Measurements of impurity flows and line-radiation in the W7-X scrape-off layer

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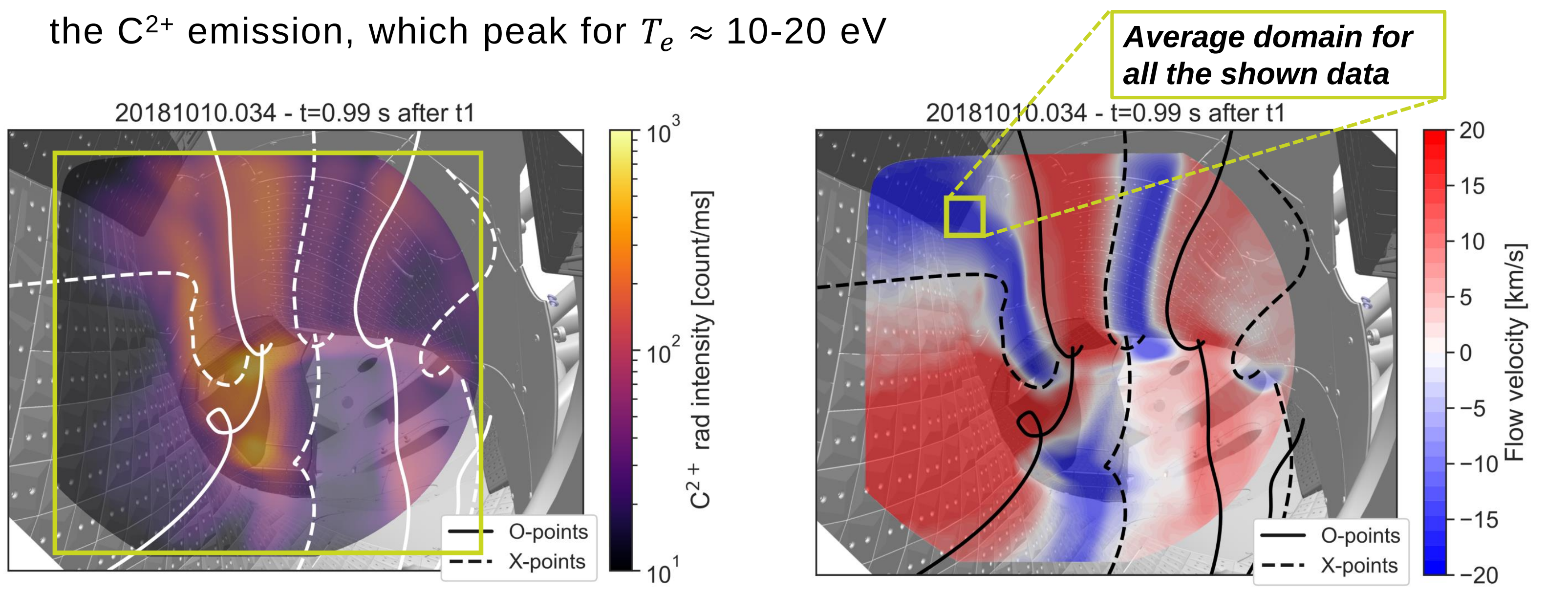
1. MOTIVATION

- Scrape-off layer (SOL) of W7-X: island divertor, i.e. unique divertor configuration with long L_C in the main SOL domain → ∥/⊥ transport ratio for particles and heat is affected
- Quantification of ∥/⊥ transport for determination of divertor configuration effectiveness → here focus on ∥ for particles
- Parallel particle flows: linked to pressure gradient due to distribution of sources and sinks on SOL open field lines → Main transport channel to targets along $\boldsymbol{B}$-field for momentum and convective heat, broadened by diffusion across $\boldsymbol{B}$-field
- Comparison with attached and detached plasma scenarios for a thorough analysis

2. MAIN TOOL: COHERENCE IMAGING SPECTROSCOPY

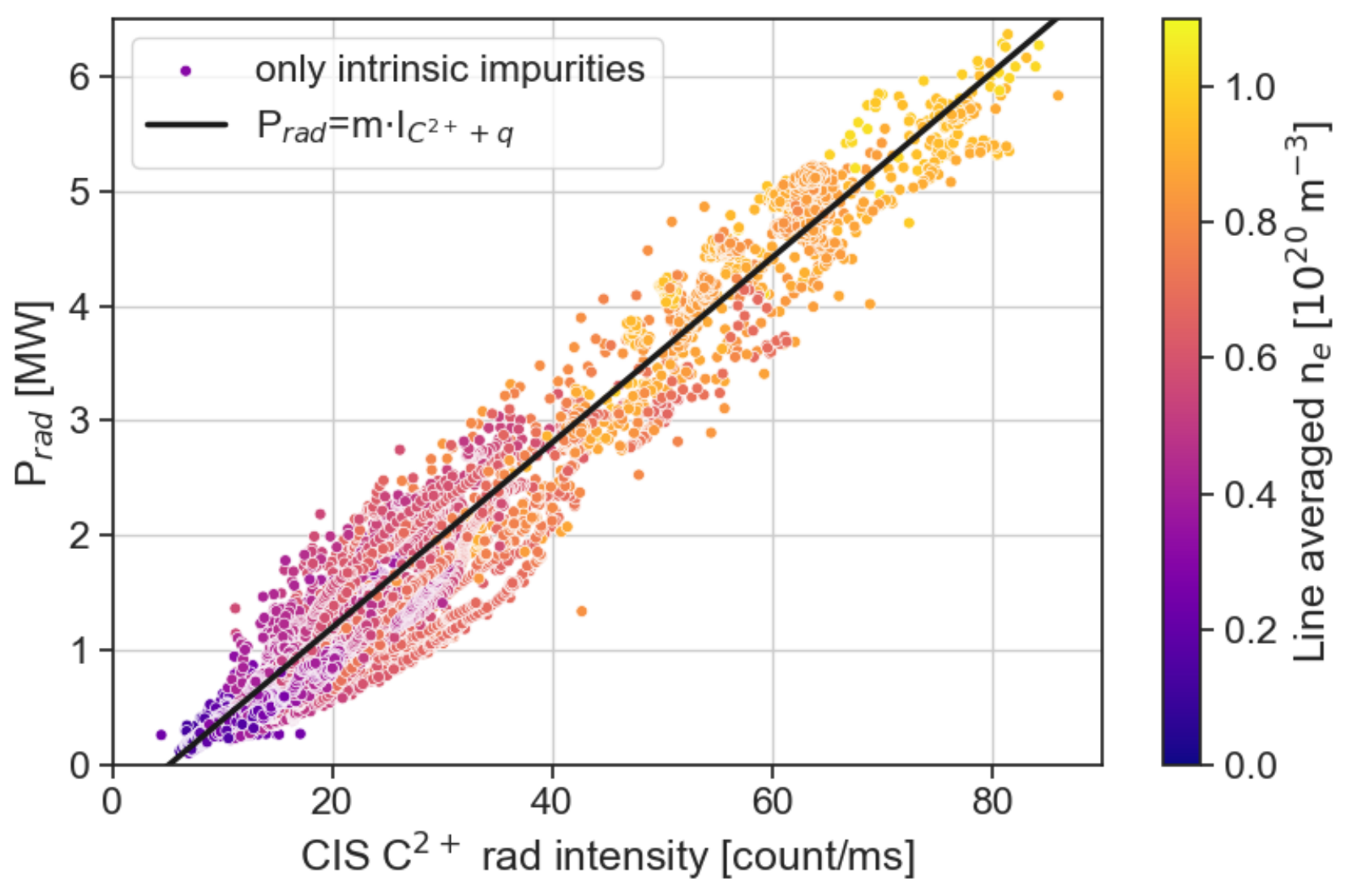
- At W7-X: possible to monitor impurity behaviour with the Coherence Imaging Spectroscopy (CIS) diagnostic
- Main characteristics of the W7-X CIS measurements:
  - 2D images of line emission intensity and flow velocity of a selected particle charged state
  - Passive measurements of C^{2+} impurity in hydrogen plasmas throughout the entire last operational campaign (OP1.2b, year 2018)
    → line-integrated measurements restricted to the SOL by the temperature dependence of the C^{2+} emission, which peak for $T_e \approx$ 10-20 eV

