Max-Planck-Institut für Plasmaphysik

Particle and energy transport of the improved confinement NBI scenario at W7-X

O. P. Ford, S. Bannmann, M. Beurskens, S. Bozhenkov, T. Romba, T. Stange, M. Wappl

A. Alonso, C. Beidler, H. Braune, K.J. Brunner, G. Fuchert, D. Hartmann, J. Knauer, A. Langenberg, H.P. Laqua, S. Lazerson, S. Marsen, P. McNeely, N. Pablant, E. Pasch, P. Pölöskei, V. Perseo, J. De la Riva Villen, N. Rust, H. Smith, D. Zhang

24th International Stellarator Heliotron Workshop, Hiroshima, Japan

Gas-fuelled ECRH discharges

In W7-X, typical scenario for long pulse, divertor experiments, parameter scans etc [as in talk by D. Gradic].
- Gas/recycling fuelled.
- Continuous ECRH.

Result:
- Steady-state
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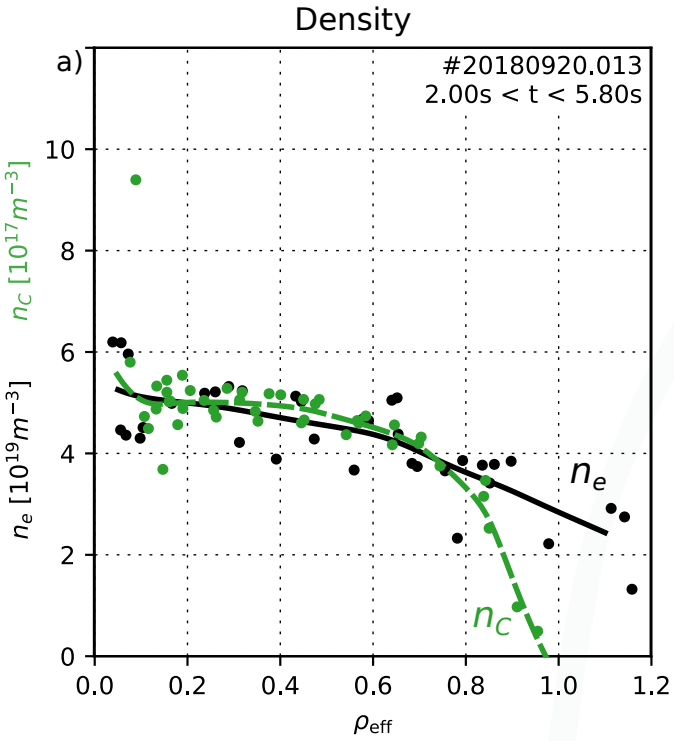
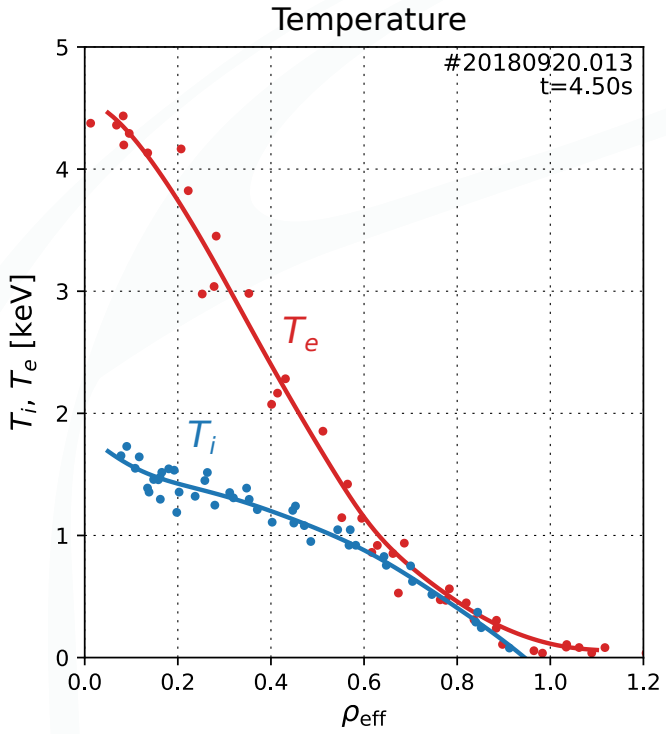
- Low, flat impurity density profiles
- Core $T_i \leq 1.5$keV





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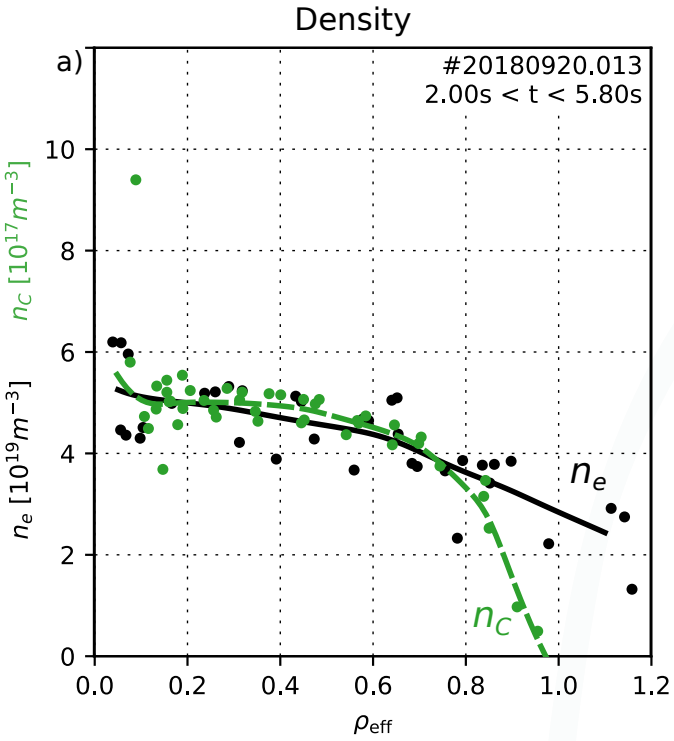

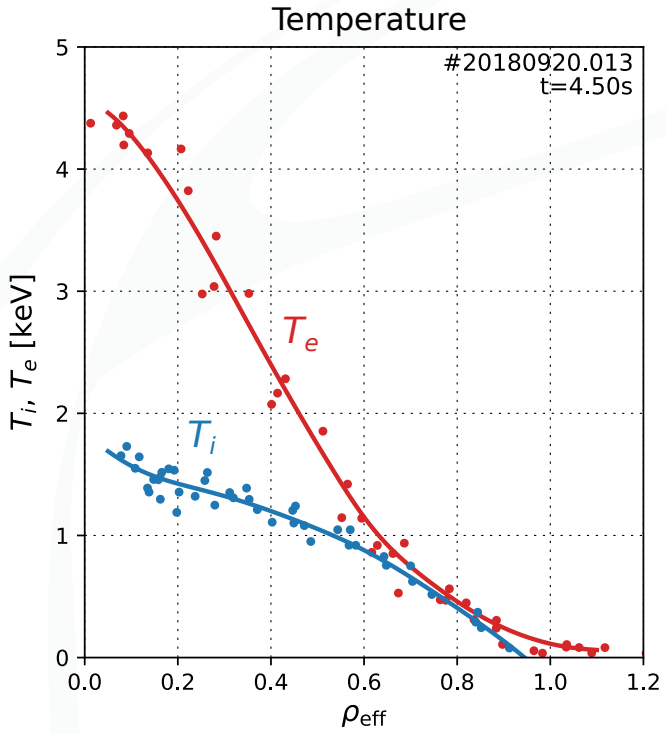

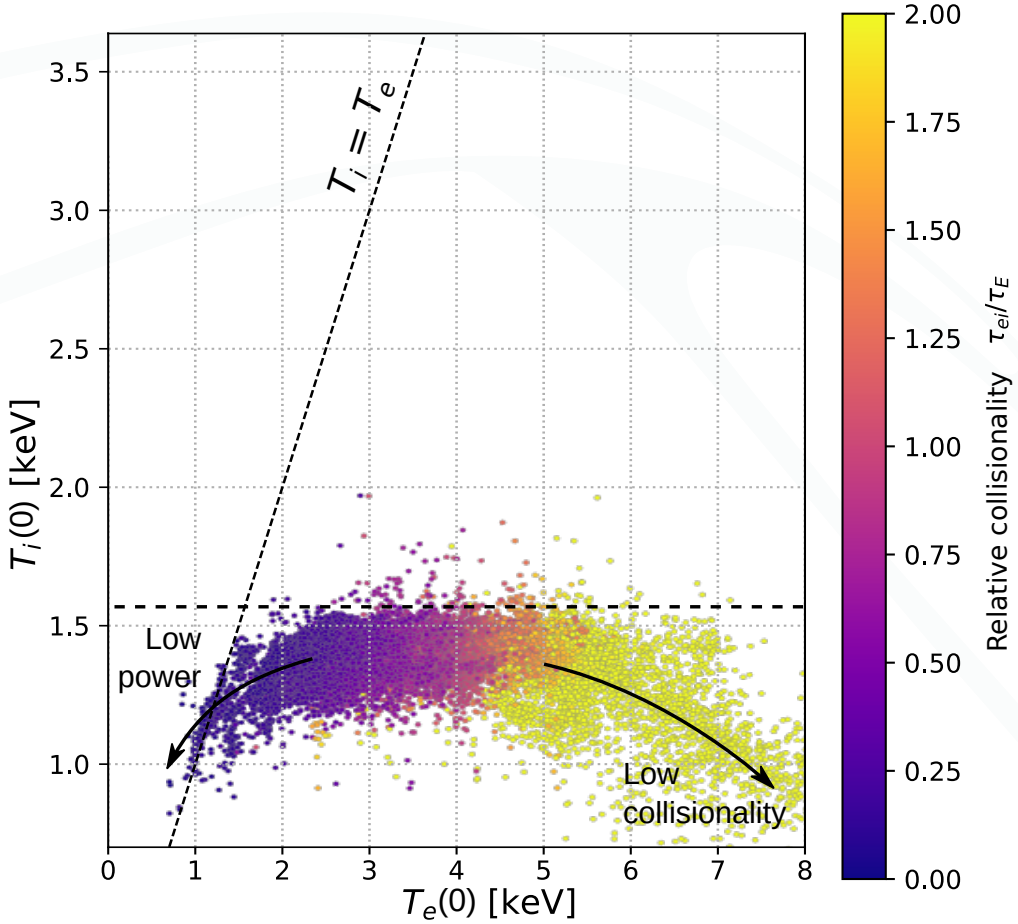

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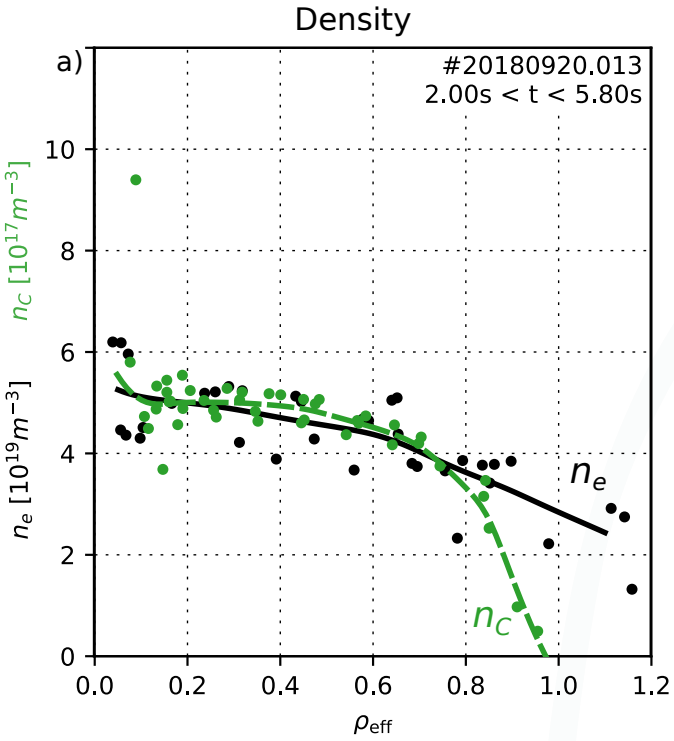

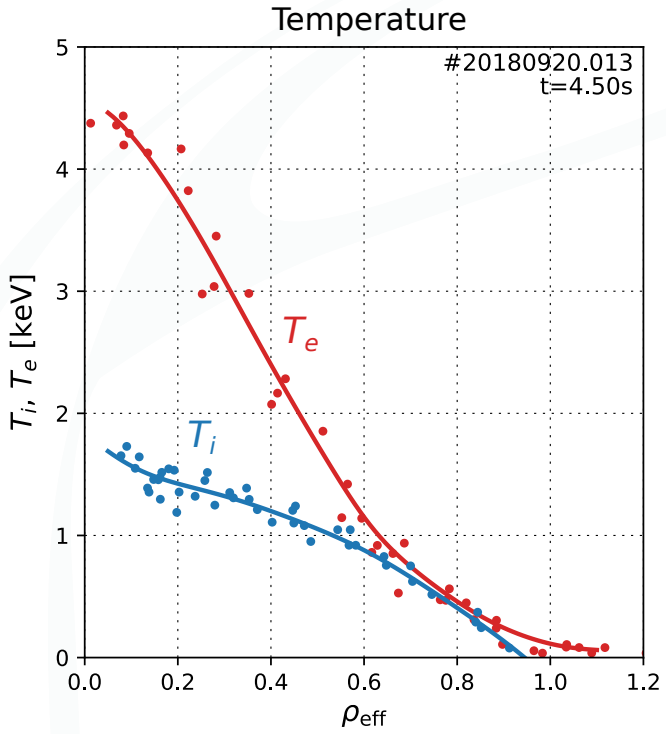

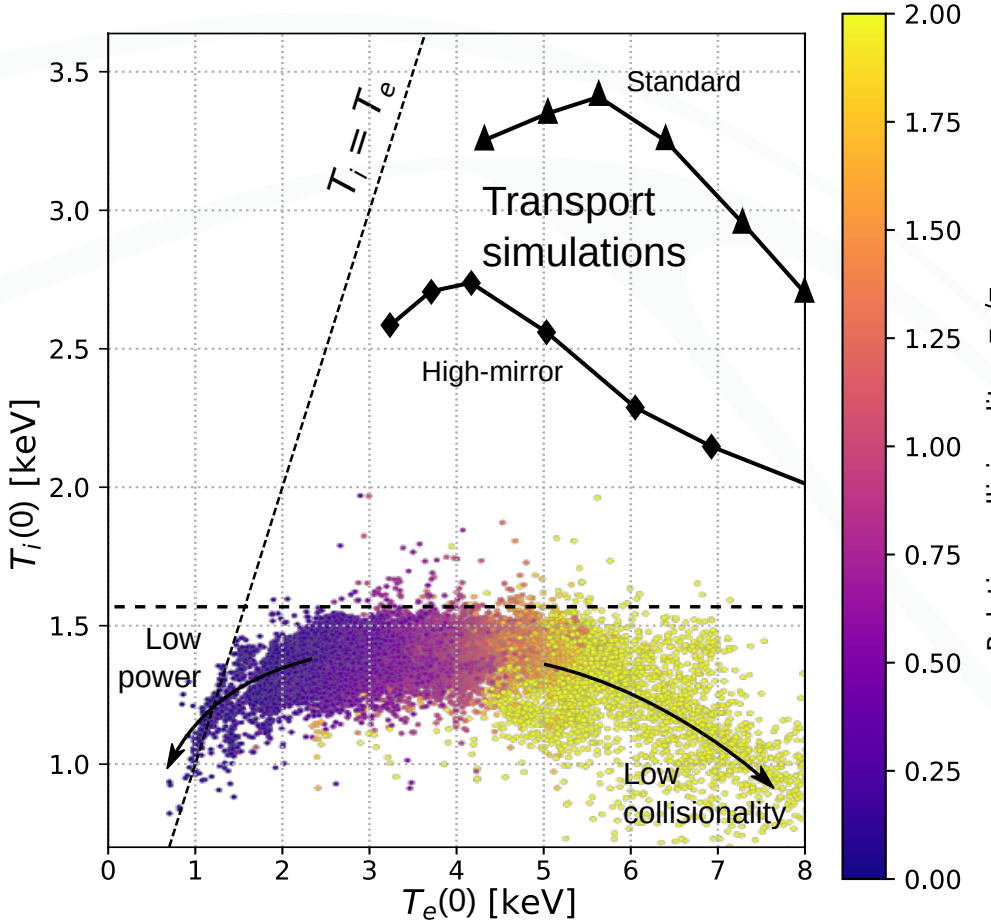

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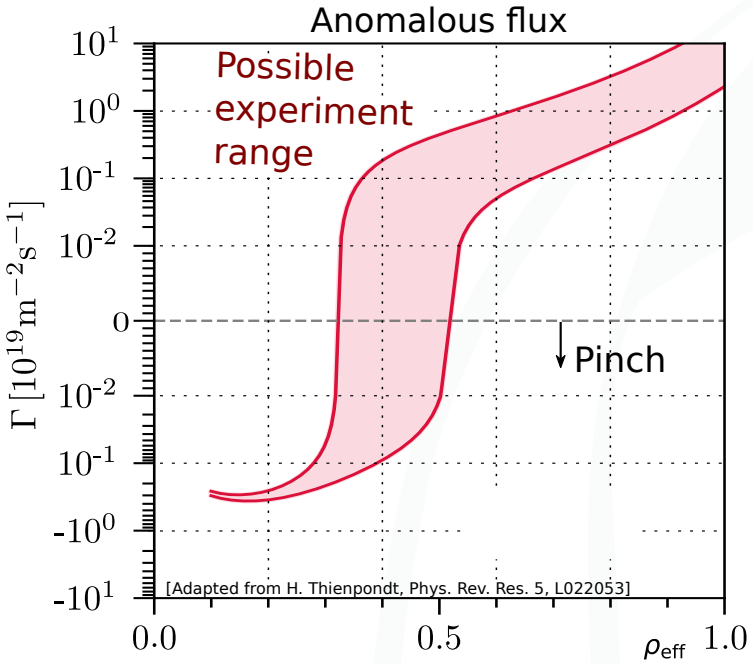

