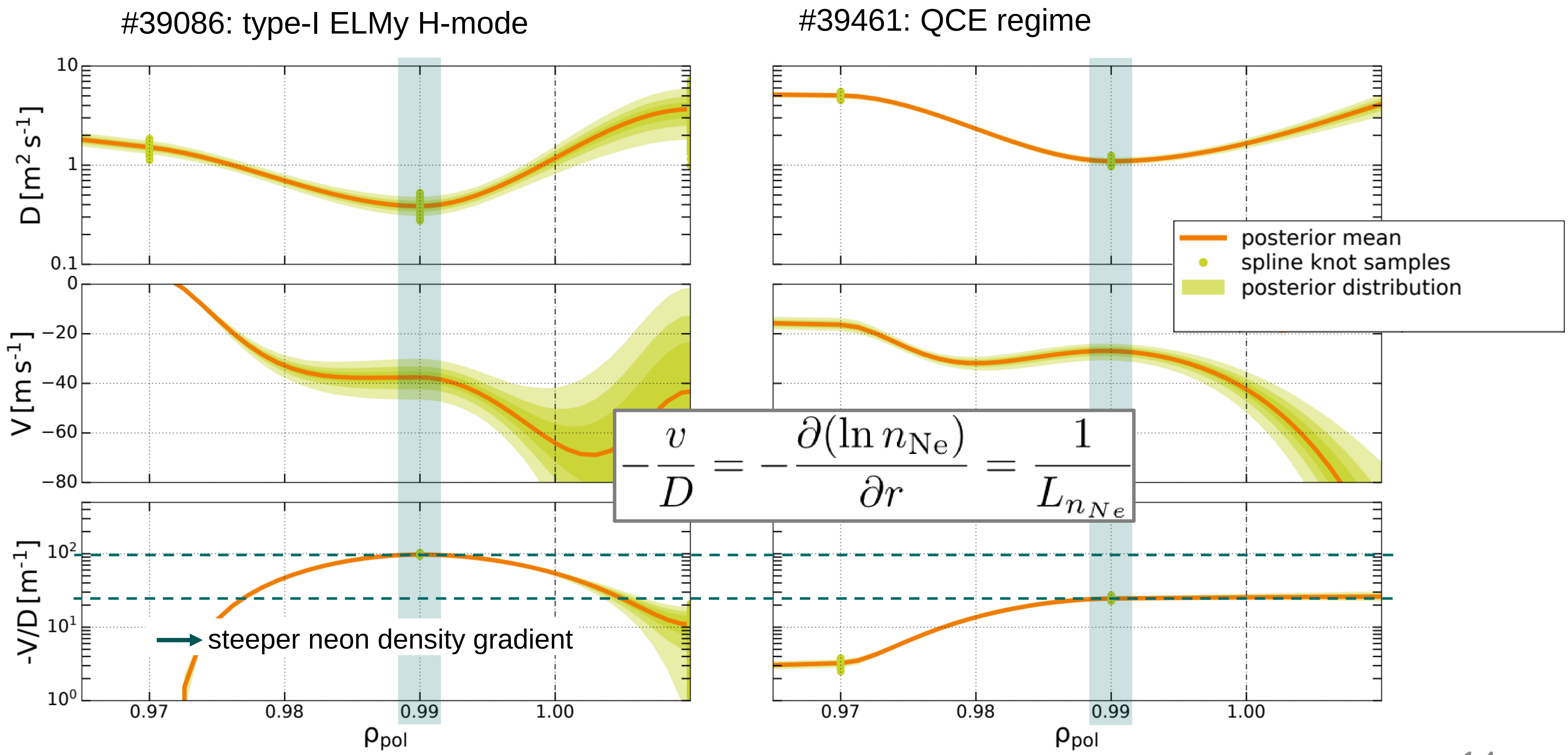


Different geometry of edge and core LOS → different LOS integrated radiances!