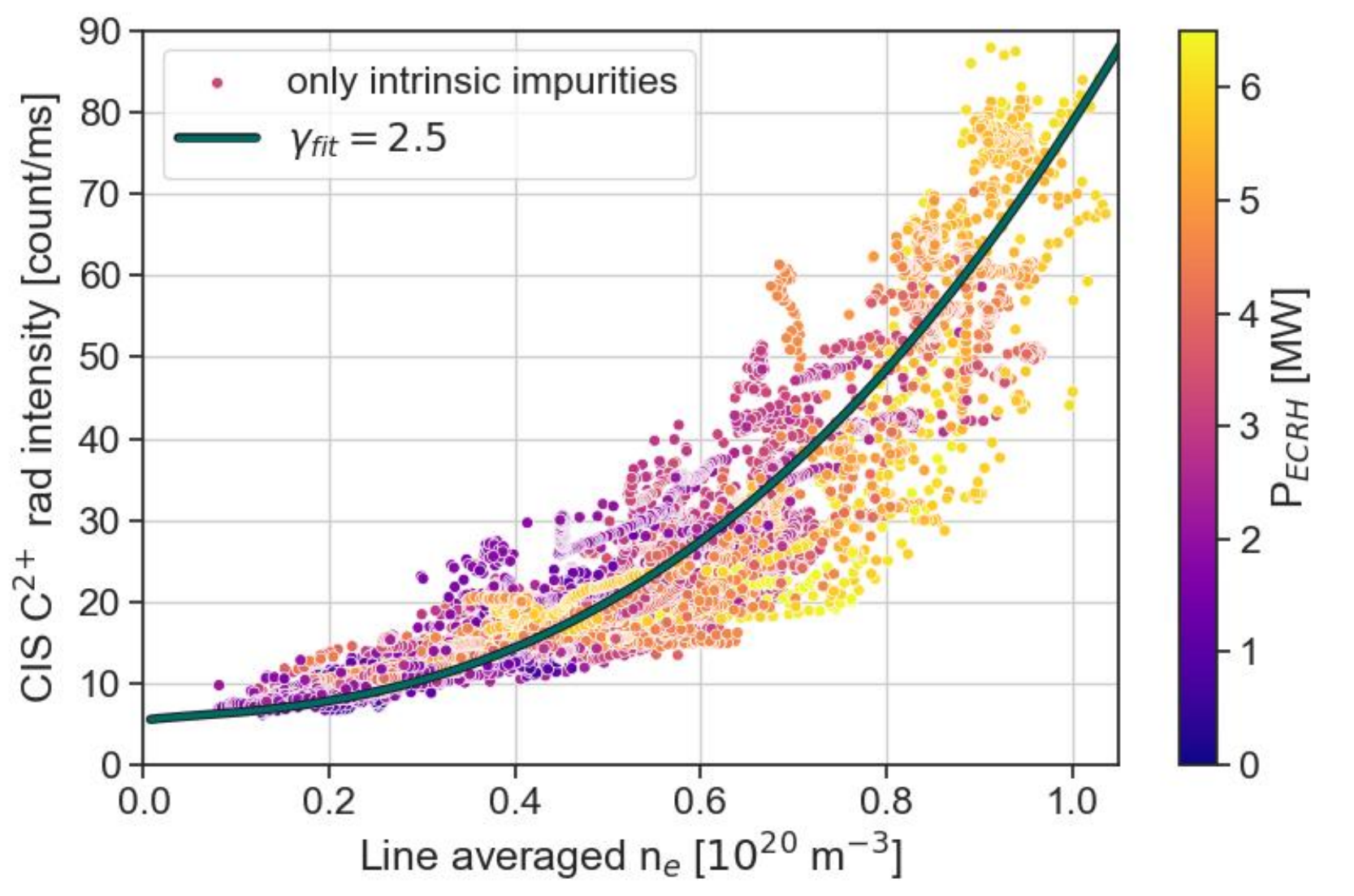


Example of CIS measurement (C^{2+} impurity, attached scenario)