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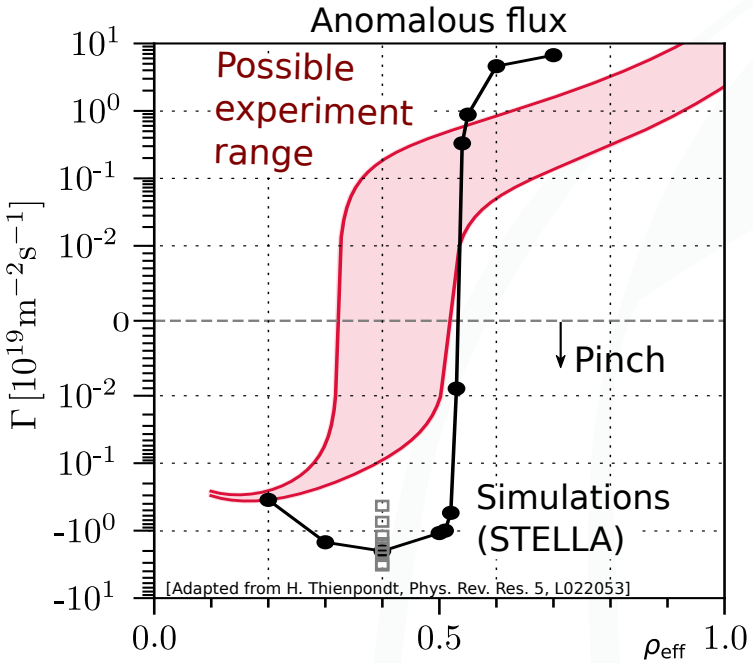

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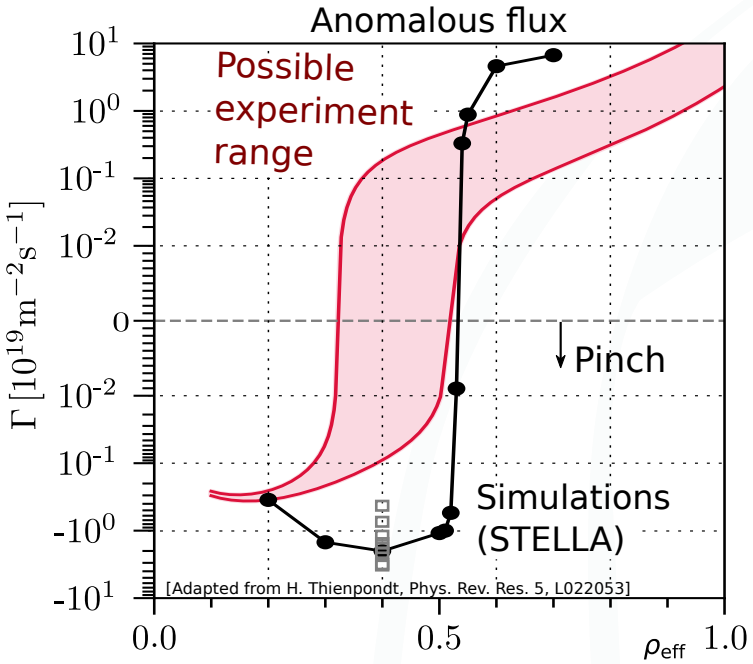


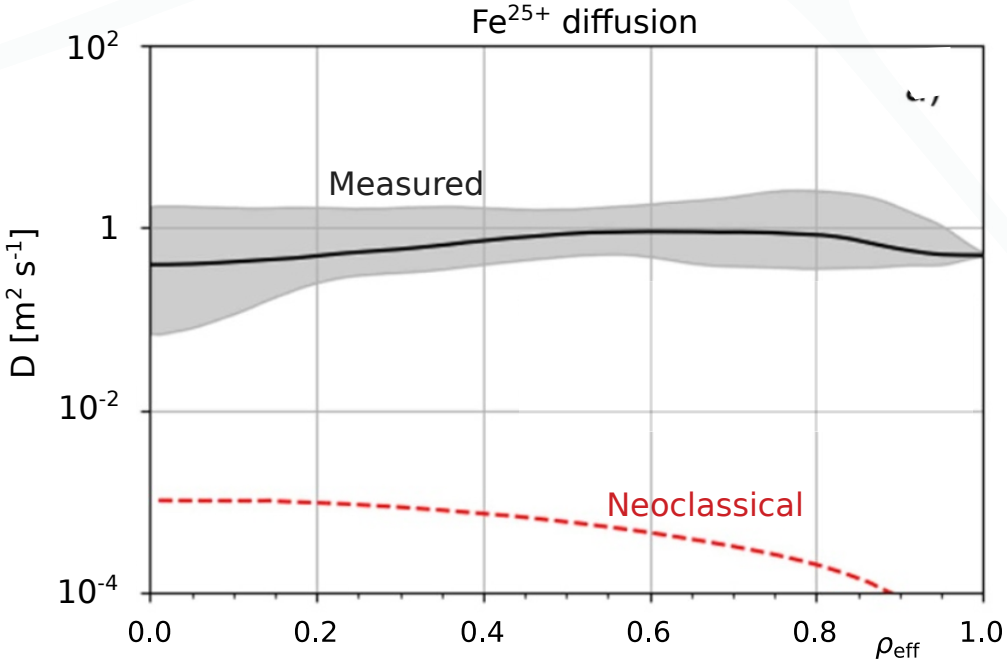
Impurities:

- Neoclassics --> peaked, Experiment = flat

  Require strong anomalous diffusion to flatten the profile ($D >> 0.1 m^2 s^{-1}$) . [T. Romba PPCF **65** 075011 (2023)]

- Measured *v, D* in LBO injections show strong anomalous diffusion [Swee Nucl. Fus. **64** 086062 (2024), B. Geiger Nucl. Fus. **59** 046009 (2019)]

- Gyrokinetic predictions of $D \sim O(1)\ m^2 s^{-1}$ from TEM+ITG turbulence. [García-Regaña JPP'21]



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ECRH + gas --> Turbulence dominated heat and main ion and impurity particle transport.

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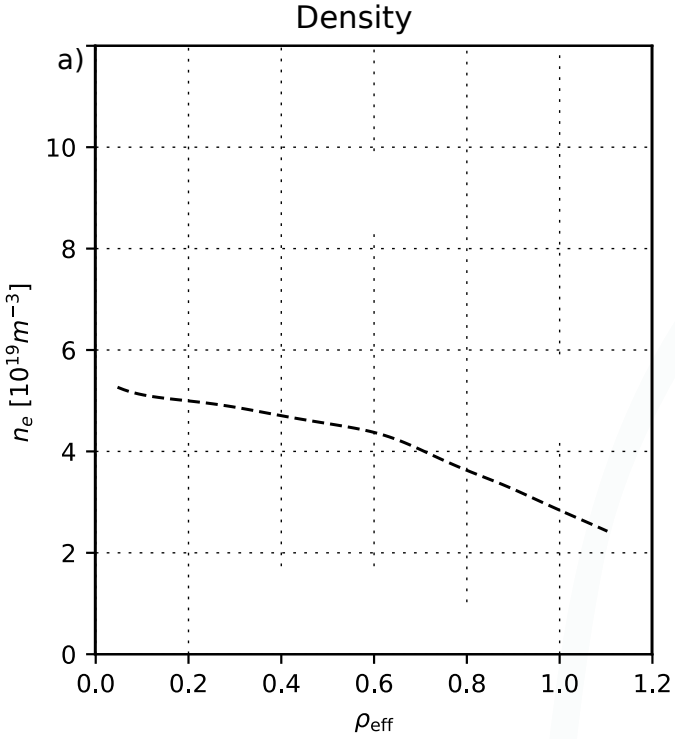

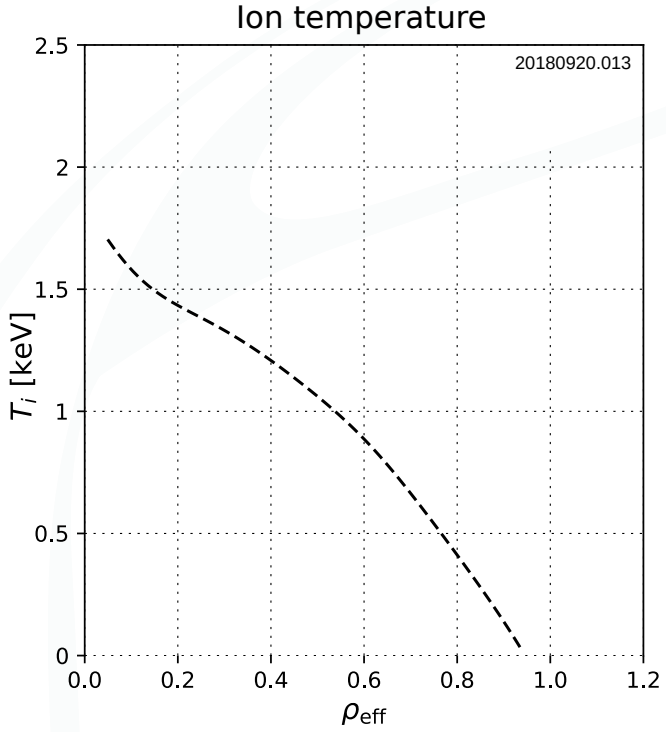

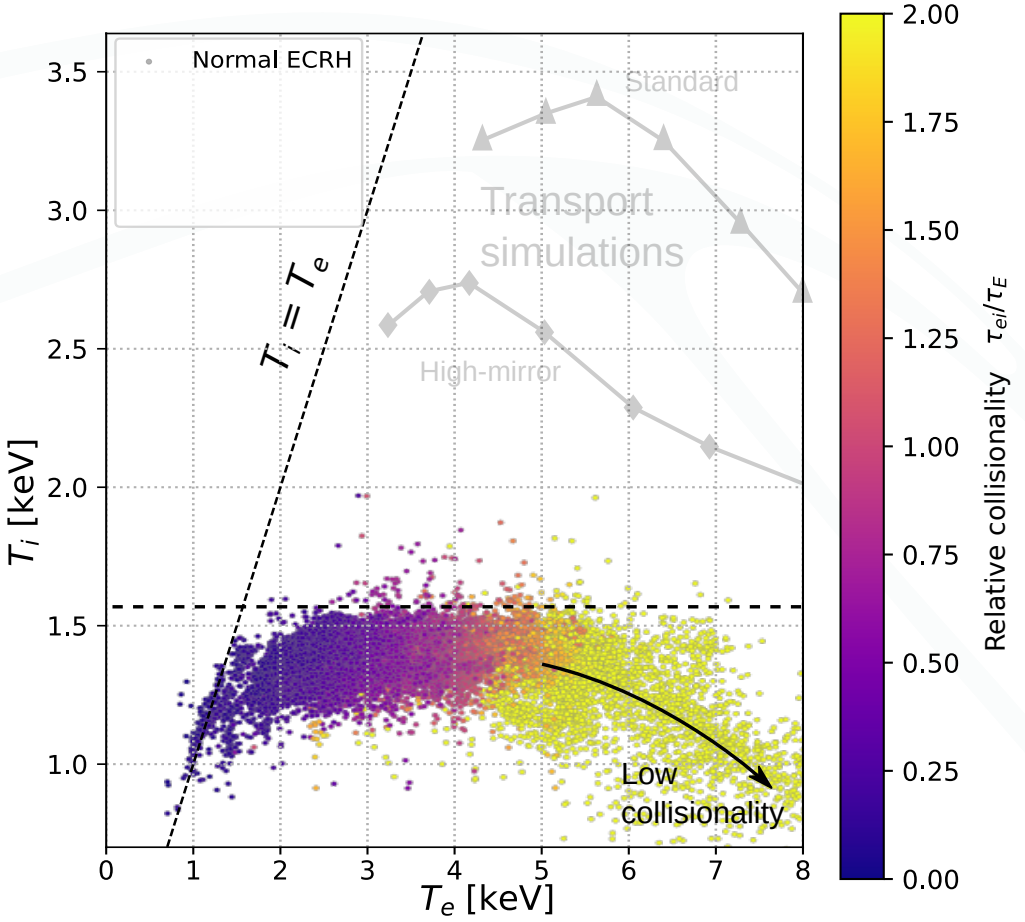

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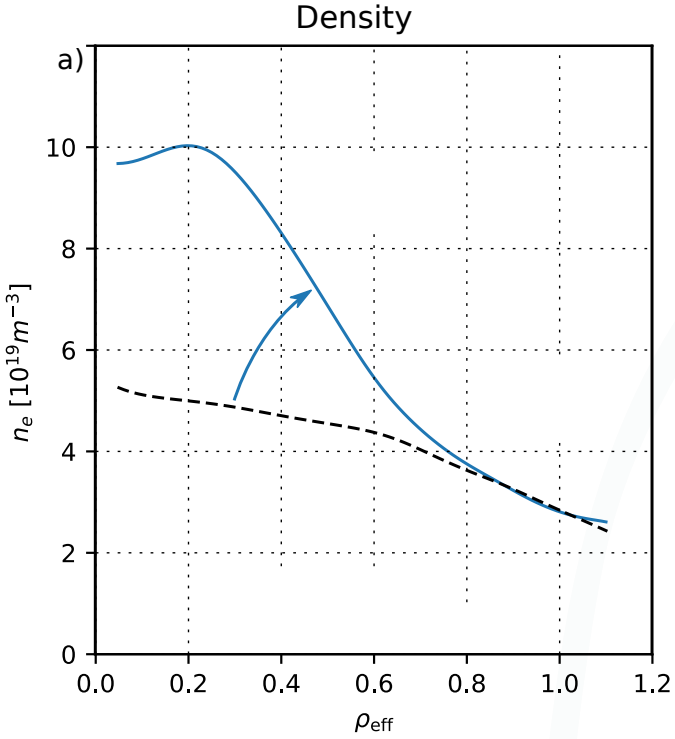

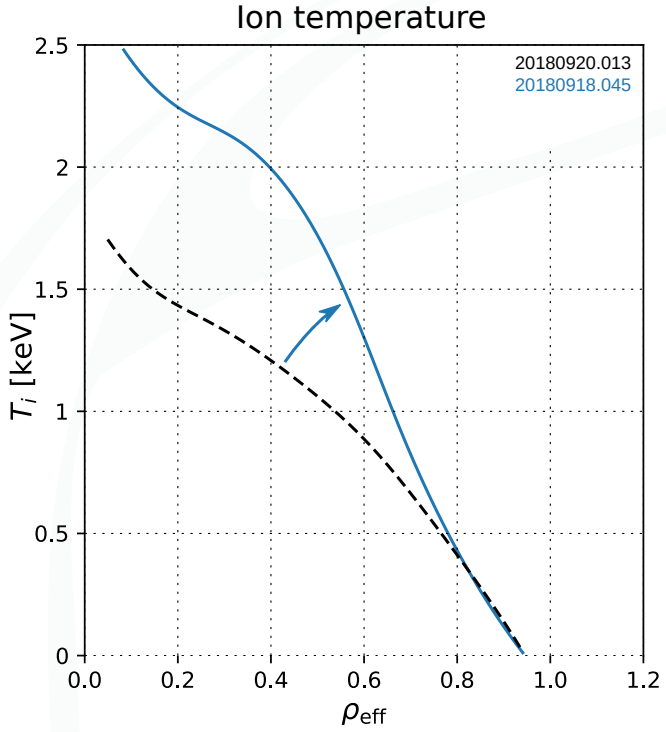

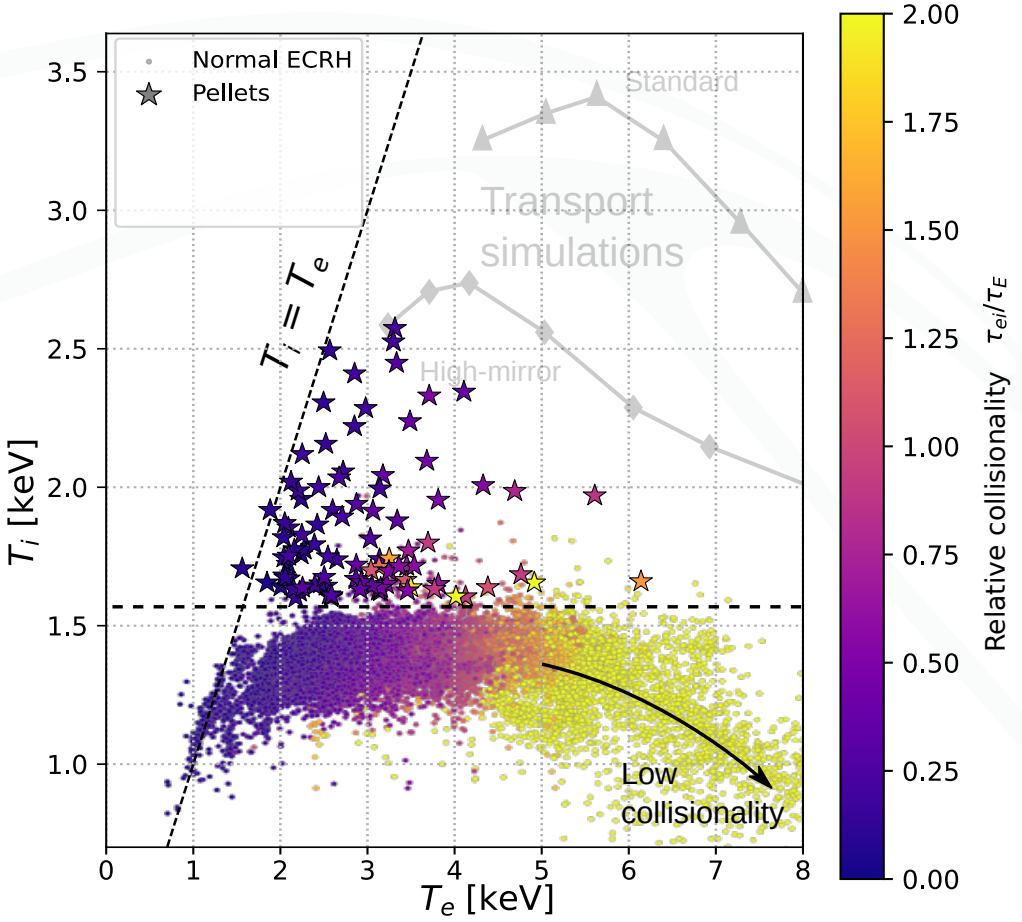

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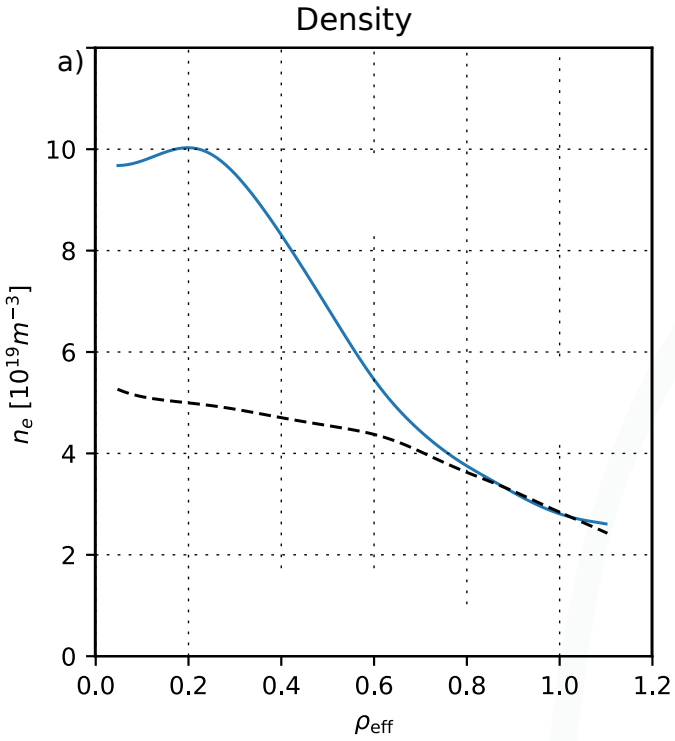