$f_{\text{edge CXRS}} = 0.82$

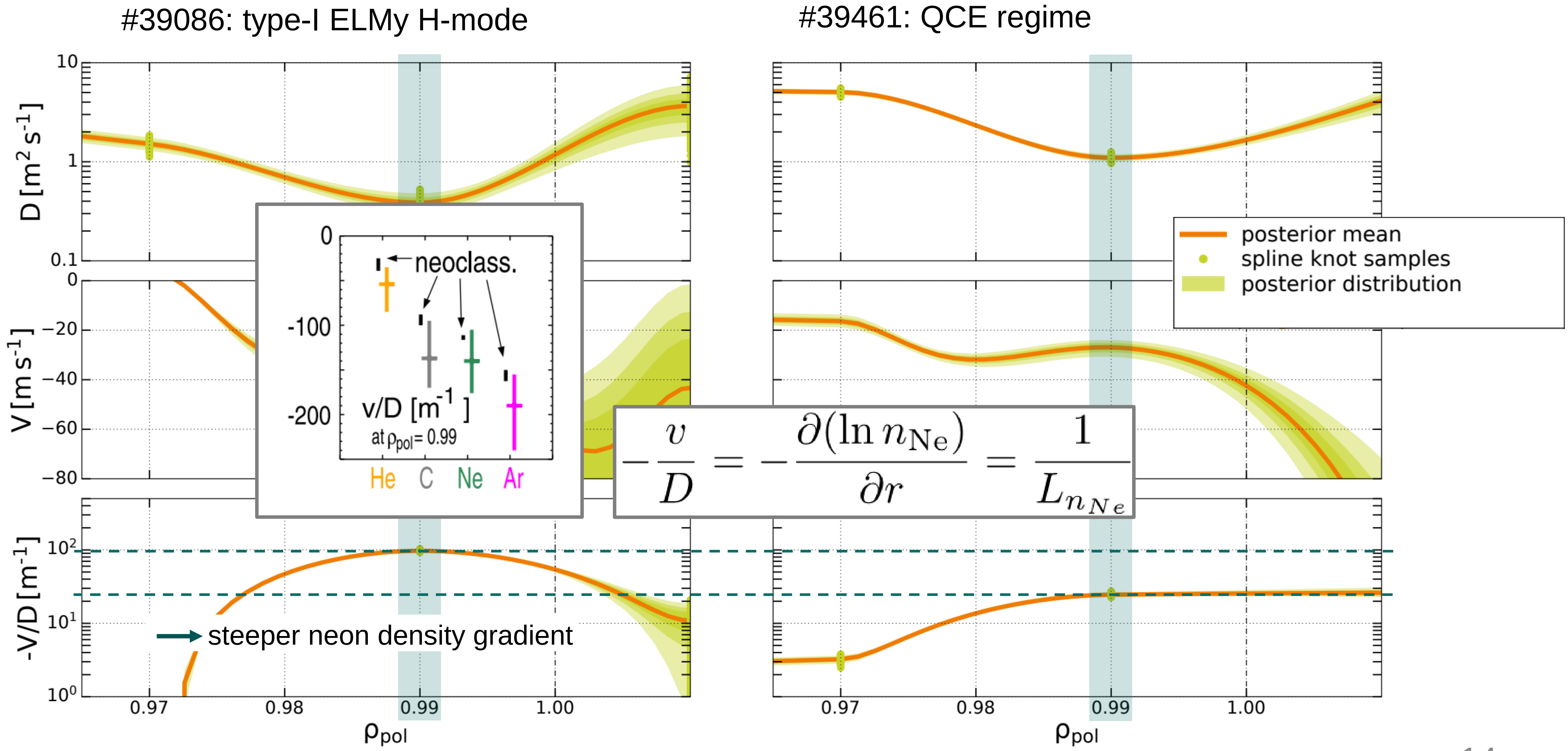
$f_{\text{edge CXRS}} = 1.00$

TRANSPORT COEFFICIENTS



$$-\frac{v}{D} = -\frac{\partial(\ln n_{\mathrm{Ne}})}{\partial r} = \frac{1}{L_{n_{Ne}}}$$