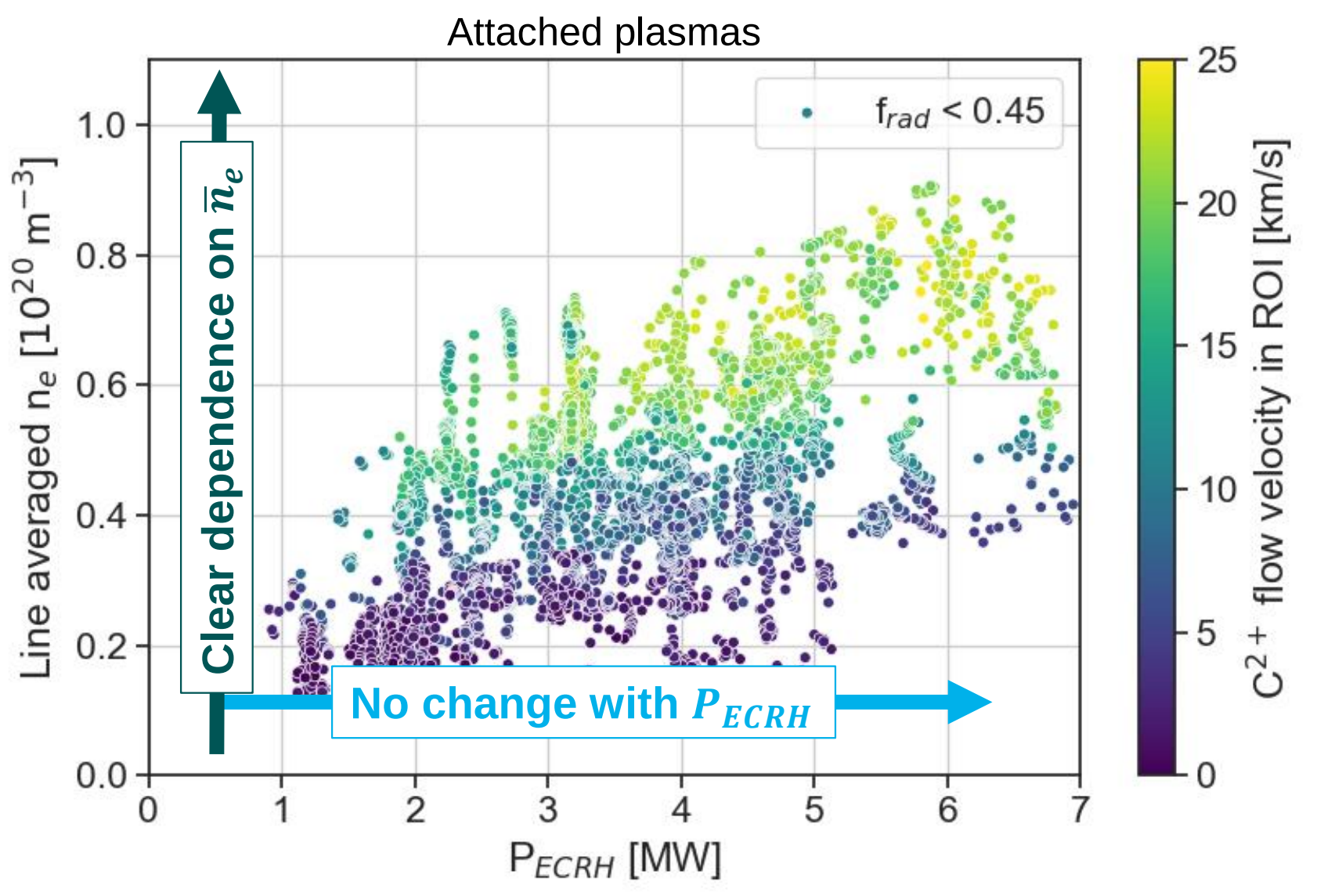
3. CIS OBSERVATIONS

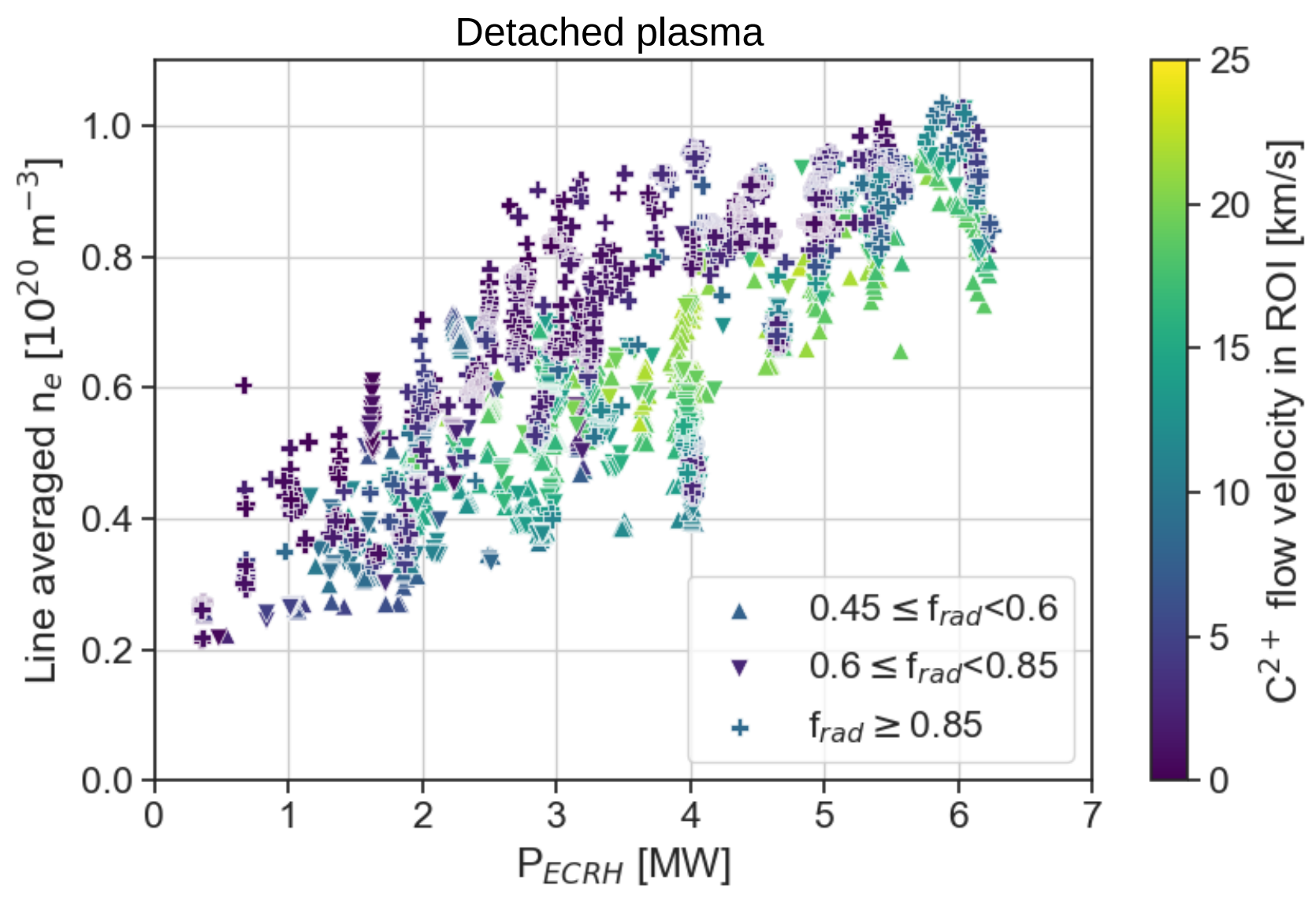
- Data: full OP1.2b (year 2018) after boronization in one magnetic configuration (standard), each data point = 200 ms of plasma (no NBI/pellets experiments, power $P_{in} = P_{ECRH}$)
- **C^{2+} radiation**: without impurity seeding, linear with total radiated power $P_{rad} \propto Z_{eff}\overline{n}_e^{\gamma}$