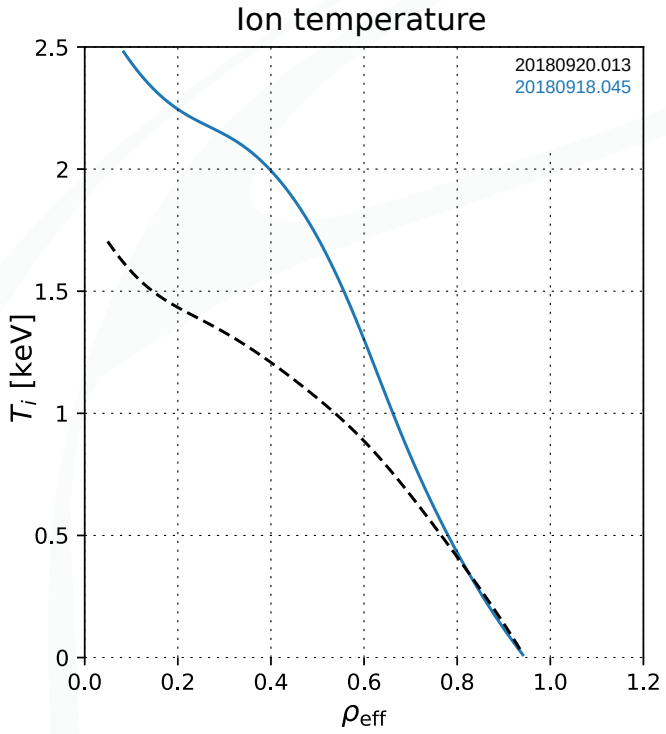

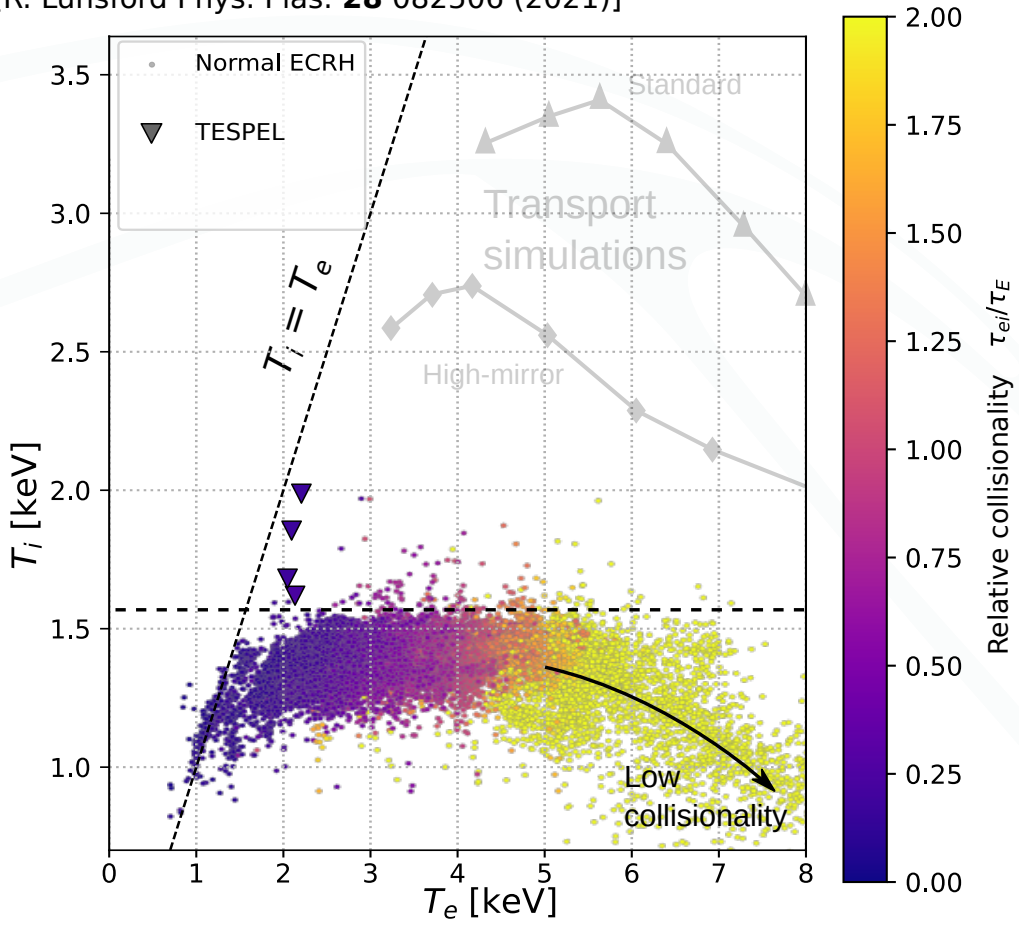

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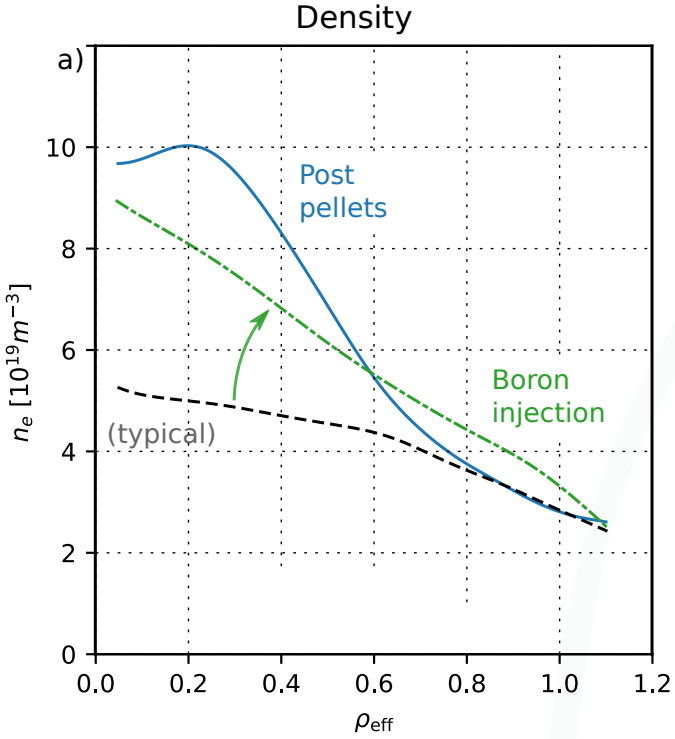

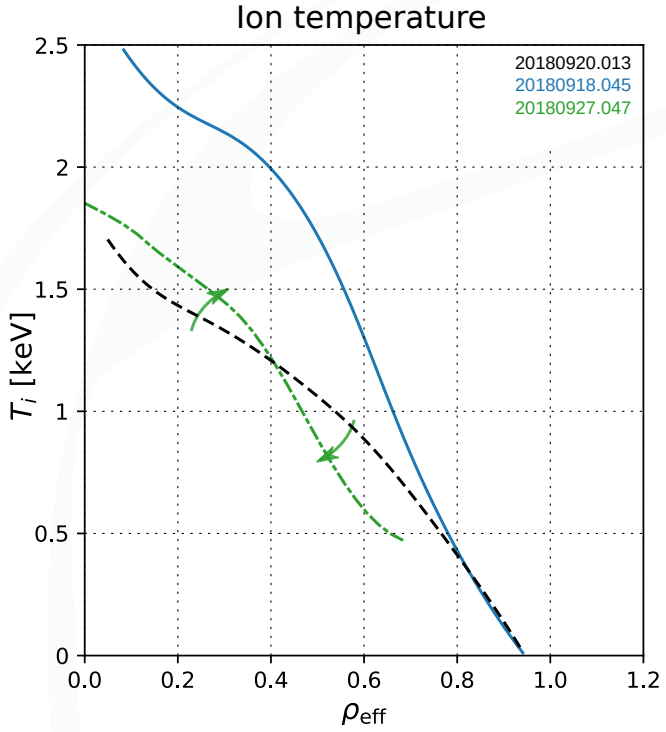

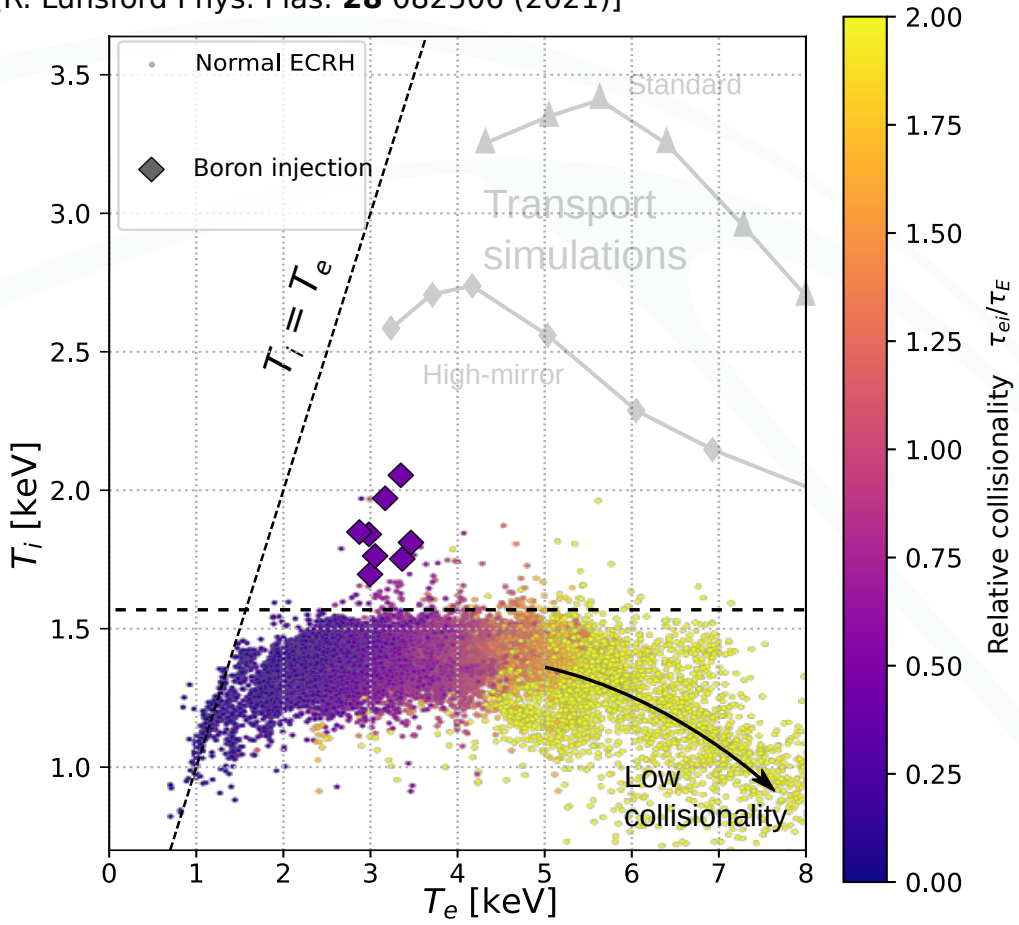

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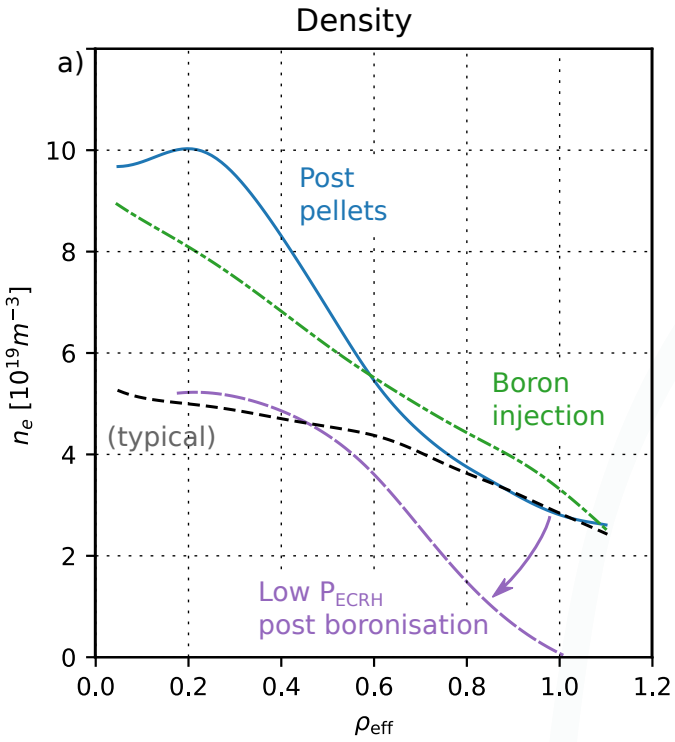