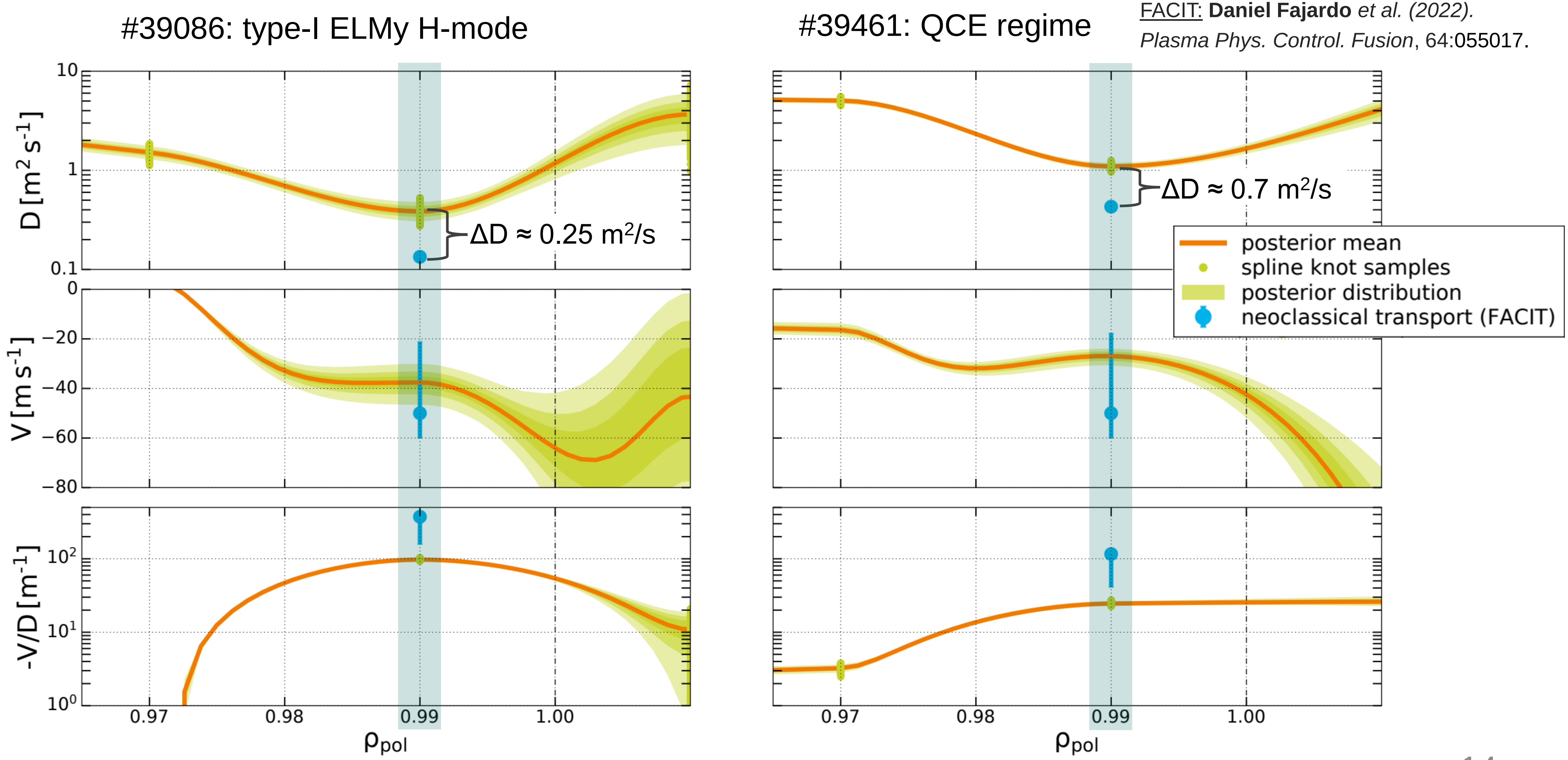
TRANSPORT COEFFICIENTS



$$-\frac{v}{D} = -\frac{\partial(\ln n_{\mathrm{Ne}})}{\partial r} = \frac{1}{L_{n_{Ne}}}$$