- C main radiator in W7-X as expected from graphite first wall, $\overline{n}_e$ can be used as actuator for CIS C^{2+} radiation intensity, no direct dependence on input power P_{ECRH}
- **C^{2+} velocity**: clear difference in behaviour in attached and detached plasmas





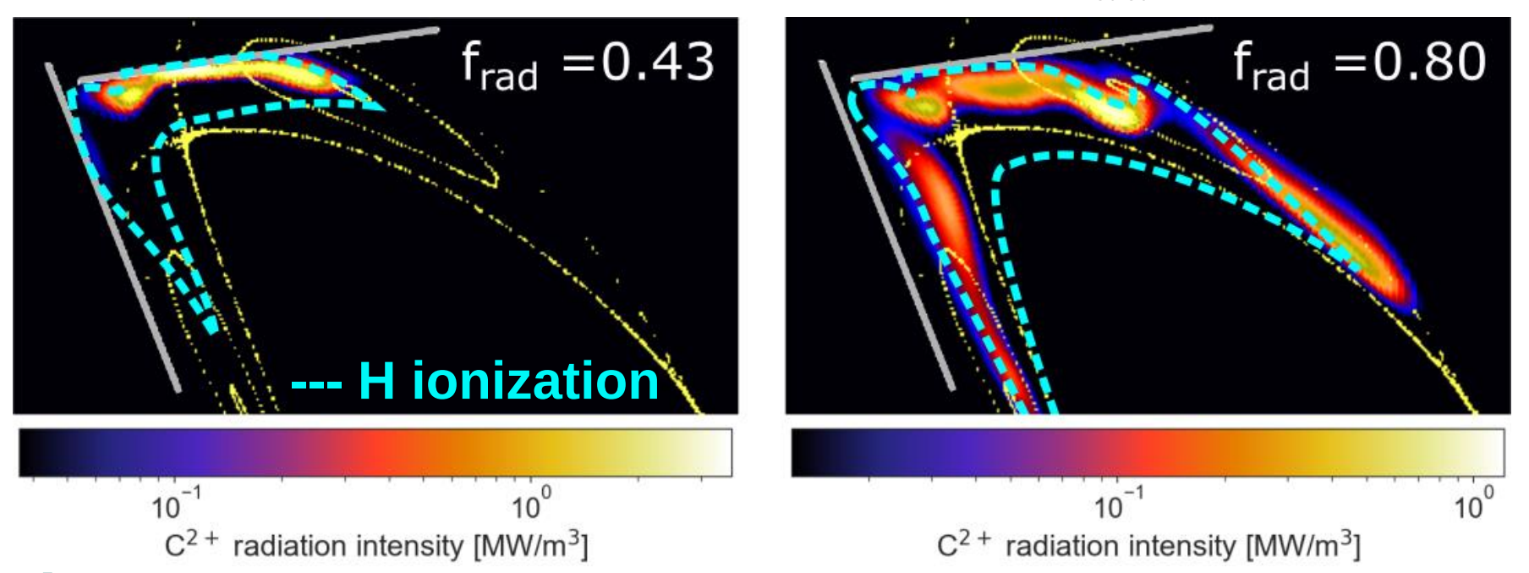
  - Attachment: C^{2+} velocity increases with increasing n_e while staying insensitive to P_{ECRH}
  - Detachment: C^{2+} velocity decreases with increasing n_e, drop $\propto P_{rad}$
- Roll-over of velocity and increase in radiation intensity: correlated to increasing f_{rad}