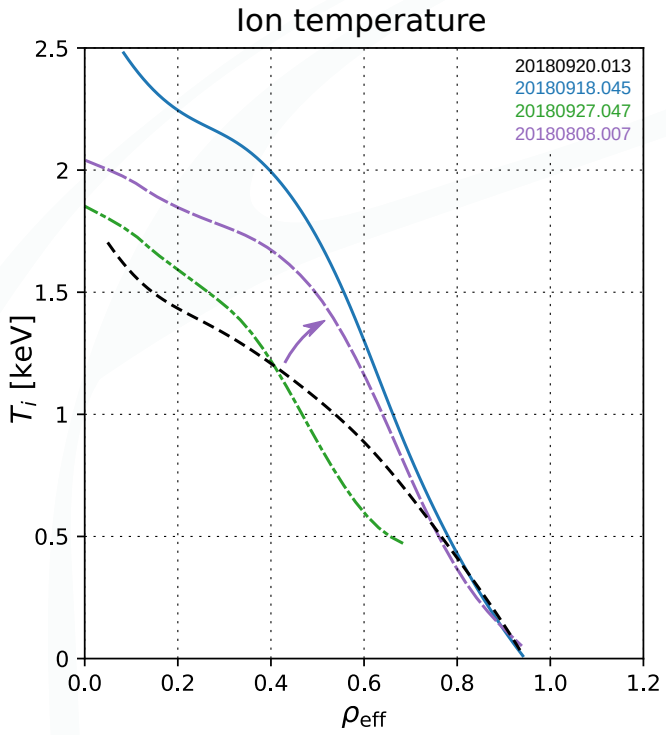

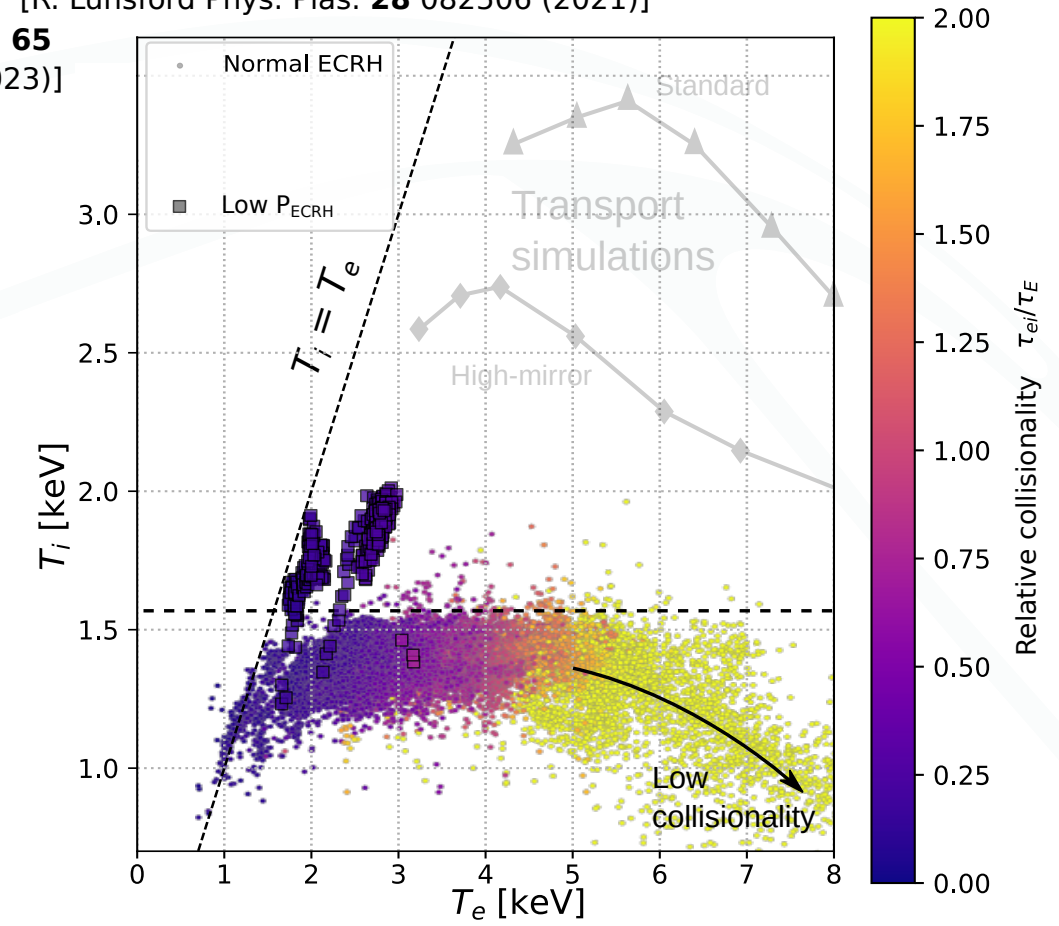

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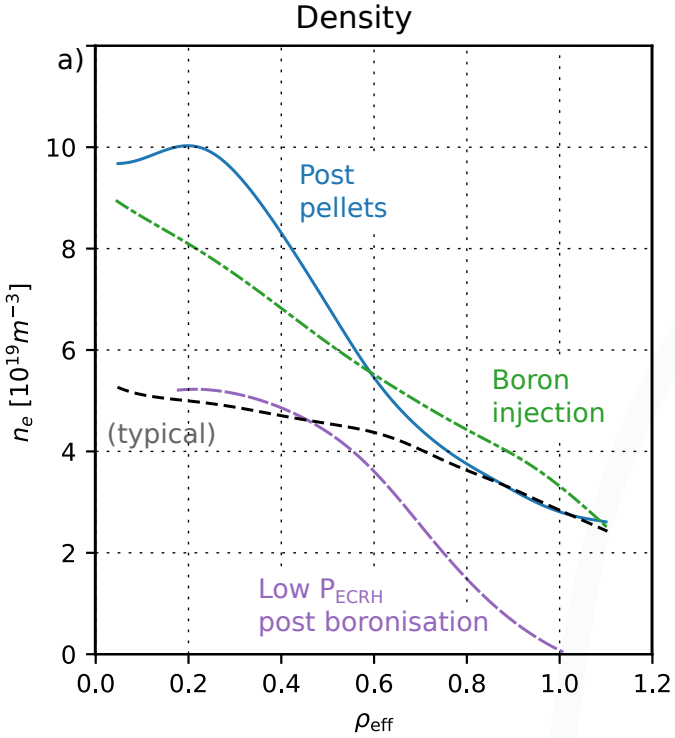
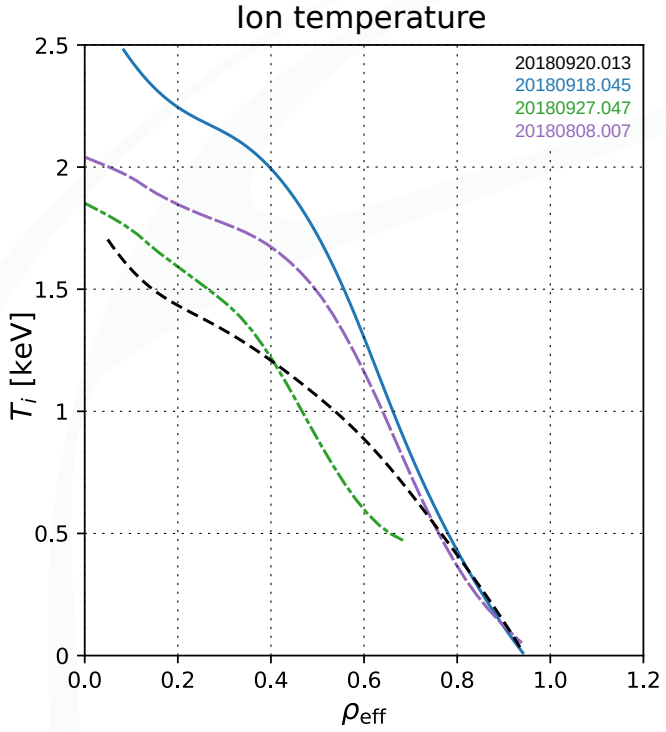
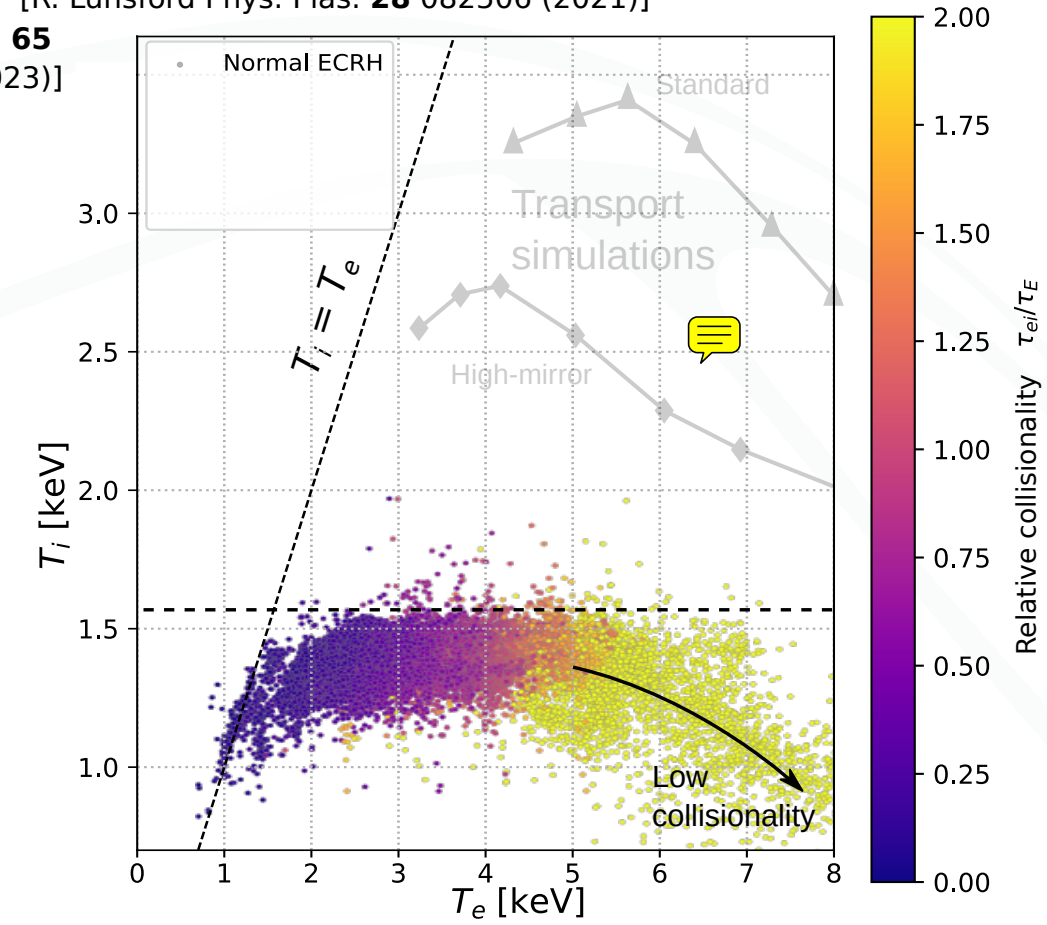
∇n_e --> ITG suppression [Xanthopoulos, PRL **125** 075001 (2020)]
--> Reduced χ_i --> Higher ∇T_i *(see Poster M. Wappl)*







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- NBI also *sometimes* gives density gradients.
- Is the turbulent transport reduced compared to ECRH?
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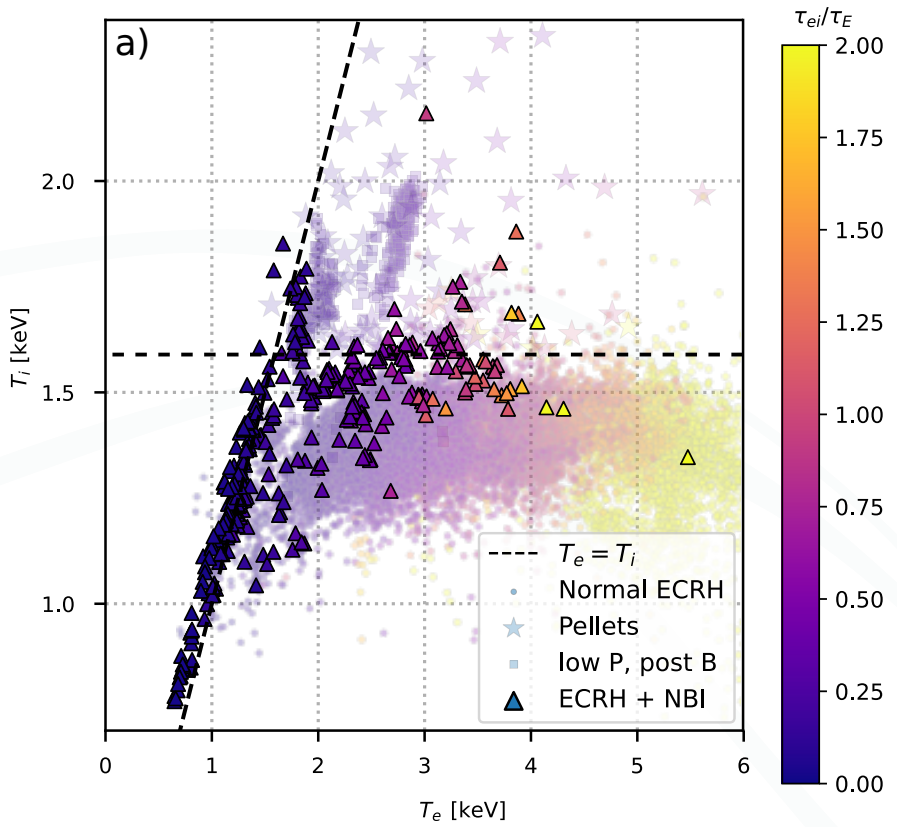

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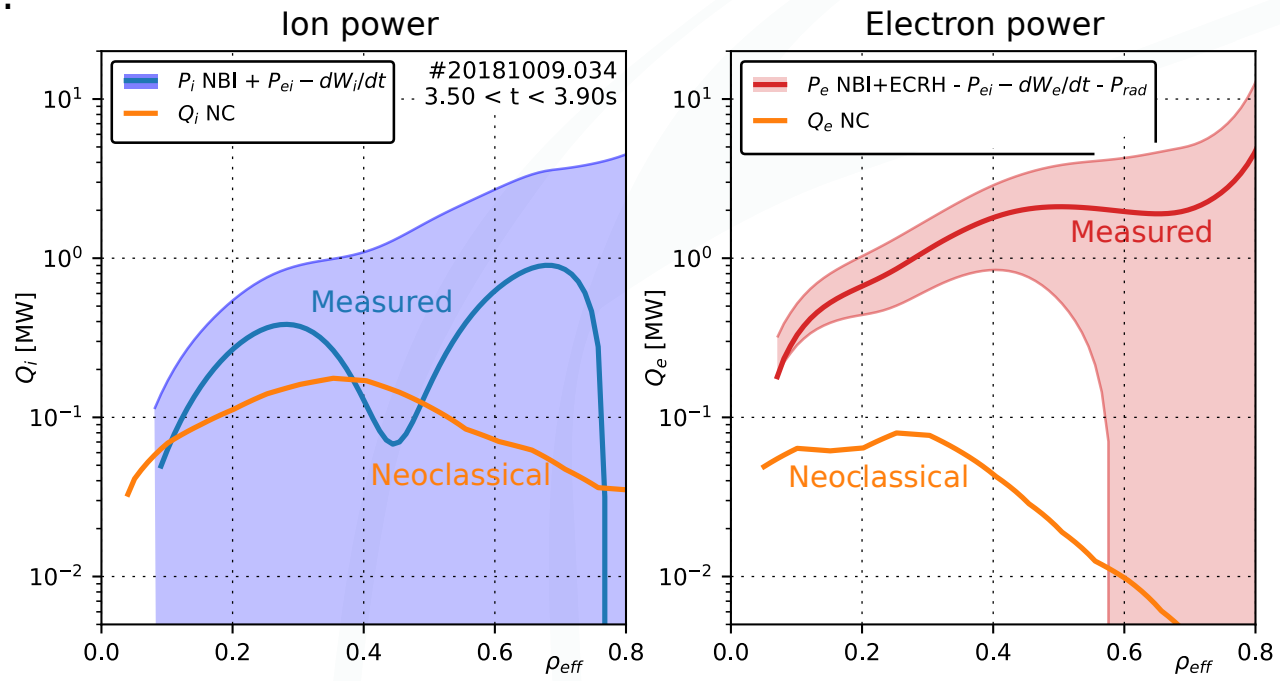
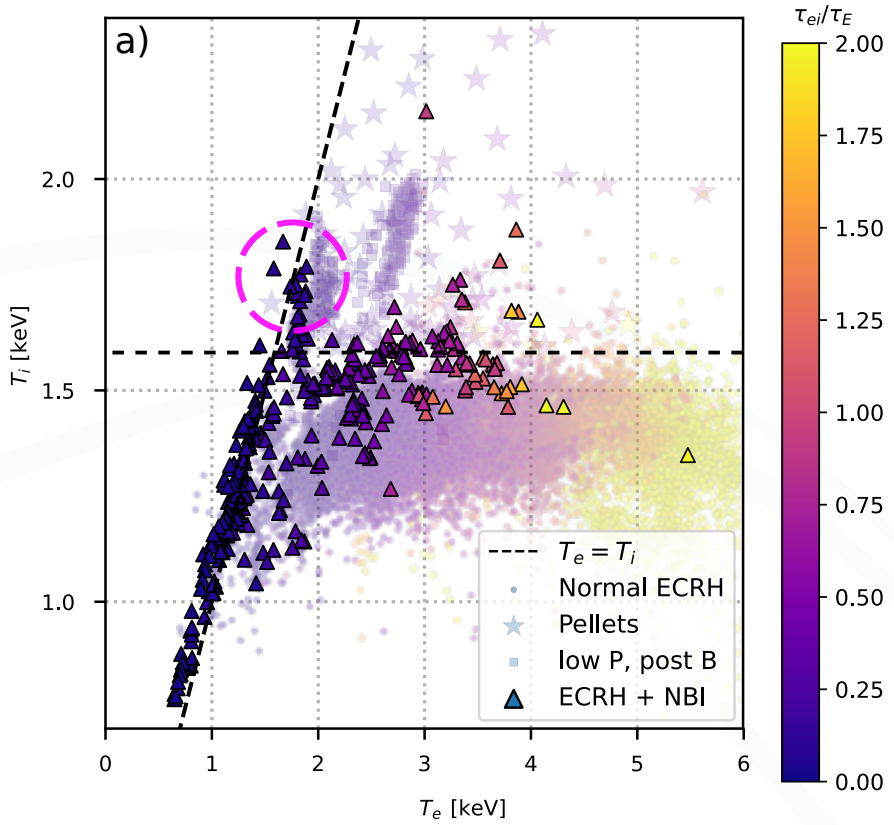
- Some NBI+ECRH plasmas hint at **possibility** of Q_i near neoclassical levels, e.g.:

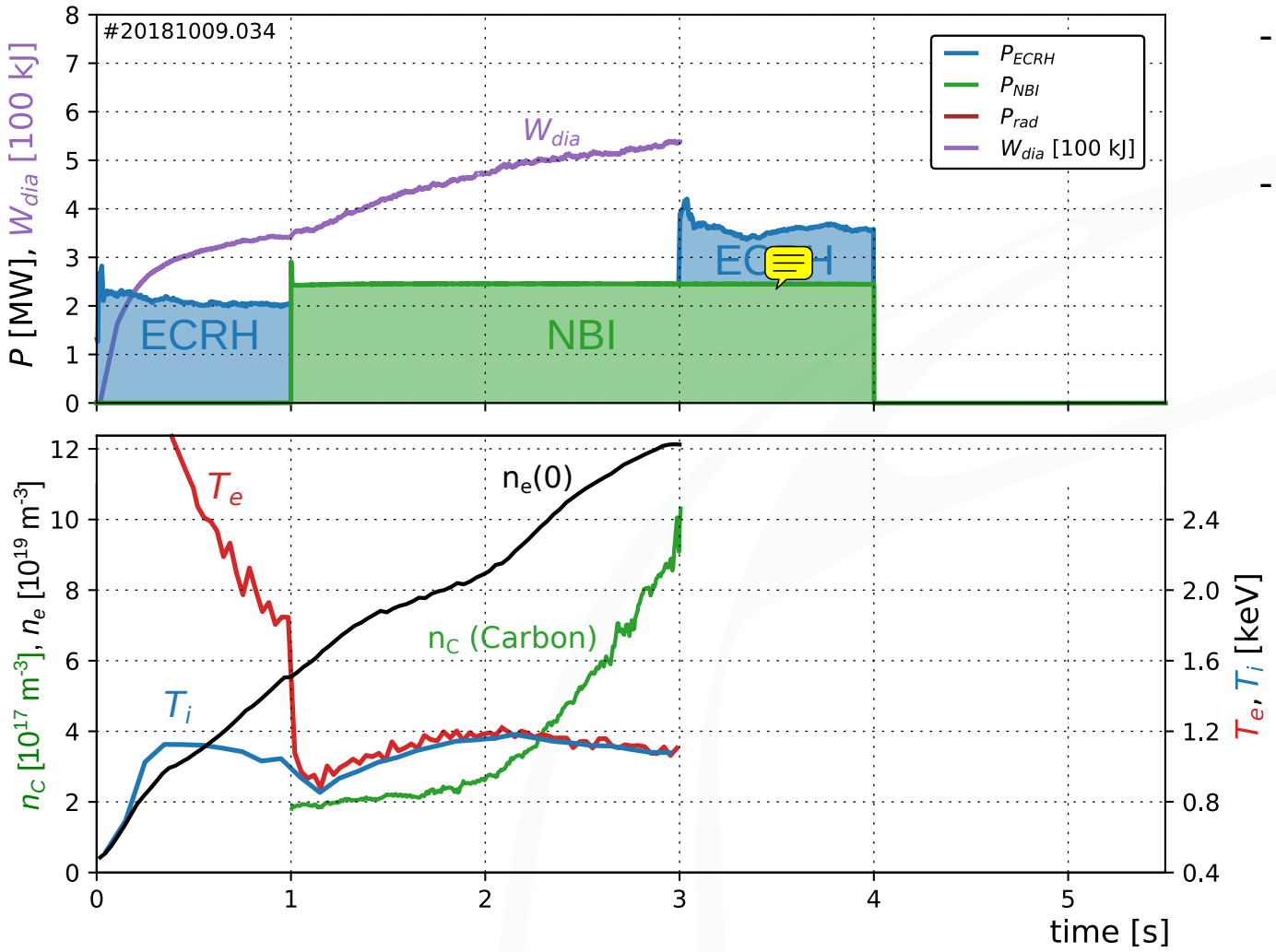
NBI 3MW
ECRH 1MW





NBI + ECRH reintroduction

- Density gradient builds up in pure NBI phase, which is exploited with reintroduction of O2 ECRH at high n_e.