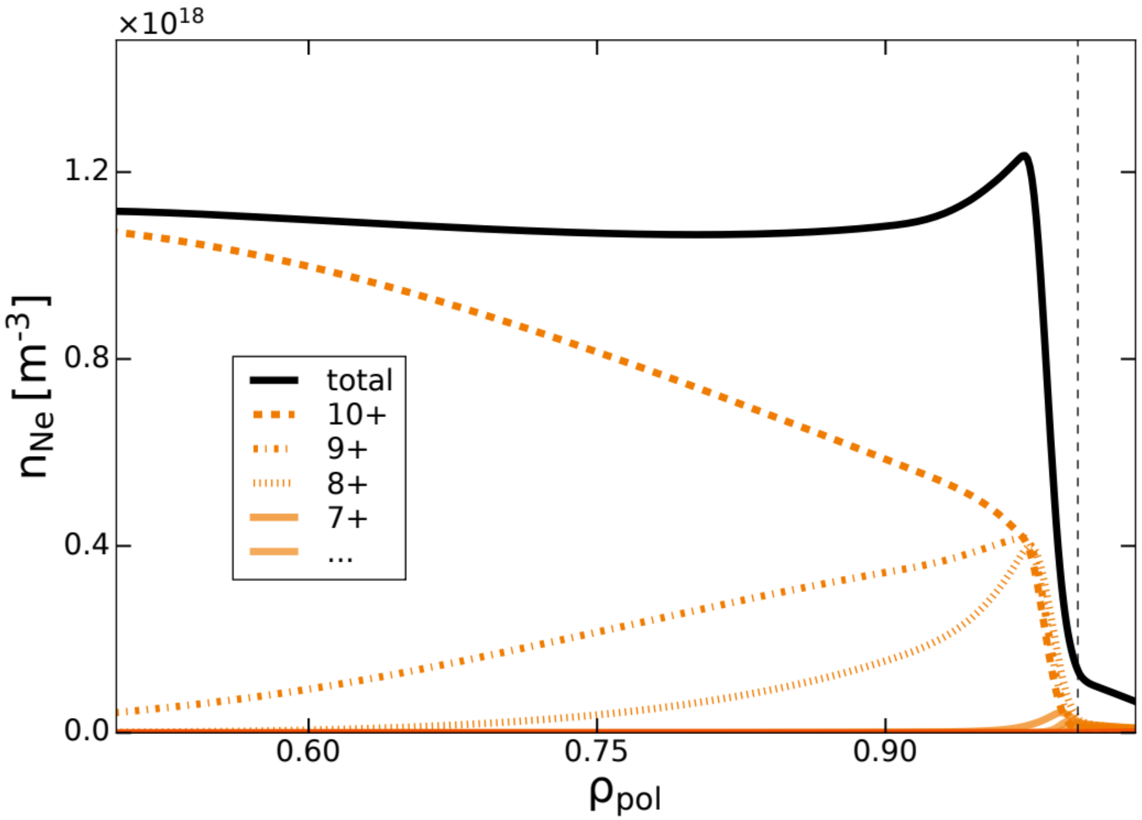
TRANSPORT COEFFICIENTS

FACIT: **Daniel Fajardo** *et al. (2022). Plasma Phys. Control. Fusion*, 64:055017.