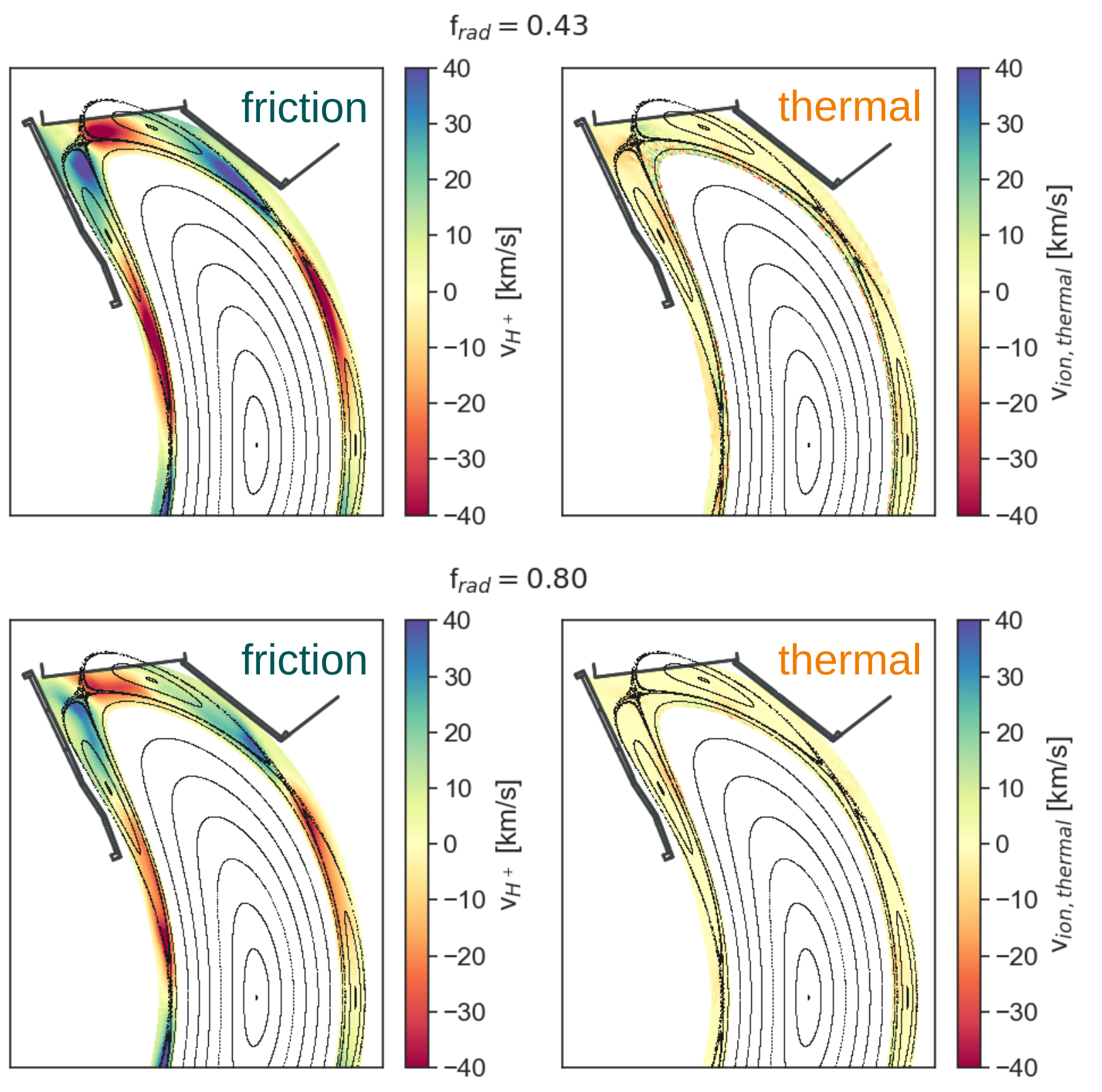
4. COUPLING BETWEEN C^{2+} & H^+ VELOCITIES

- $v_{C^{2+}}$ can differ from v_{H^+} → in parallel direction $v_{C^{2+}}$ determined by force balance

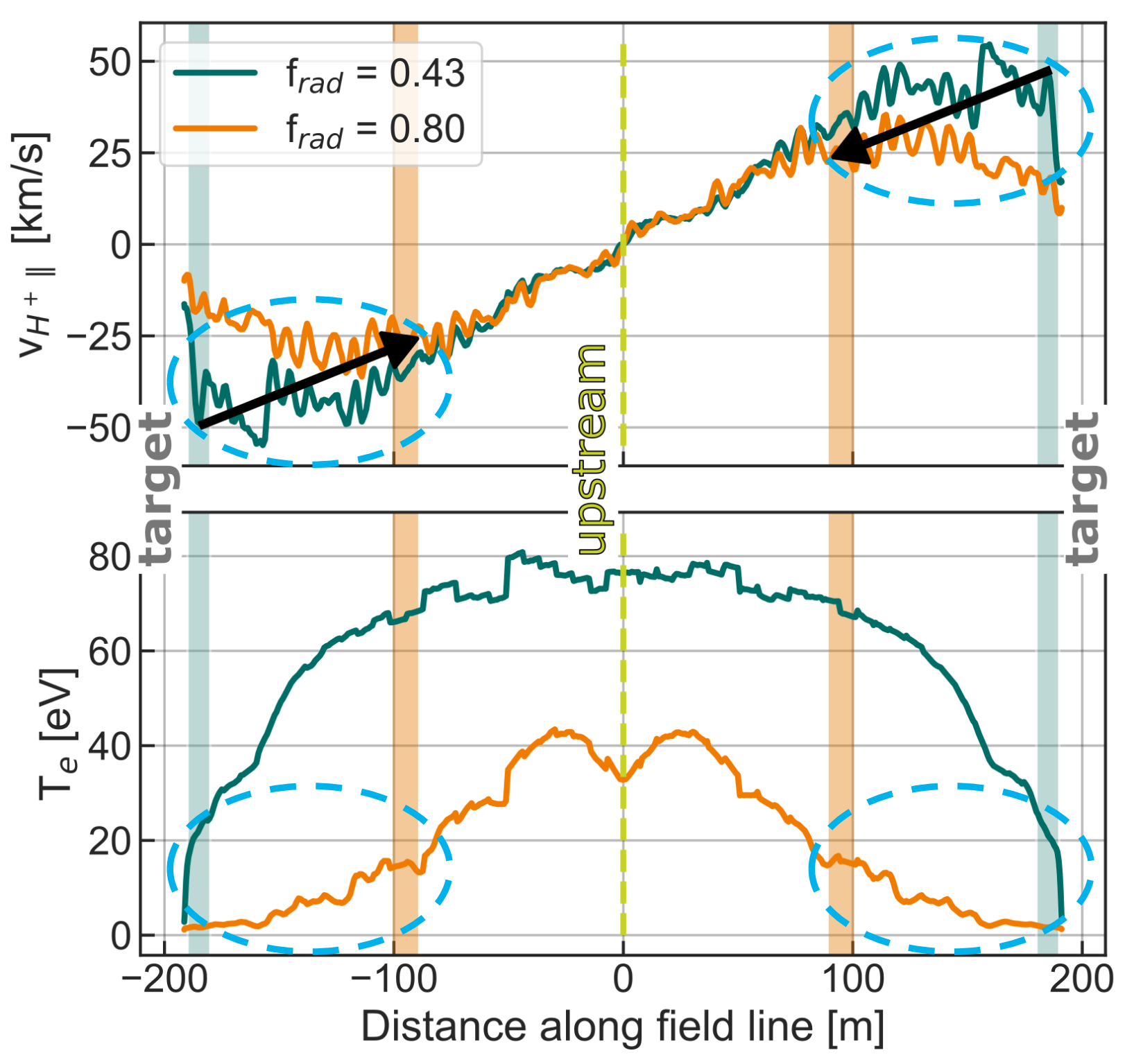
$$v_{C^{2+}} \cong \underbrace{v_{H^+}}_{\text{friction}} + \underbrace{\frac{\tau_s}{m_C}(\alpha_{H^+}-1)\frac{dkT_{H^+}}{dx}}_{\text{thermal}}$$