- Density peaking accelerates at a given time after switch to pure NBI --> Particle transport changes.

- Impurities accumulate from this time, almost entirely determined by neoclassical transport.
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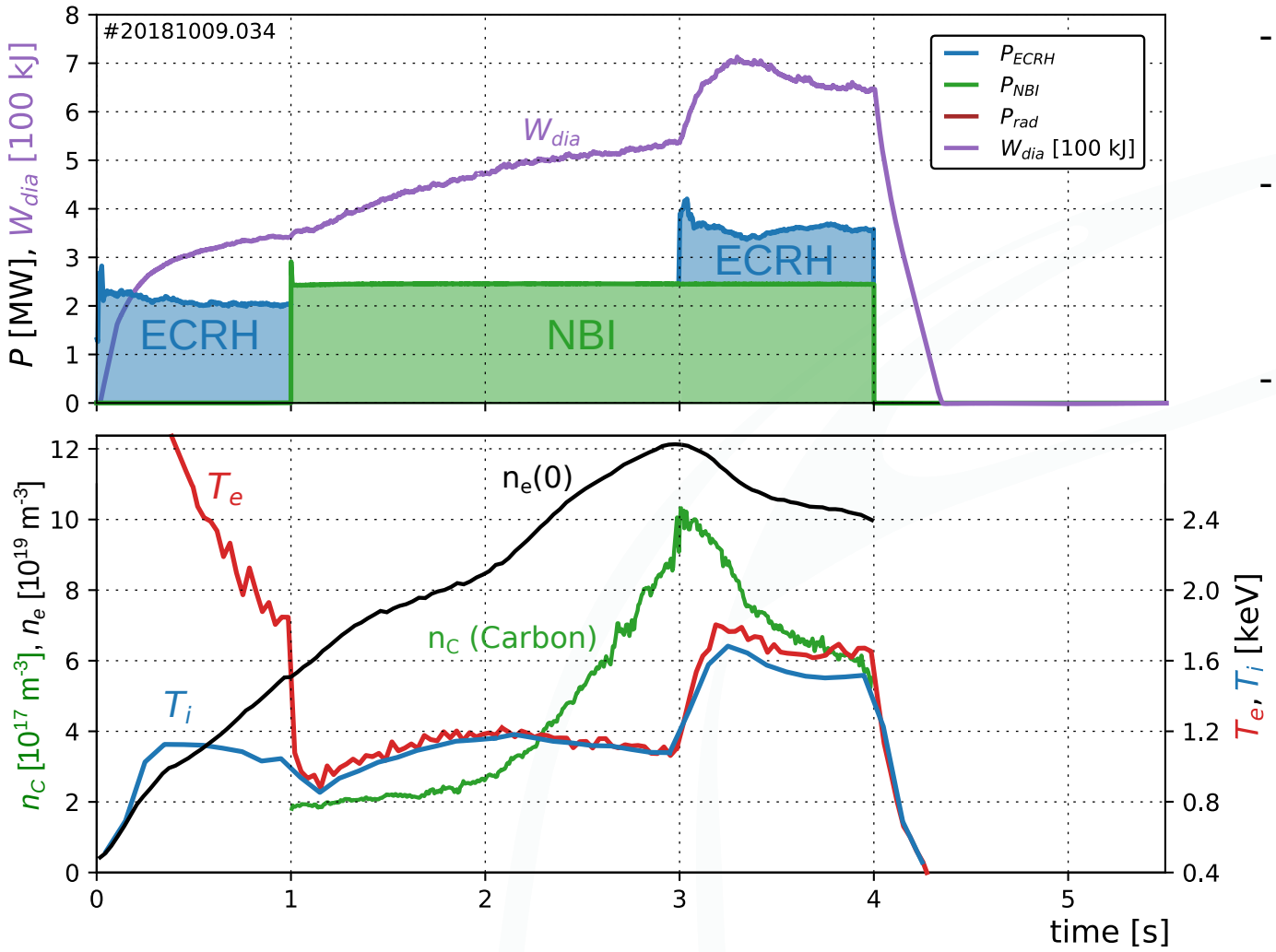

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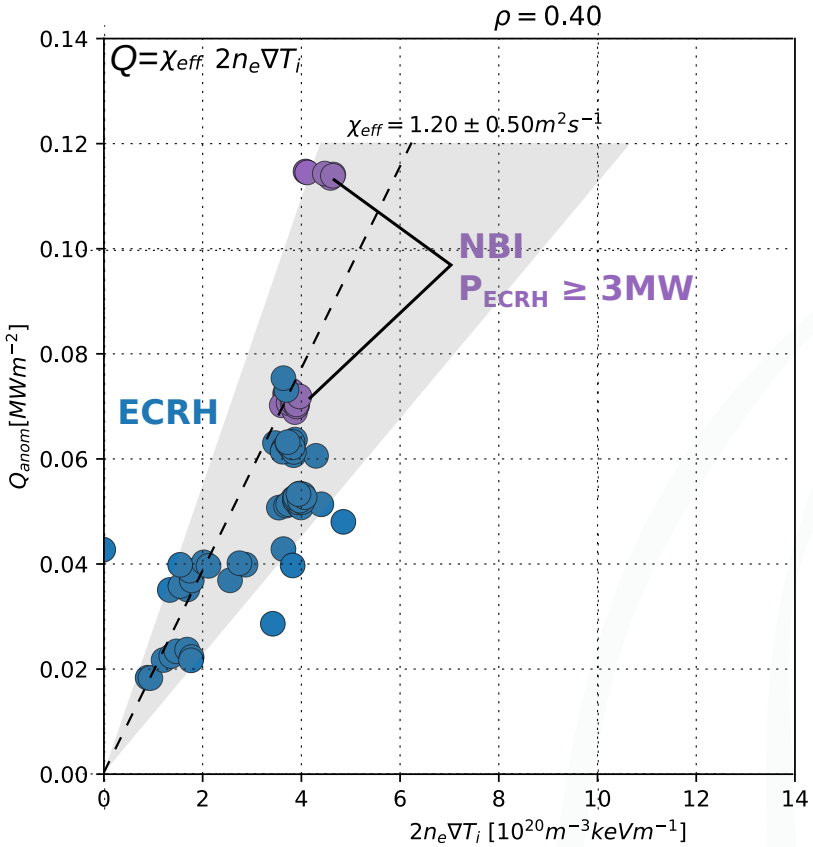
- Reintroduced ECRH stops density peaking or reduces it, and flushes out impurities.

[O. Ford Nucl. Fus. 64 086067 (2024)]

NBI (±ECRH) - Anomalous heat diffusivity

- Not possible to separate Q_i, Q_e due to high collisionality and similar heating effect of NBI - $P_e \sim P_i$.
- Look at combined χ_{eff} in gradient region ($\rho \sim 0.4$) reveals two branches:
  Dominant ECRH: $\chi_{eff} \sim 1$ m^{2}s^{-1} as in pure ECRH scenarios [M. Beurskens, Nucl. Fus. 61 116072 (2021)].

Normalised gradients at $\rho \sim 0.4$



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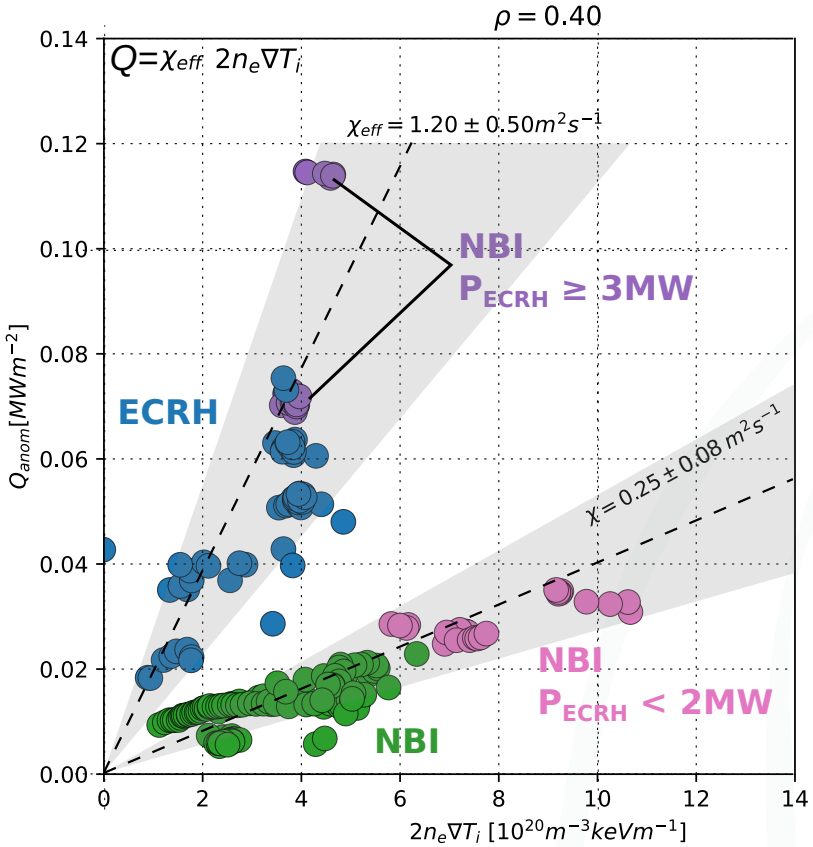

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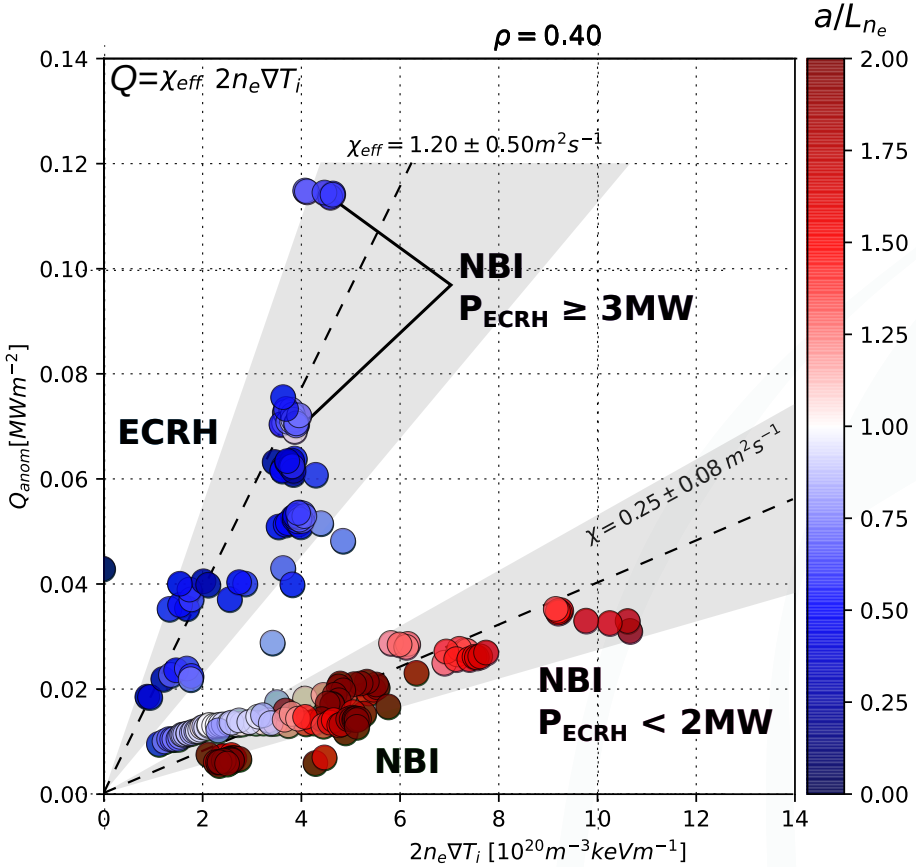

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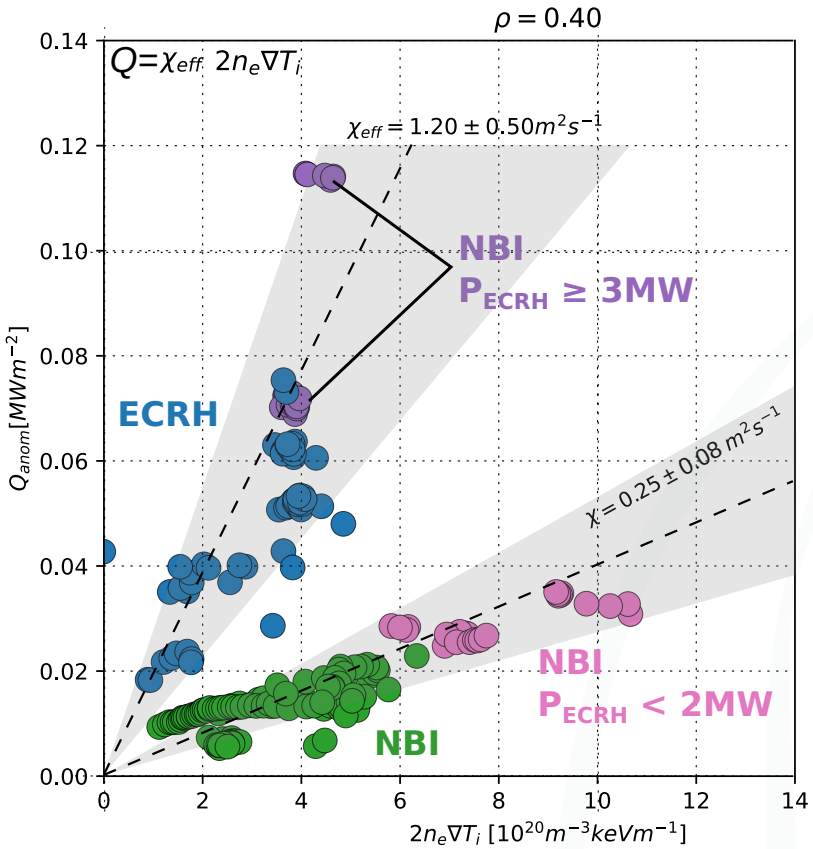

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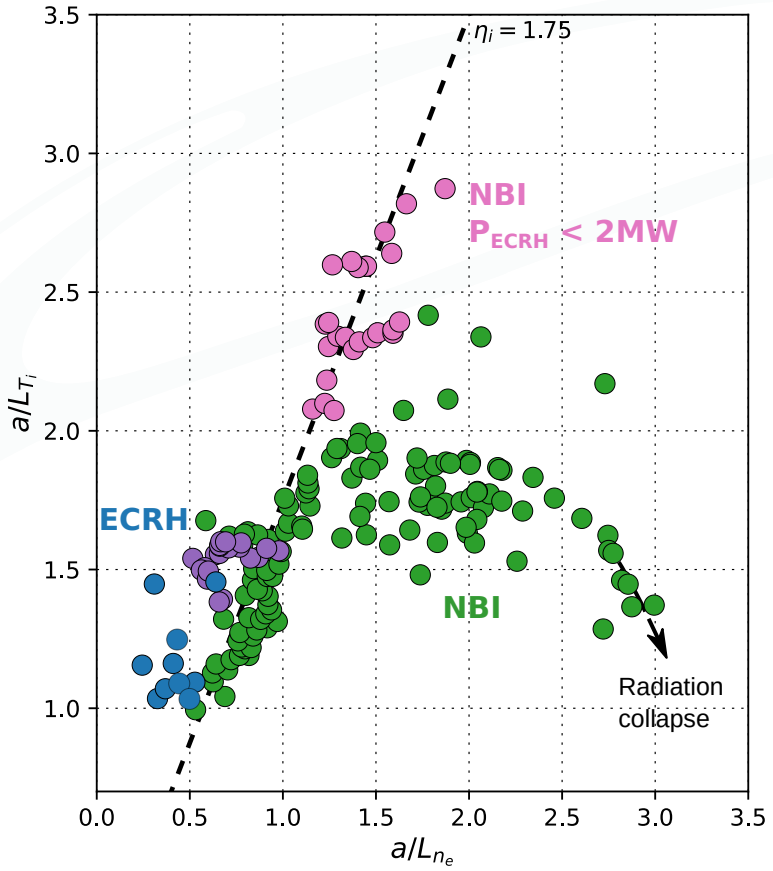

- Pure NBI has reduced χ_{eff}, but much broader power deposition results in similar ∇T_i. (and T_{i0})
- Mixed NBI with low P_{ECRH} maintains $\chi_{eff} \sim 0.25$ and can exploit it for higher ∇T_i.
- All plasmas with $a/L_{ne} > 1.0$ have lower χ_{eff}.
- Without additional ECRH, NBI plasmas can undergo radiation collapse.