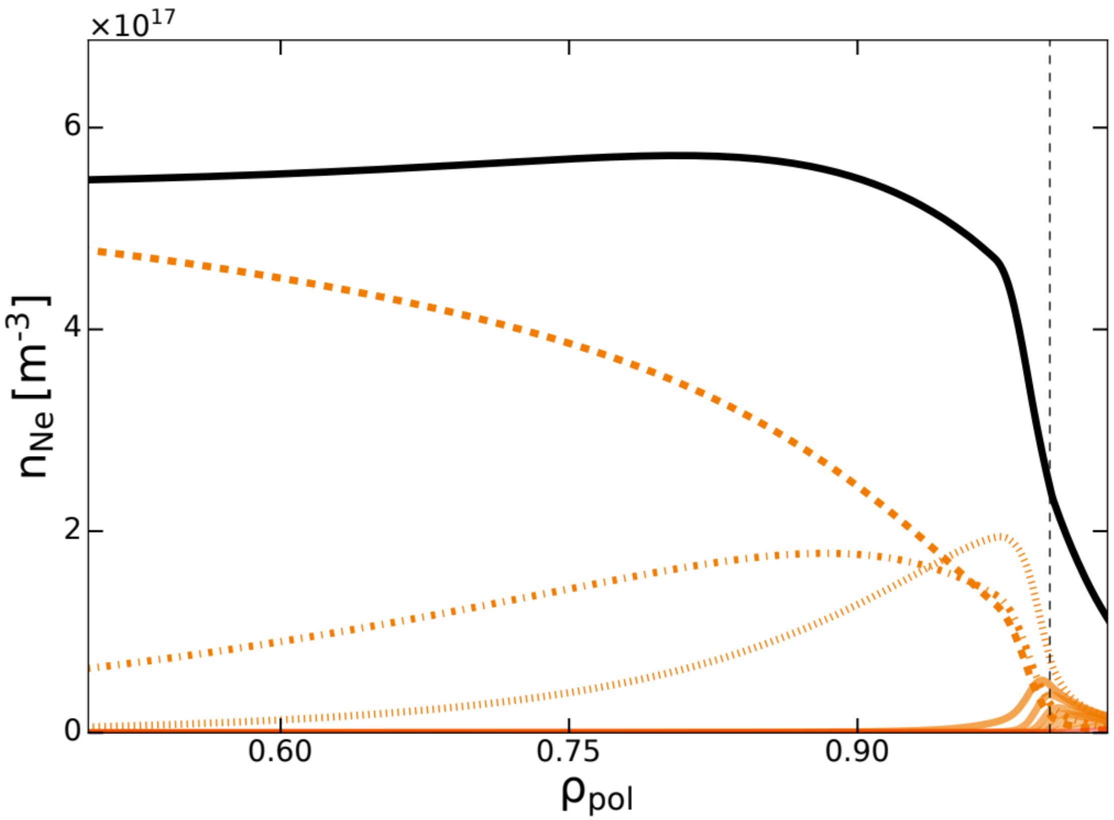


CHARGE STAGE DISTRIBUTIONS

#39086: type-I ELMy H-mode

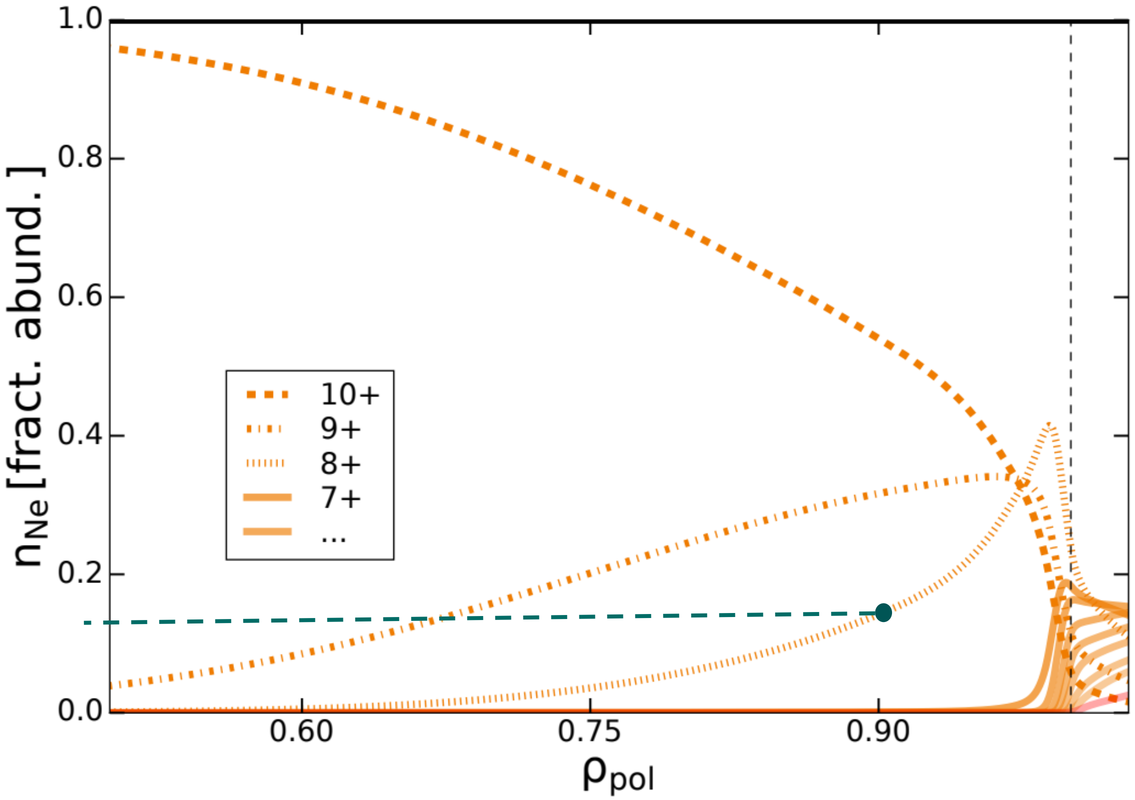


#39461: QCE regime

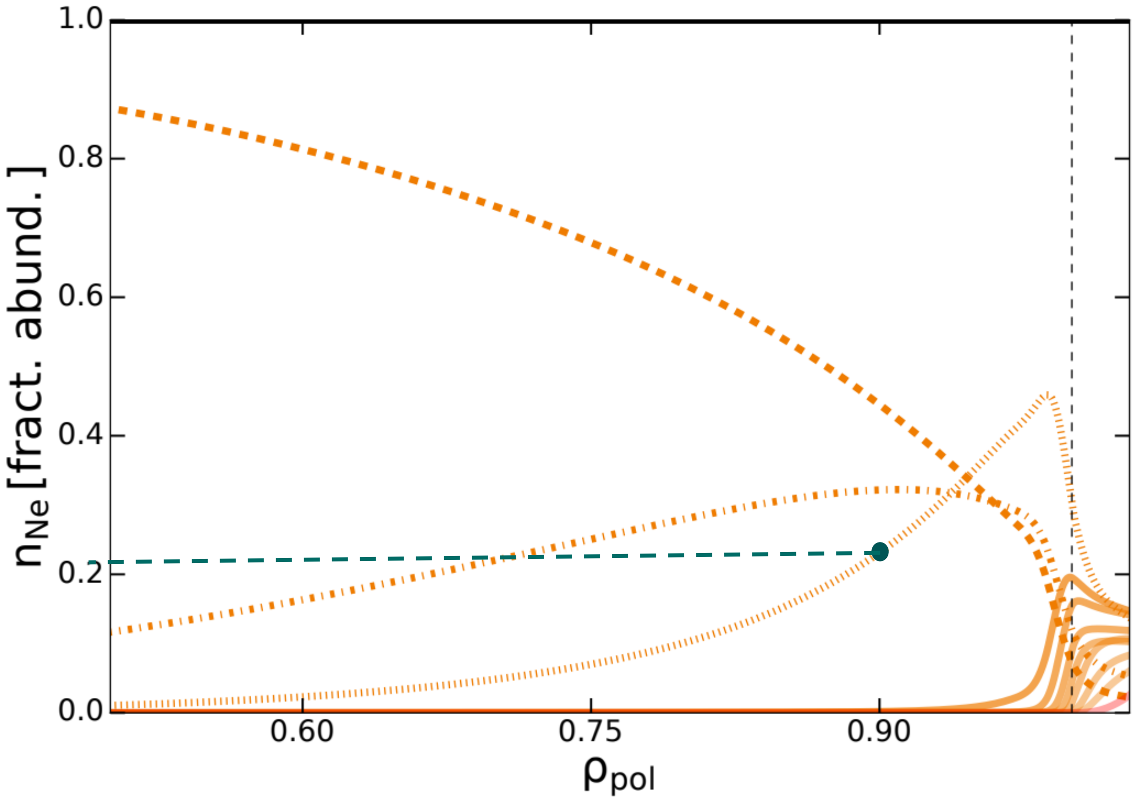


CHARGE STAGE DISTRIBUTIONS

#39086: type-I ELMy H-mode



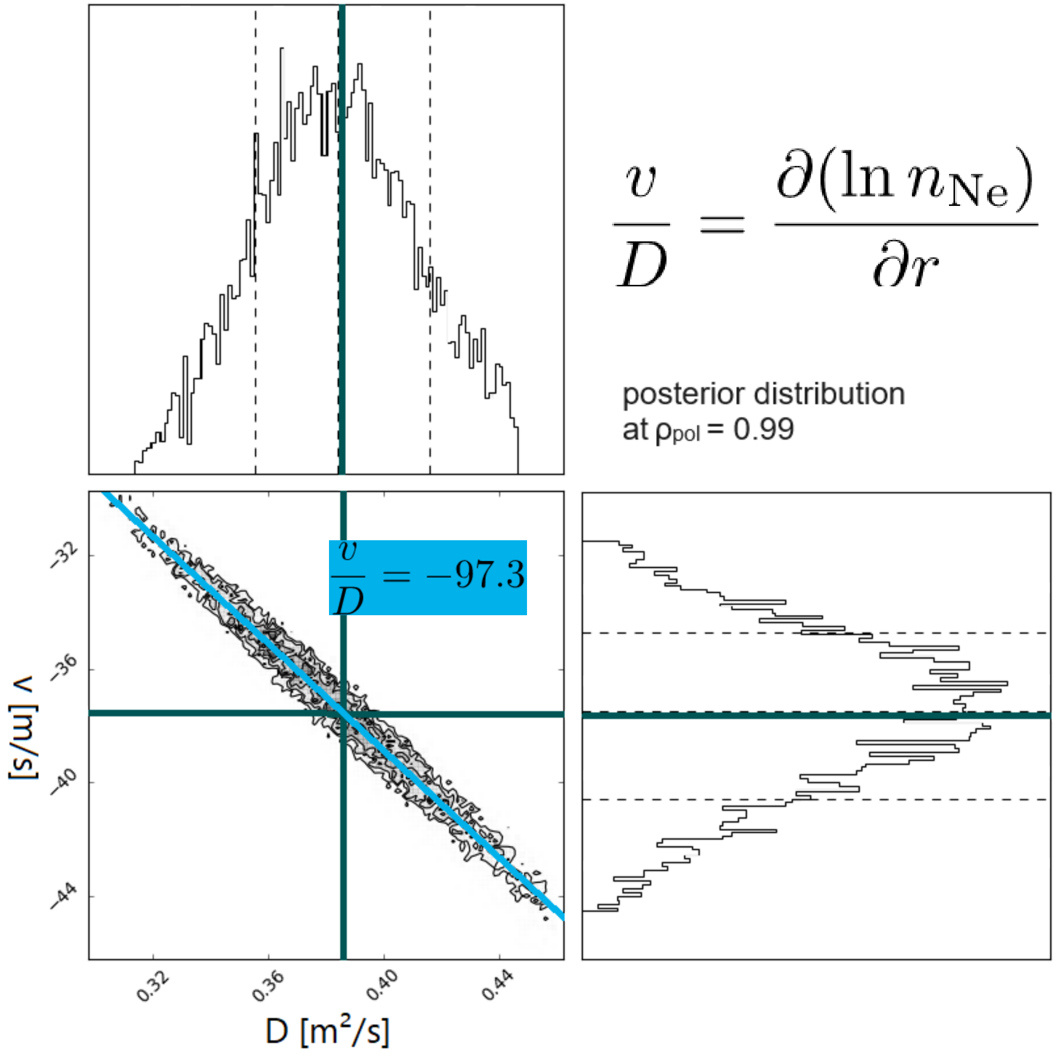
#39461: QCE regime



UNCERTAINTIES & ERROR SOURCES

$$\frac{v}{D} = \frac{\partial(\ln n_{\mathrm{Ne}})}{\partial r}$$

posterior distribution
at $\rho_{pol} = 0.99$



ERROR SOURCES

- CXRS calibrations

  → Cross calibration discharges & fudge factors!
- Edge gradients & alignment of kinetic profiles
- Atomic data
- Neutral density profiles (from KN1D) for thermal CX

- **Sampling volume scales exponentially with dimensionality of parameter space**

  → Wise selection of parameters and priors crucial!

SUMMARY

- **Comprehensive set of discharges** performed at AUG with **tailored high resolution CXRS measurements**

- **Complete framework** for impurity transport inferences in different confinement regimes set up **–** first inferences achieving **good data agreement**

- **Neon transport in QCE regime**: smaller pedestal neon gradients / pedestal pinch of v/D; diffusion at the plasma edge enhanced

- FURTHER METHODOLOGY TESTING & ANALYSIS OF MORE DATA PLANNED…

THANK YOU!