- Offset not yet measured but from EMC3-Eirene:
  - dominant role of friction for in most of islands
  - C^{2+} radiation located between targets and H^+ ionization region (radial direction)
- Results invariant even at high P_{rad}





- **→ CIS measurements good proxy for study of main ion dynamics where C^{2+} radiates**
- **→ C^{2+} radiation in regions of H ionization**
- Movement of radiation due to change in plasma parameters (e.g. T_e)
- Along open magnetic field line in detachment:
  - Shallow T_e profile between radiation front (cyan highlight) and target
  - Flattening of $v_\parallel$ in the same region
- **→ Movement of radiation changes CIS measurement location but flat $v_\parallel$ ensures that CIS results are still representative for what happens in the divertor area**



CONCLUSIONS

- Database of line radiation and flow velocity measurements to identify major tendencies:
  - C^{2+} line radiation (without impurity seeding) and C^{2+} flow velocity (coupled with H^+ in explored measurement conditions) show clear dependencies on plasma parameters, in particular P_{rad} and n_e, and no direct influence of P_{ECRH}
- C^{2+} flow velocities respond to line integrated density increase in both attached and detached plasmas, but in opposite ways
- C^{2+} flow velocities tendencies can be explained with 1D fluid model, characterized by the major role of ionization in the SOL: any change in the source term causes a change in v_{ion}
- Main assumption: constant cross-field transport with plasma parameters change → limits of validity to be assessed with future modelling
- Roll over of C^{2+} flow velocities at fixed P_{rad} still under investigation

5. PHYSICS INTERPRETATION OF v_{ion} – 1D MODEL

- C^{2+} impurity and main ion coupling in the region probed by CIS → explanation of CIS measurements with respect to main ions $v_\parallel$ (simple 1D fluid model)
- Continuity equation in steady state along magnetic field lines (x-direction) & $n = n_i = n_e \ \propto \overline{n}_e$ (flat density profile):

$$\frac{d\Gamma}{dx} \equiv \frac{d(n\,v_\parallel)}{dx} = \underbrace{S_i}_{\text{ionisation source}}$$

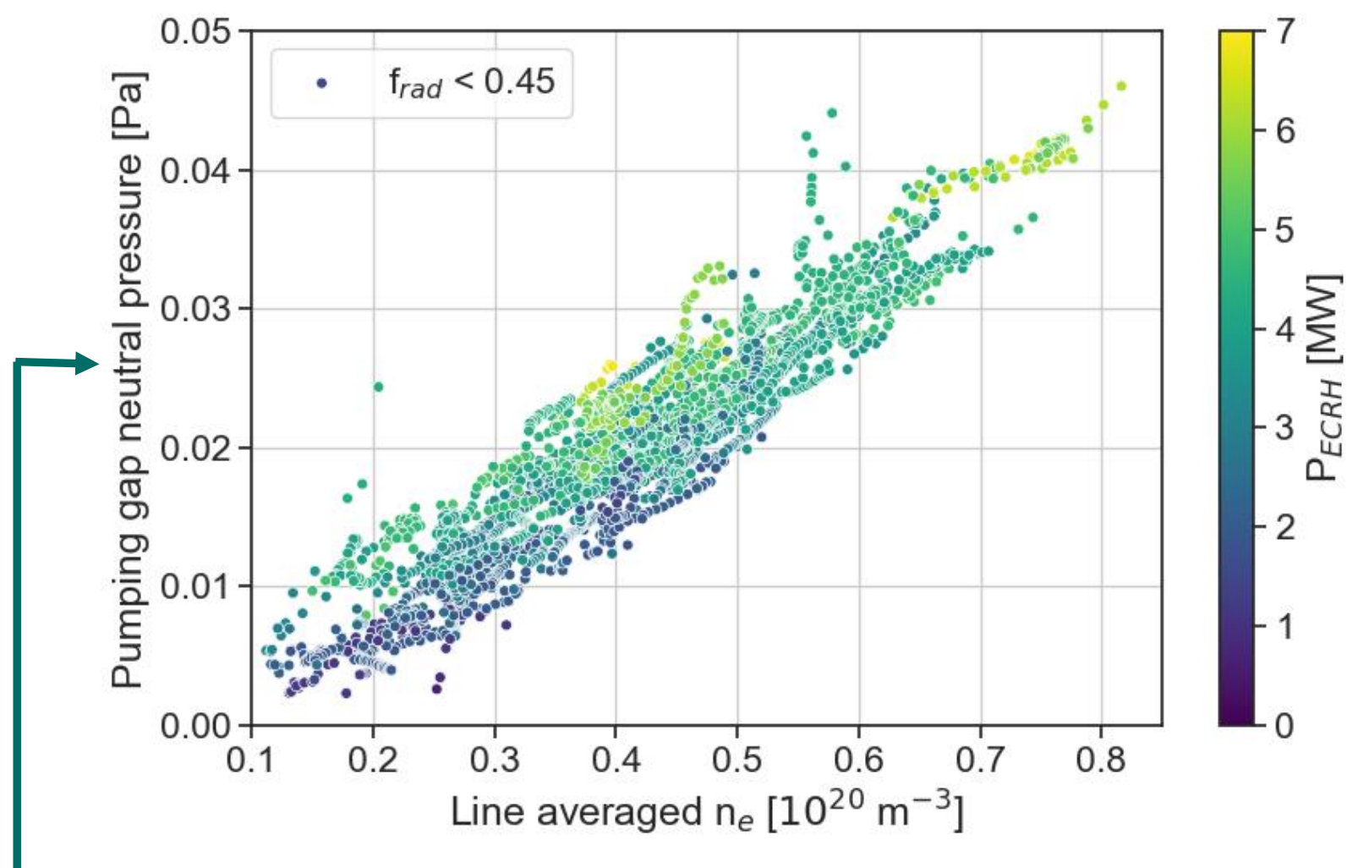
$$S_i = n\,n_n\,\langle\sigma v_e\rangle$$