[O. Ford Nucl. Fus. 64 086067 (2024)]

Pure NBI - Particle flux

- Particle balance during pure NBI phase shows:
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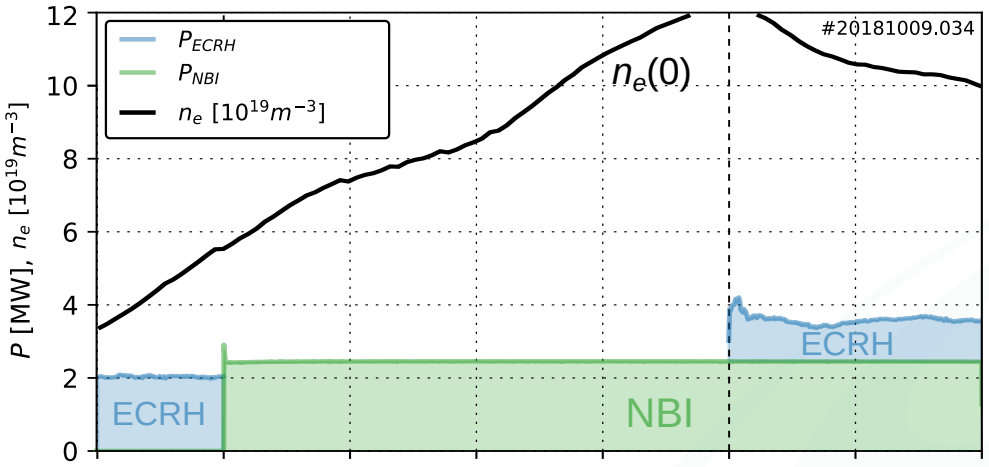

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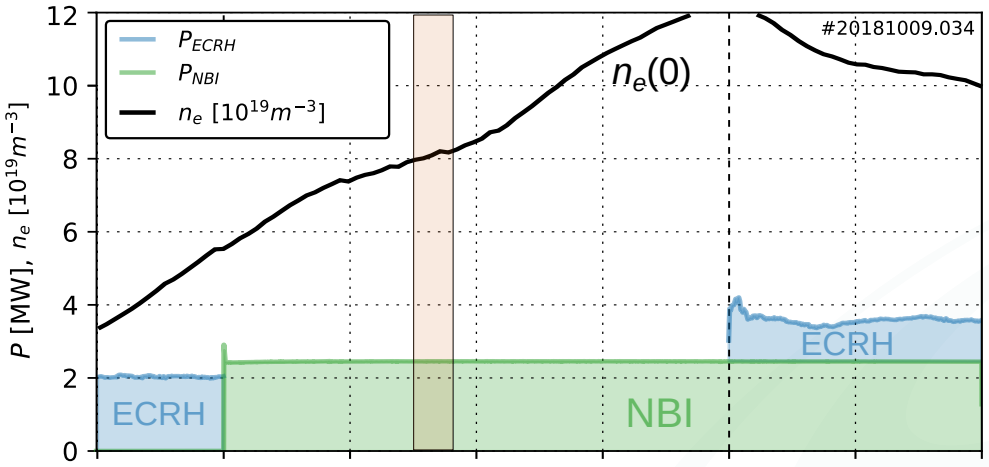

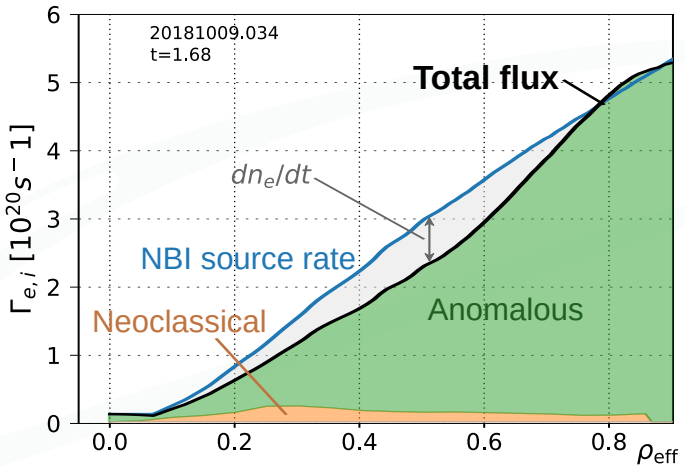

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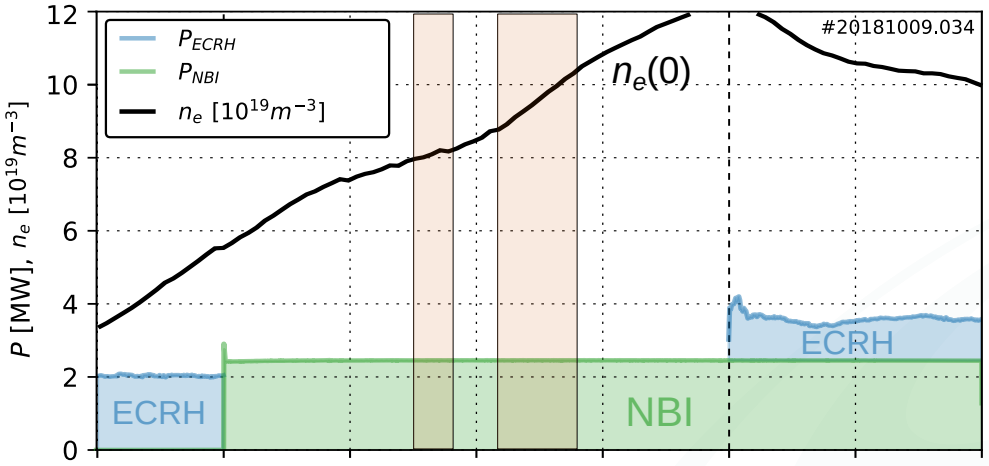

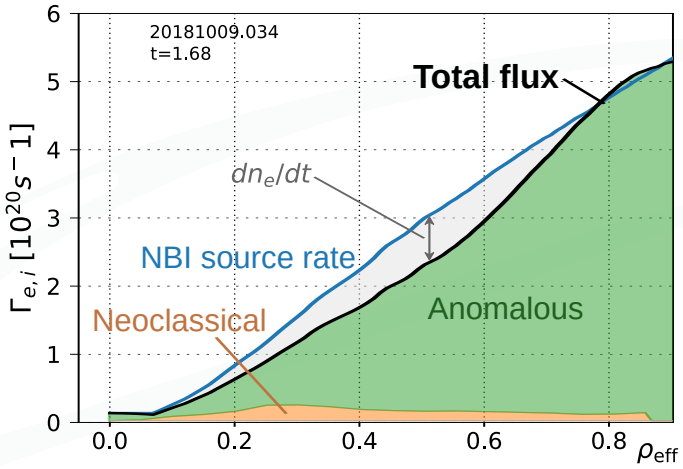

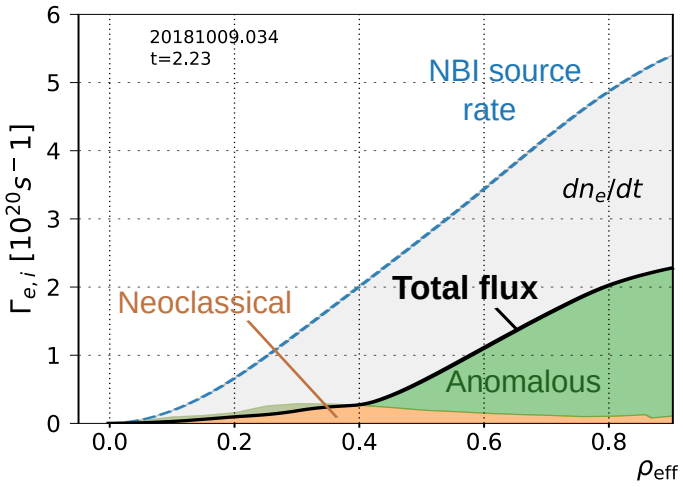

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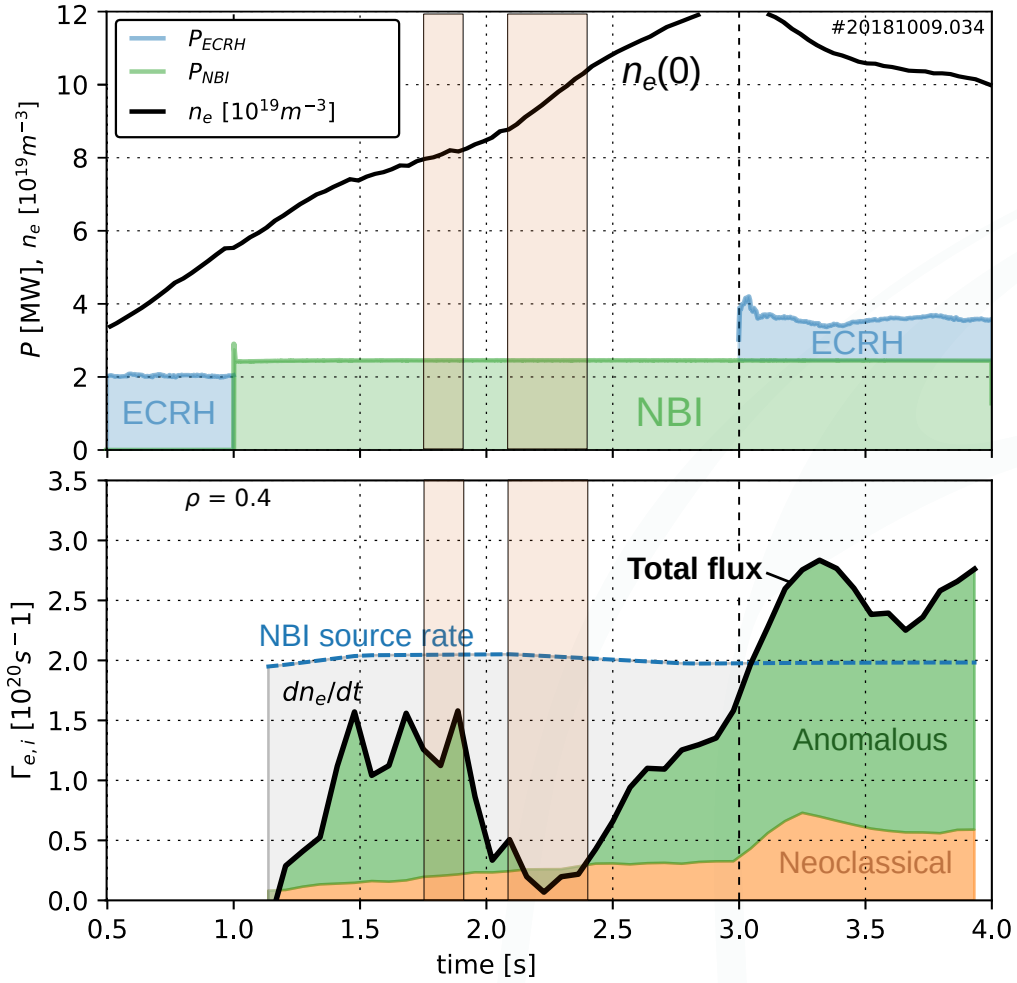

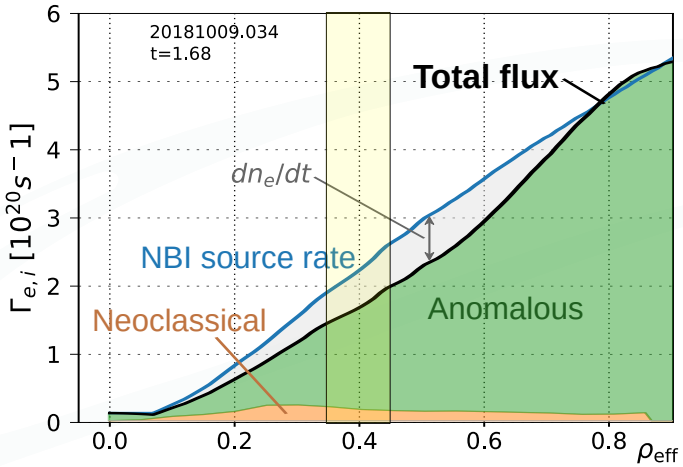

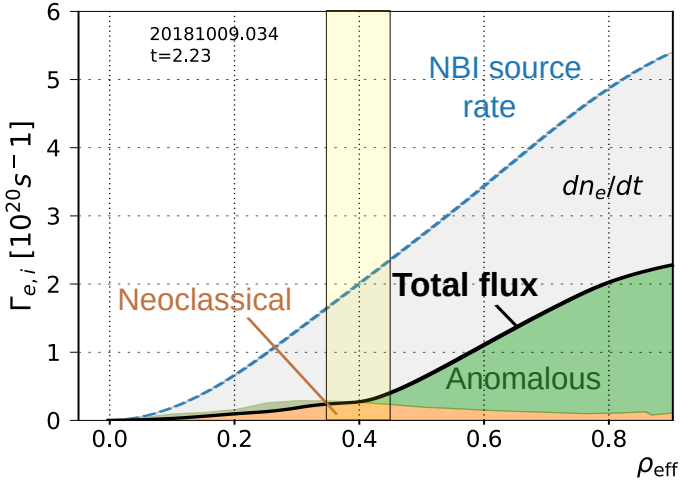

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[S. Bannmann Nucl. Fus. 64 106015 (2024)]

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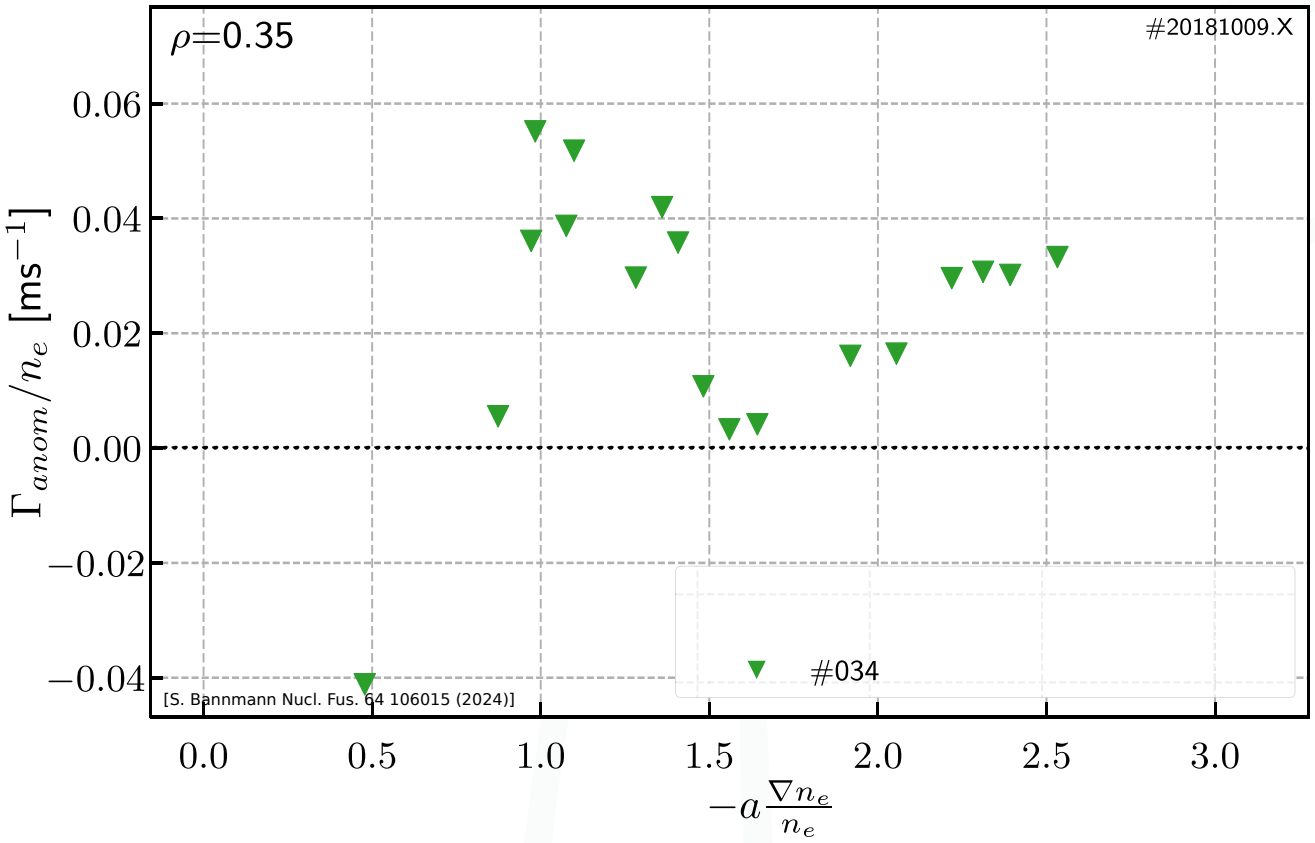

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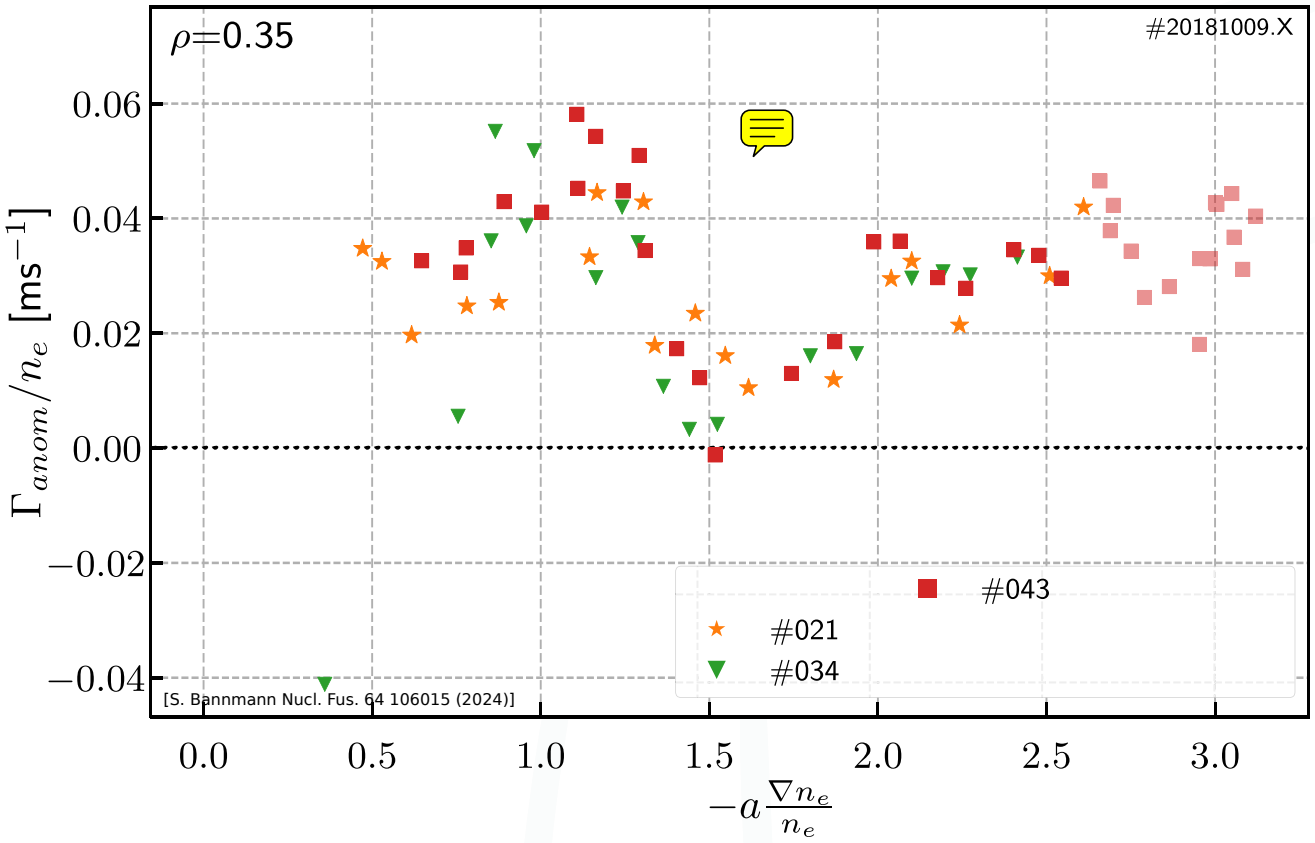

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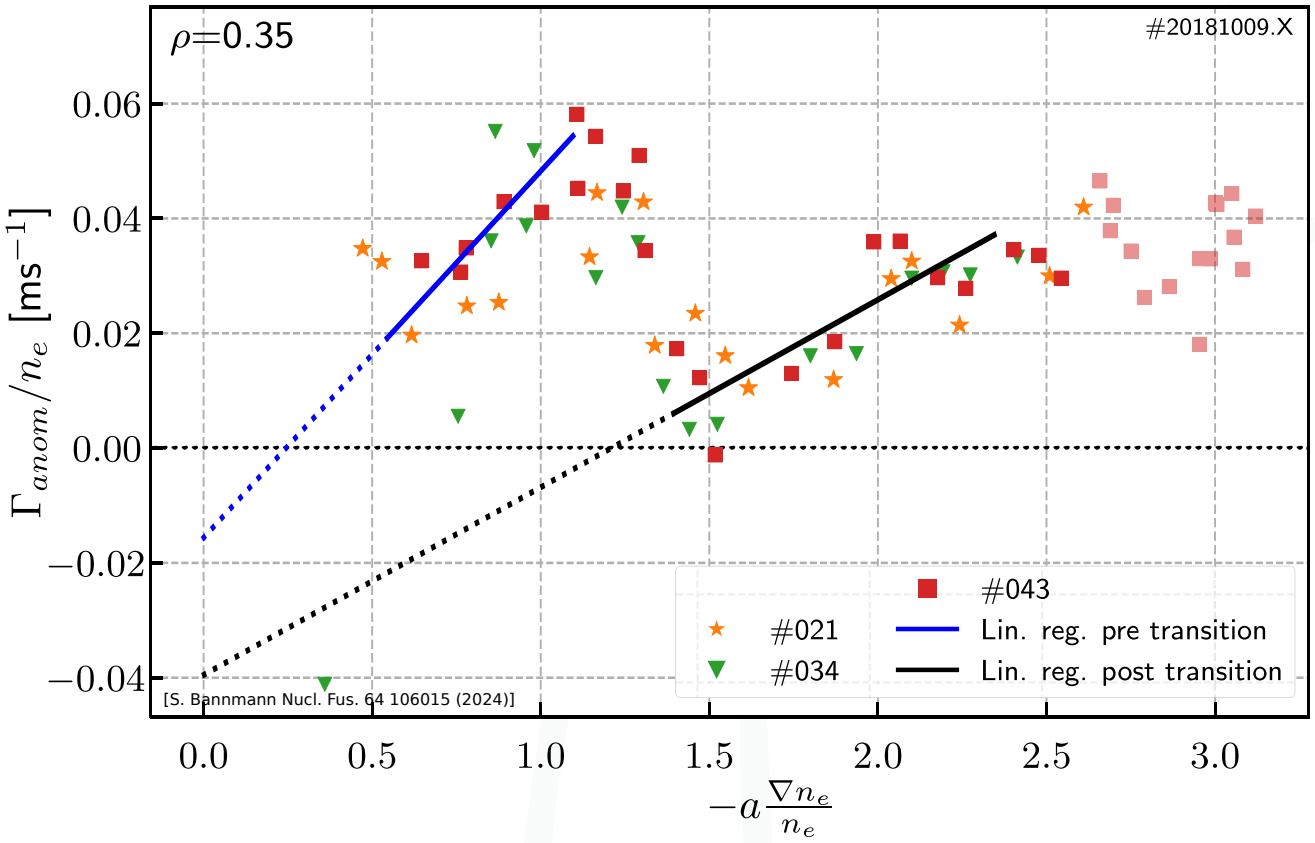

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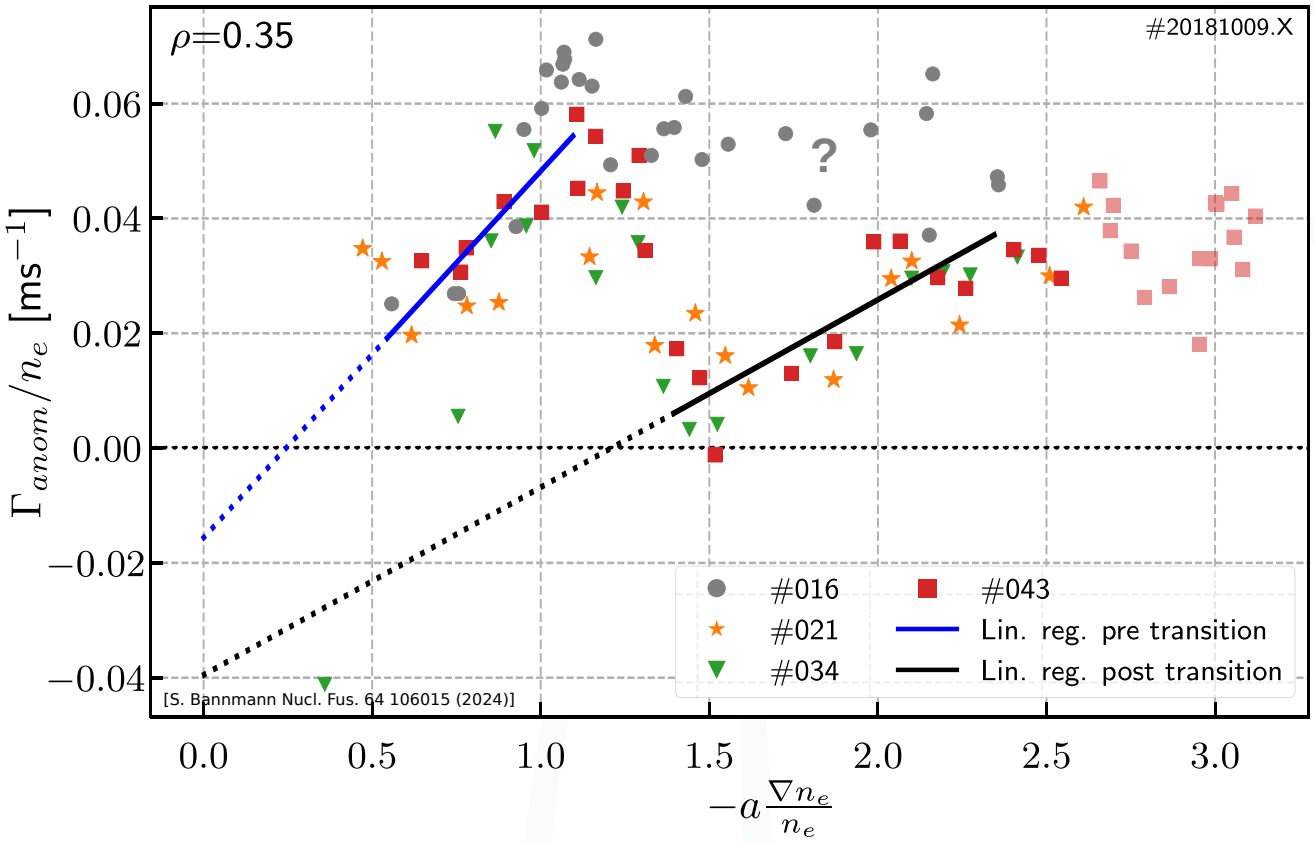

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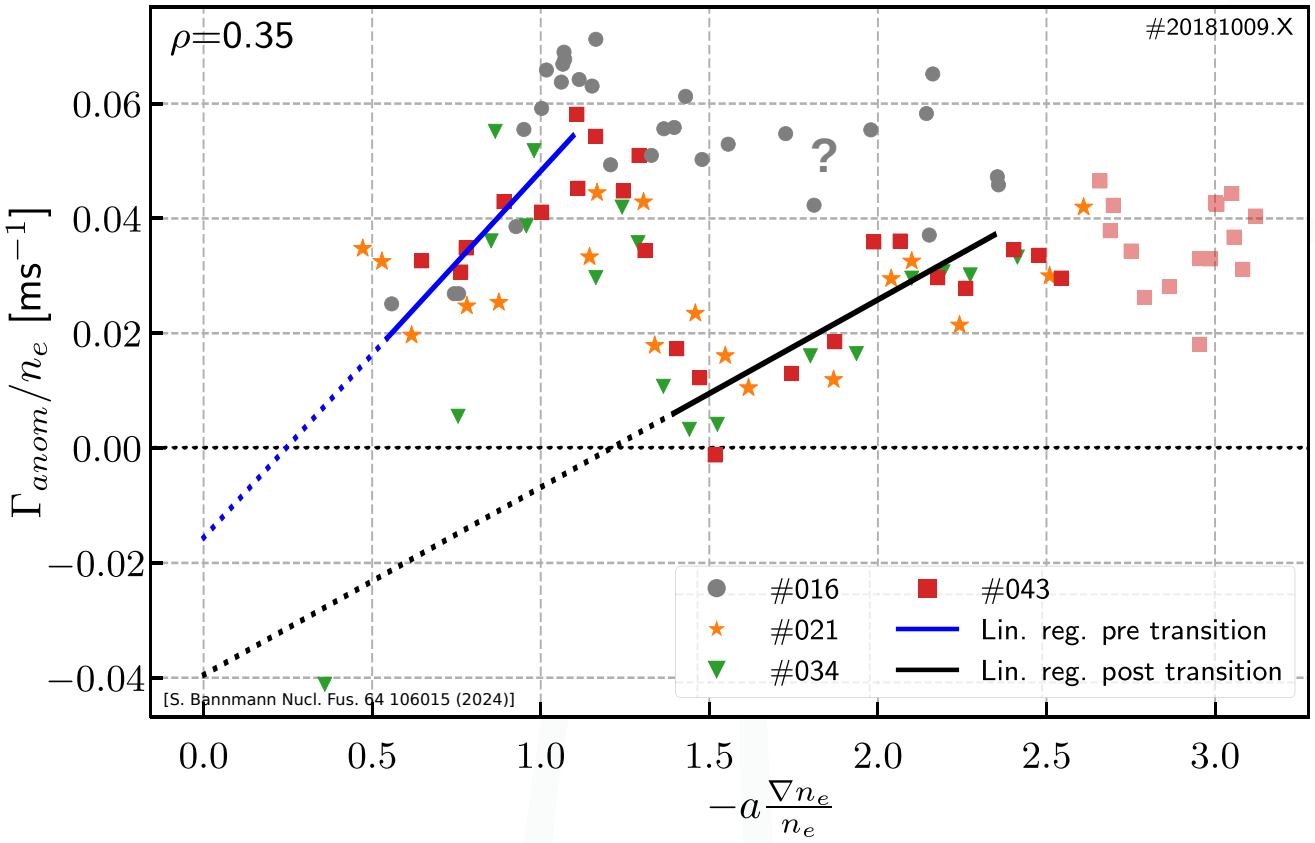
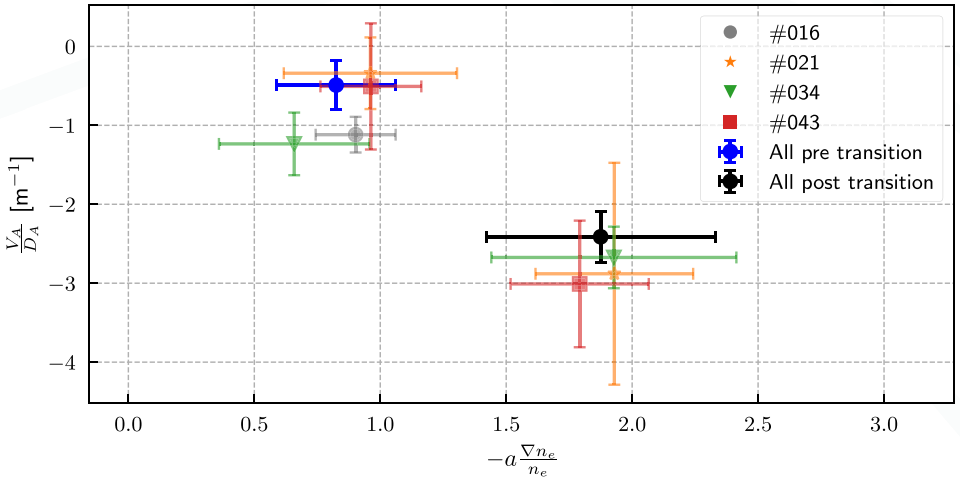


- Indicates two phases of ~consistent *v, D* with significant drop of *D* at $a/L_n \sim 1.3$.

- *v/D* ratio increases by factor ~ x5 leading to strong peaking.



- Threshold not yet seen in modelling. (Range not covered by STELLA study [H. Thienpondt, Phys. Rev. Res. 5, L022053 (2023)])

Pure NBI - Radial Electric Field

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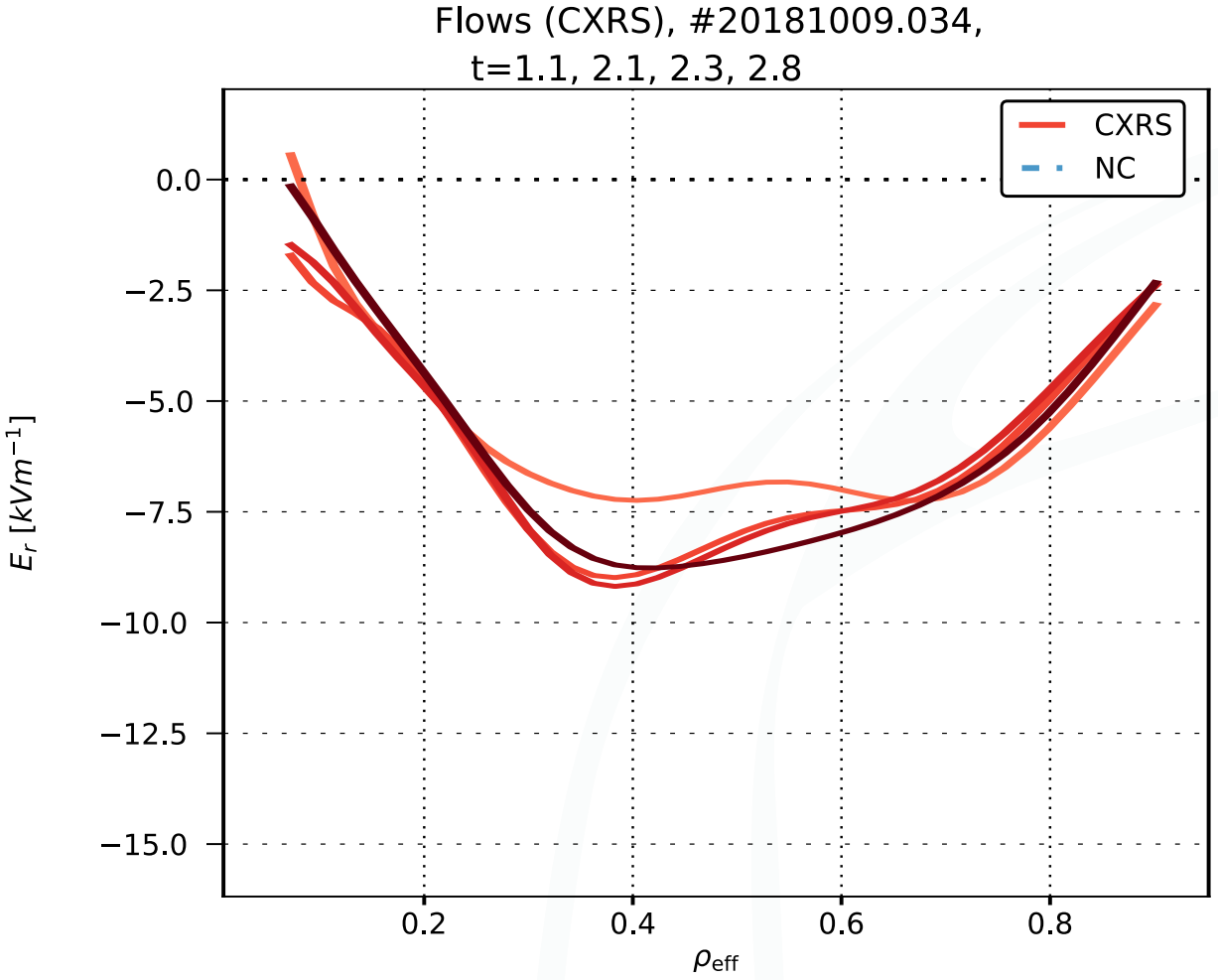