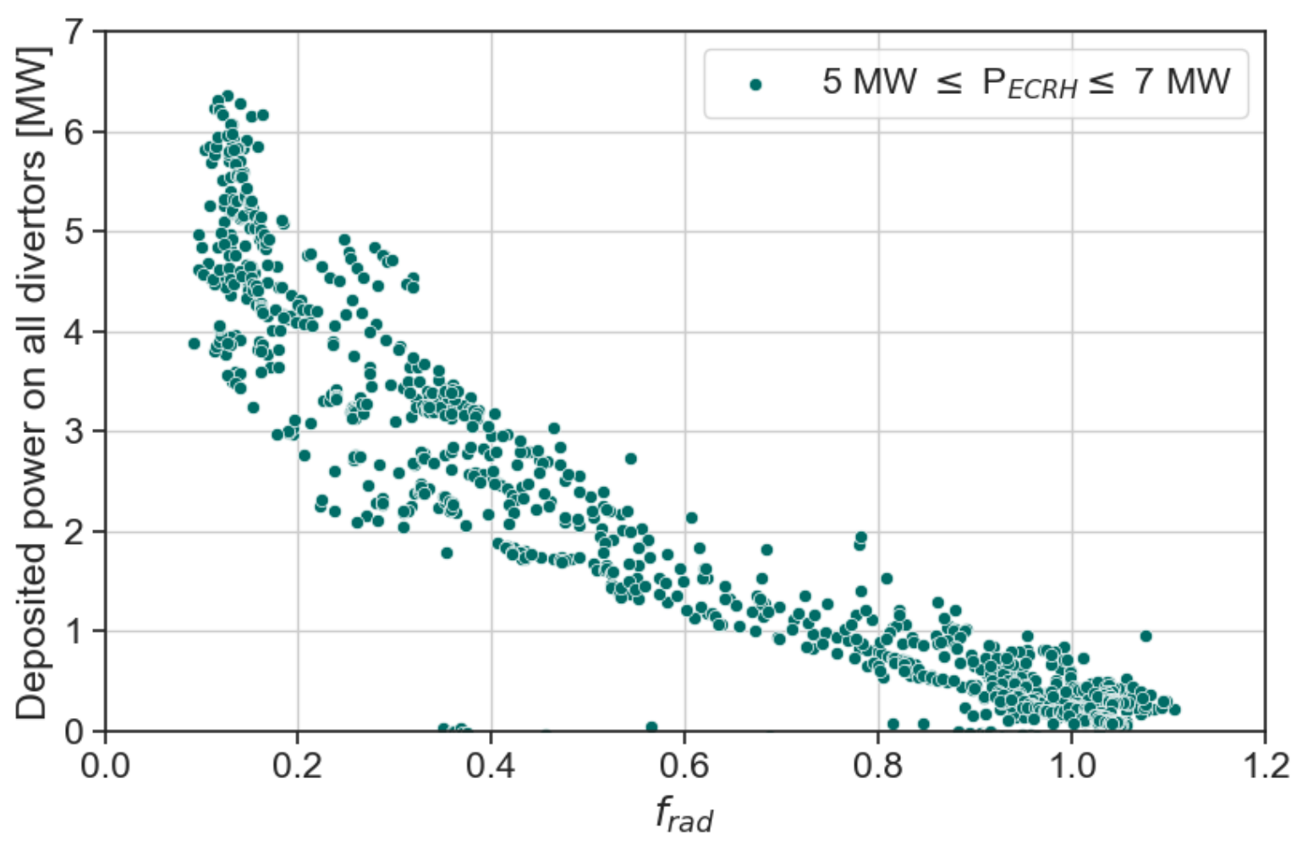
- From experiments **in attached conditions**:
  $n_n \sim C\,n$ → $S_i \sim C\,n^2\,\langle\sigma v_e\rangle$
  ➔ $\frac{d(n\,v_\parallel)}{dx} \sim C\,n^2\,\langle\sigma v_e\rangle$ → if $n\ \uparrow \Longrightarrow v_\parallel \uparrow$
- **At high f_{rad}** movement of radiation, lifting from the target: n_n not scaling linearly with $\overline{n}_e$ anymore → simplification $n_n \sim C\,n$ no longer valid
- Use of SOL global power balance instead of continuity equation:

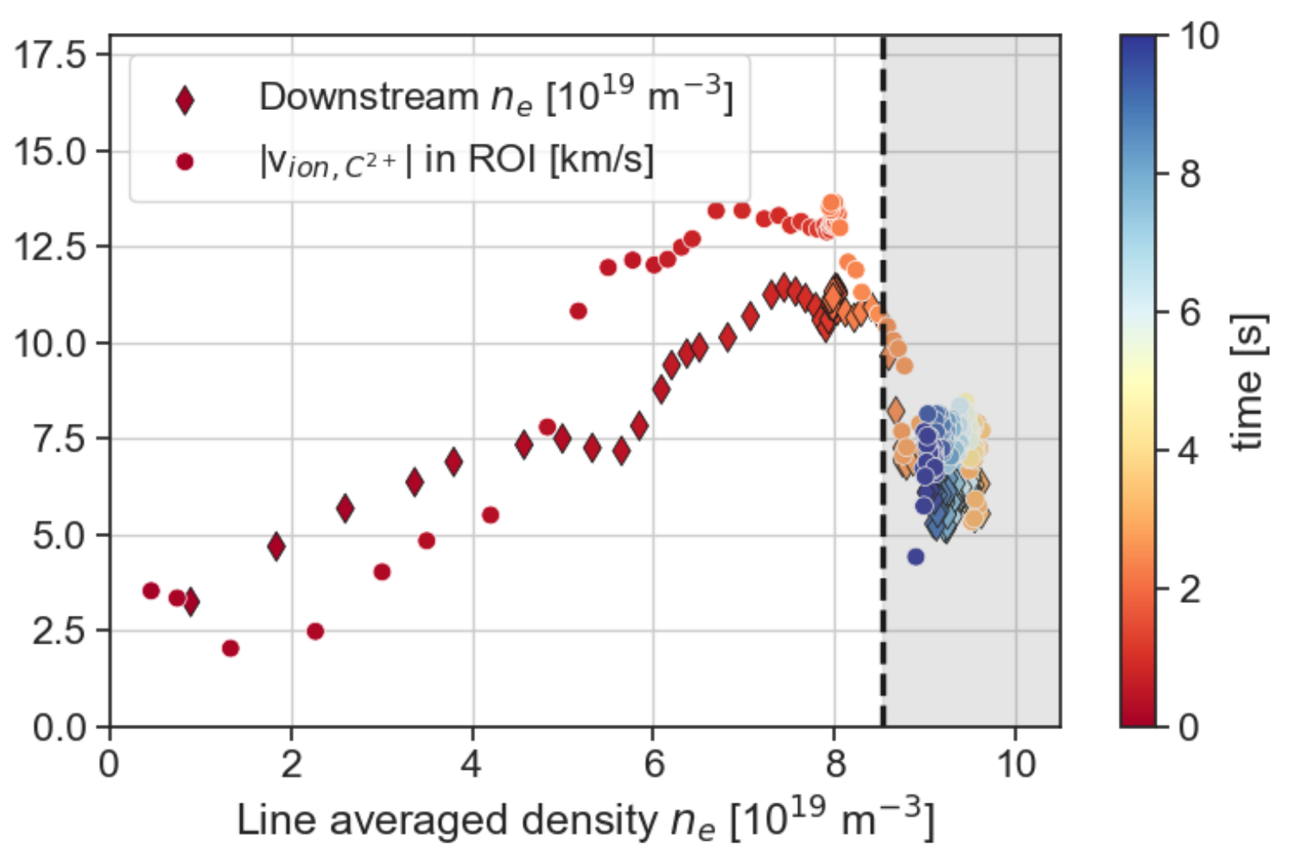
$$P_{in} = \underbrace{\boxed{P_t}}_{\text{deposited on targets}} + \underbrace{\boxed{P_{\varepsilon_i}}}_{\text{interactions with neutrals}} + \underbrace{\boxed{P_{rad}}}_{\text{radiated}}$$

  - At high f_{rad}: $P_t \to 0$
  - $P_{\varepsilon_i} = \ \varepsilon_i\,\langle n\,v_\parallel\ \rangle_t$ $\qquad A_t\,P_{rad} = P_{in}\,f_{rad}$

  ➔ $\langle n\,v_\parallel\rangle \approx \frac{1}{A_t}\frac{P_{in}(1-f_{rad})}{\varepsilon_i}$
- $f_{rad}\ \uparrow$, ε_i & P_{in} const. ⇒ $n \downarrow$ and/or $v_\parallel \downarrow$
- Observations show:
  both n ($\neq \overline{n}_e$ at high f_{rad}) and $v_\parallel \downarrow$

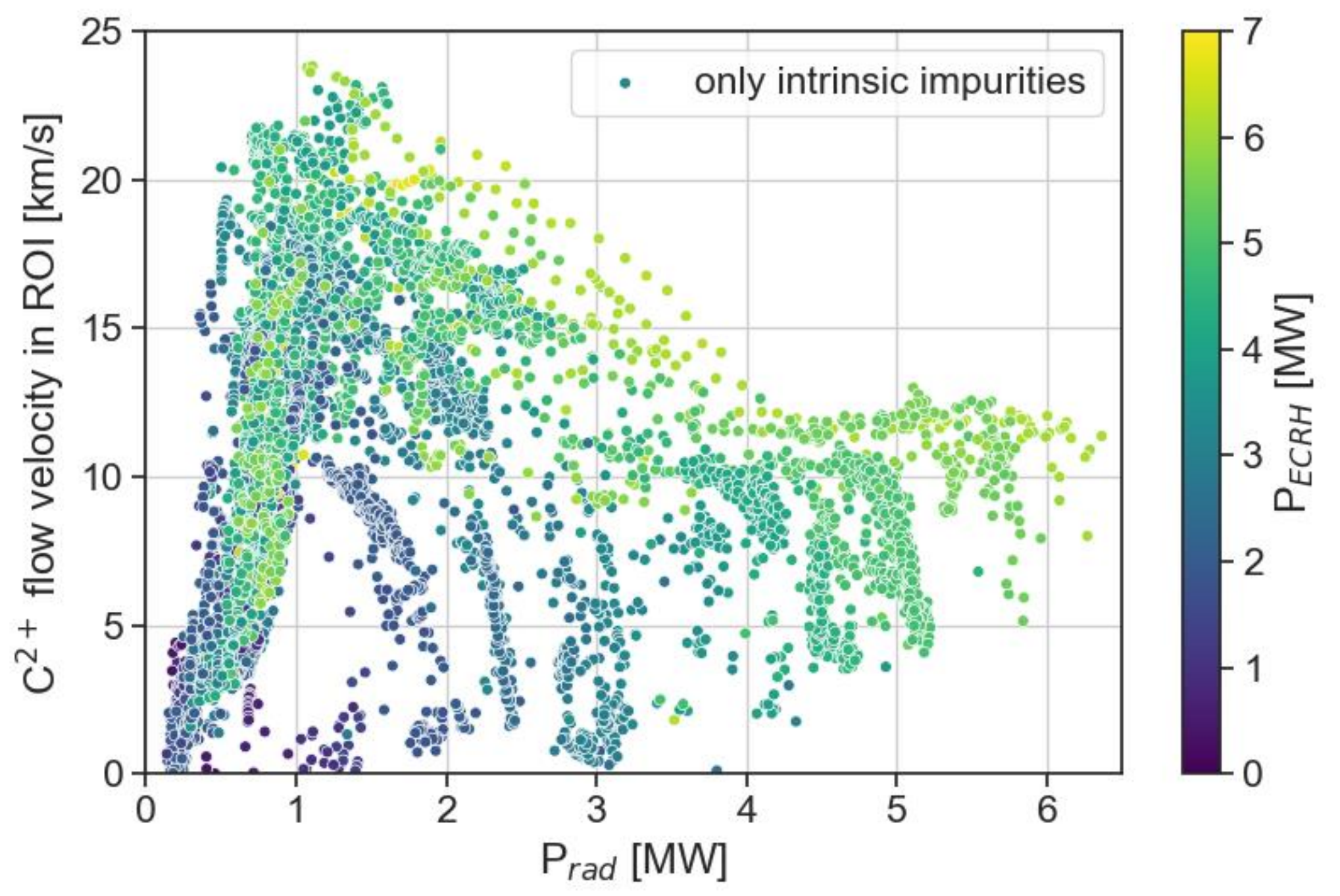






6. v_{ion} TRENDS WITH P_{rad}

- Due to the different trends of v_{ion} with density at different P_{rad} → direct study of v_{ion} vs P_{rad}
- Dataset restricted to avoid major changes of magnetic topology
- Peak value of v_{ion} changing with P_{ECRH} and $\overline{n}_e$ **but** clear roll over observable at P_{rad} = 1-2 MW independently of P_{ECRH} and $\overline{n}_e$
- Fixed value of P_{rad} for roll over of v_{ion} unexpected and still under investigation



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