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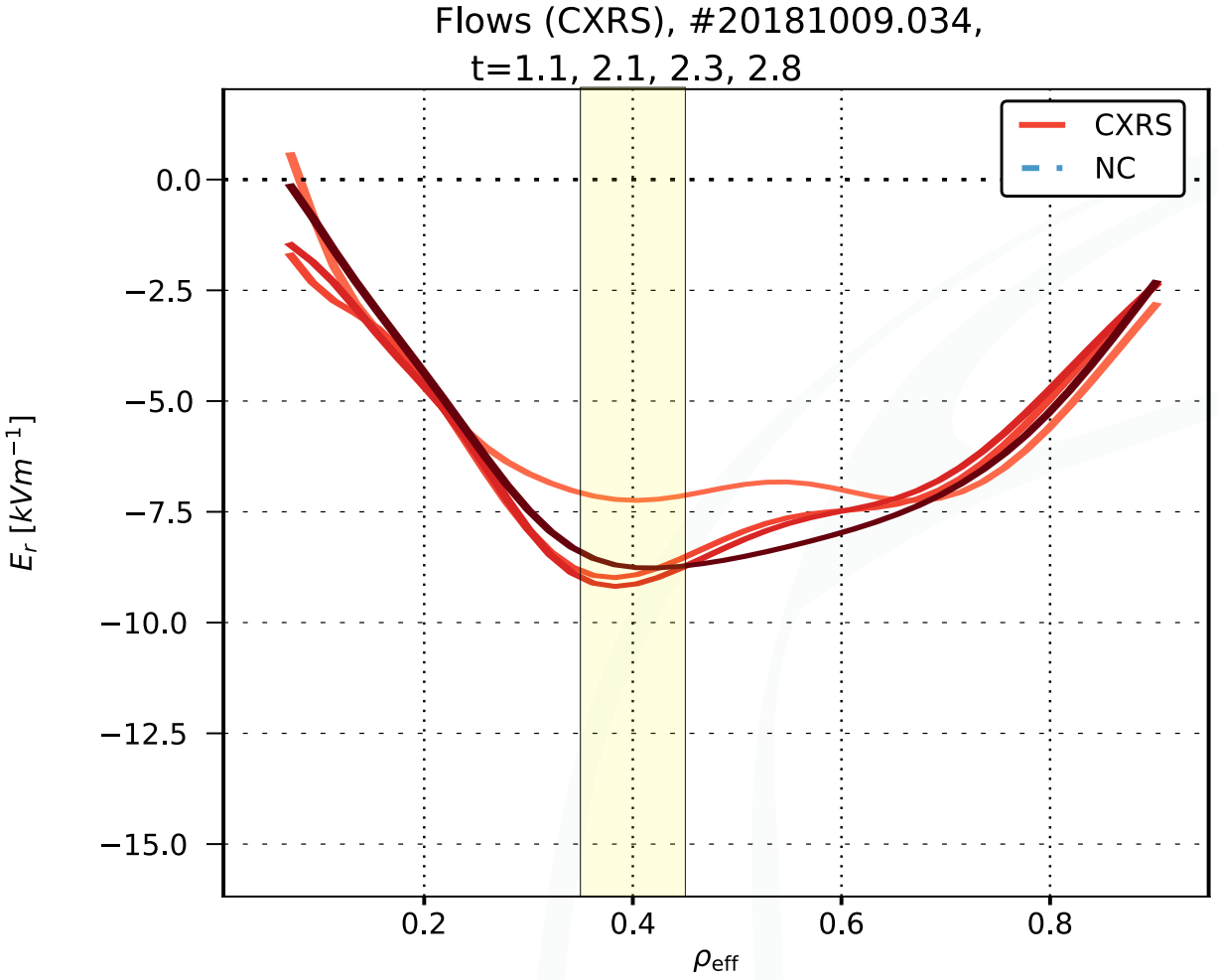

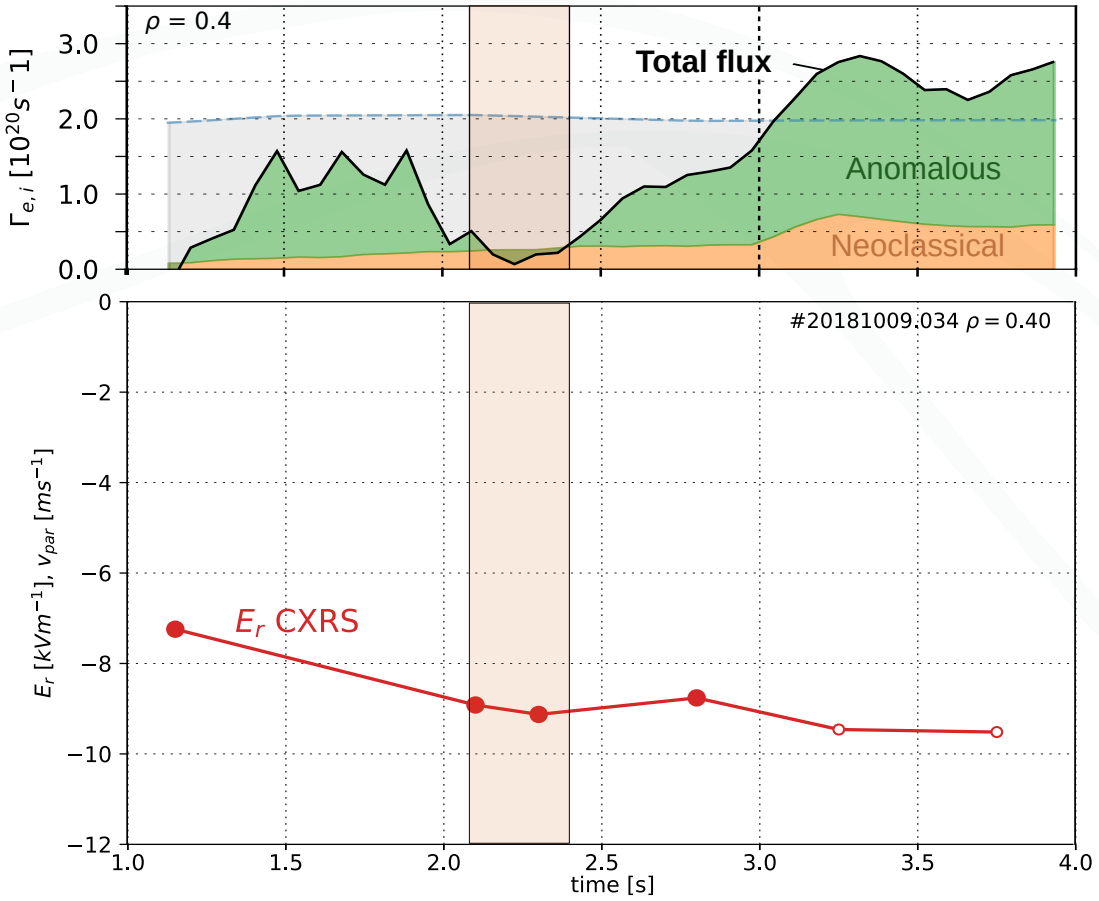

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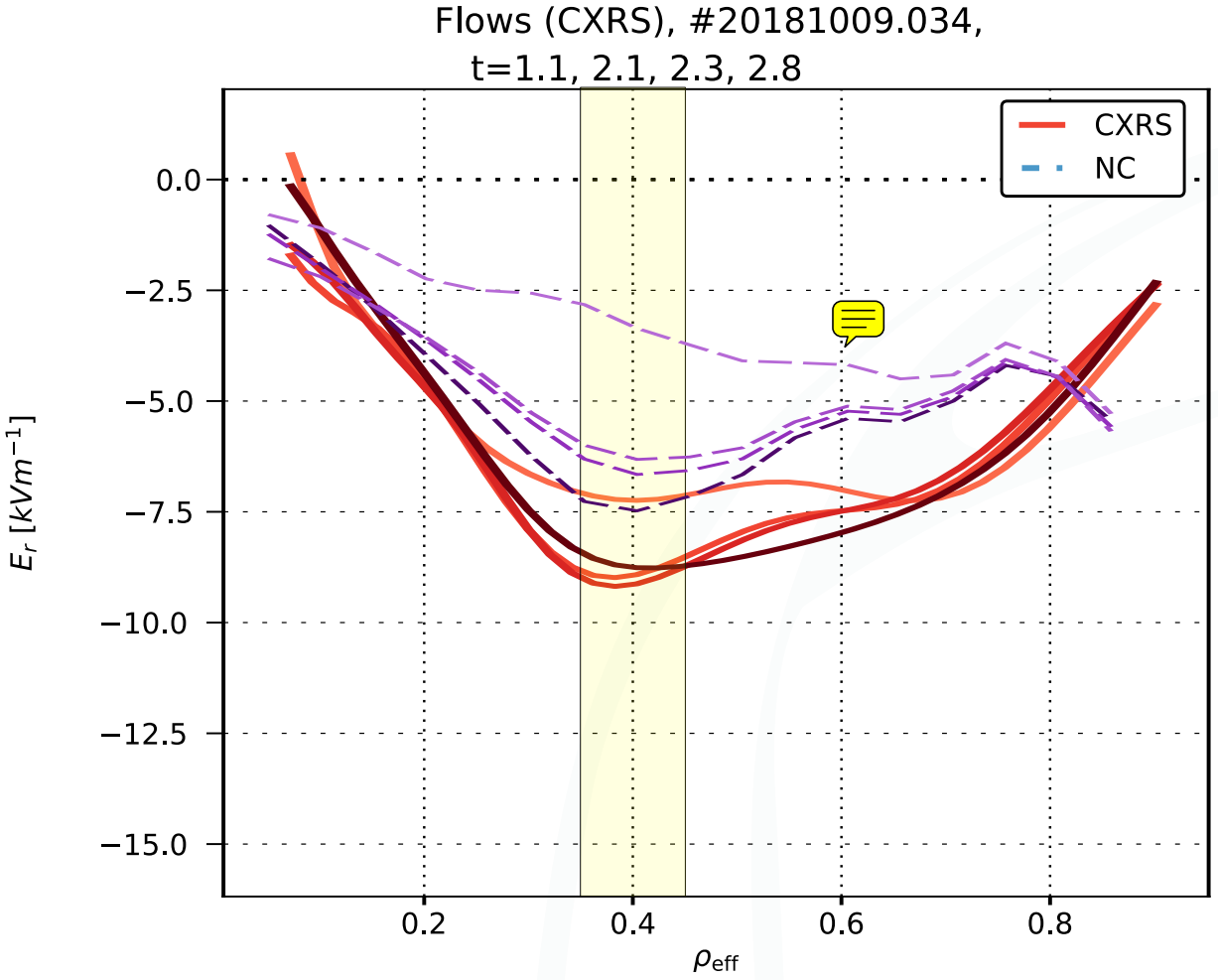

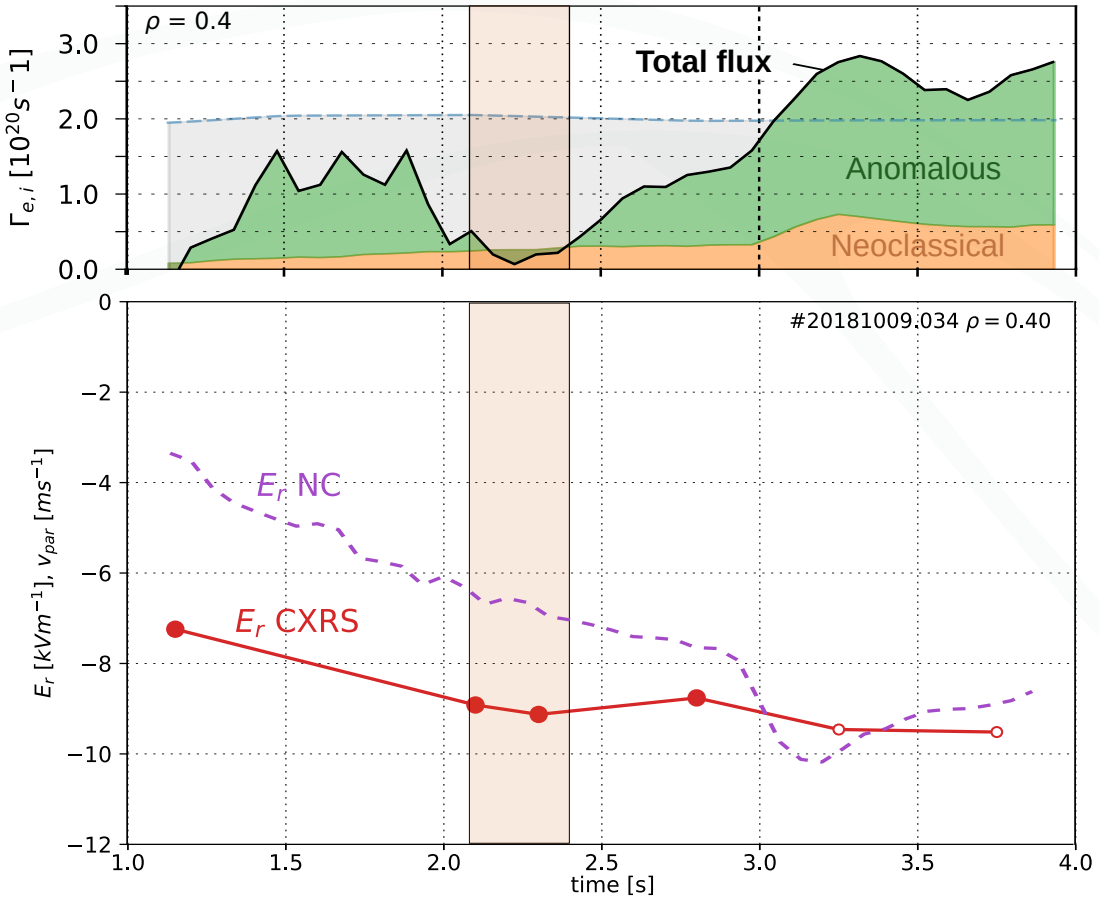

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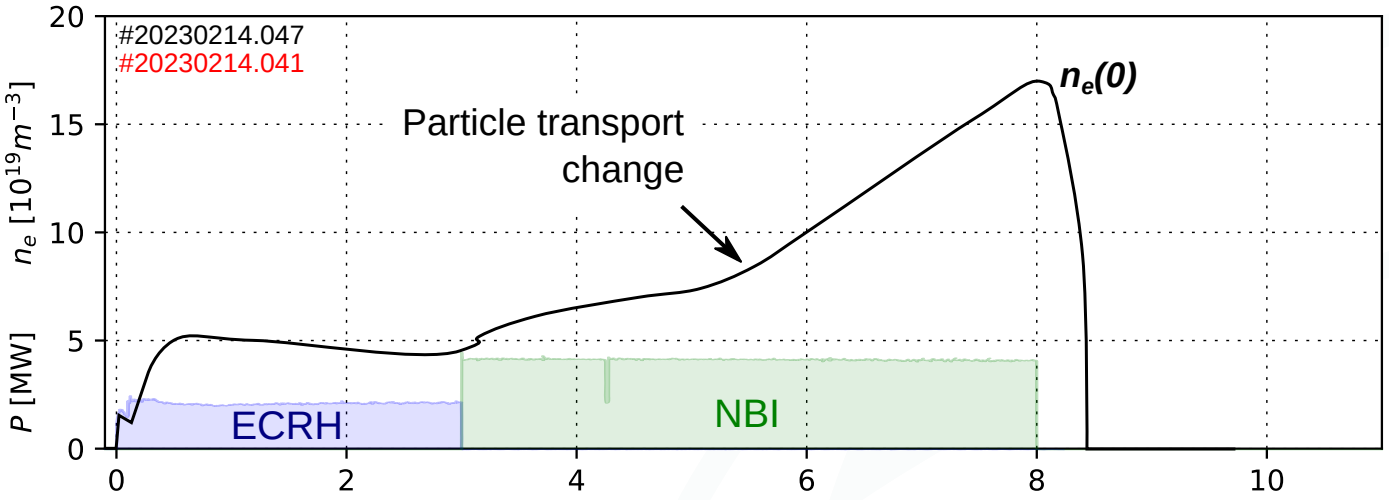

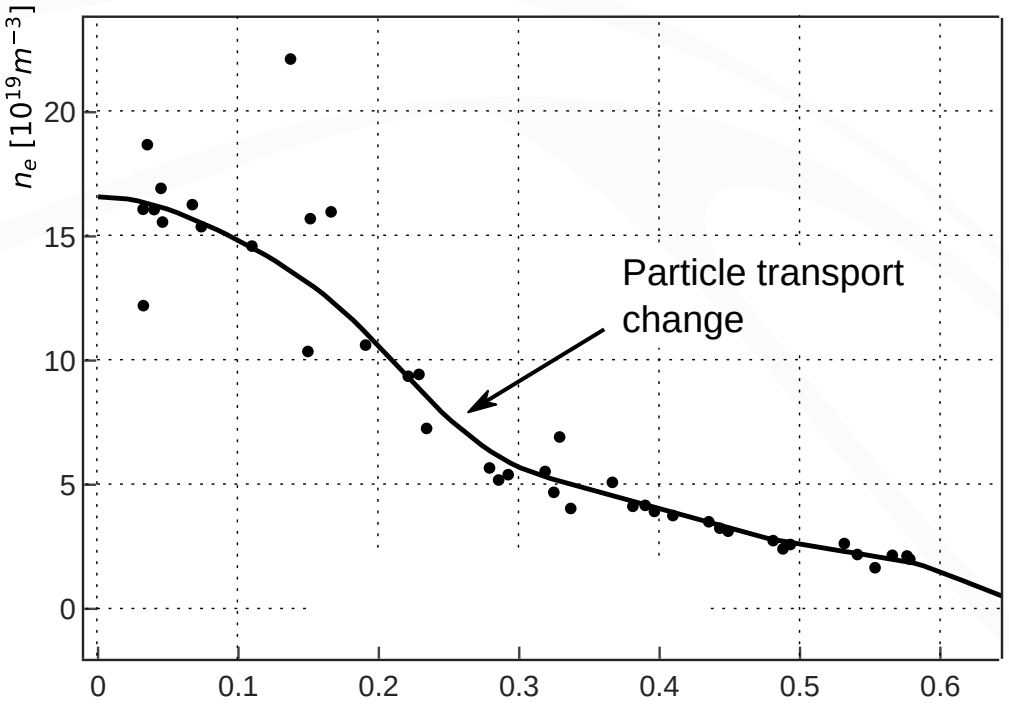

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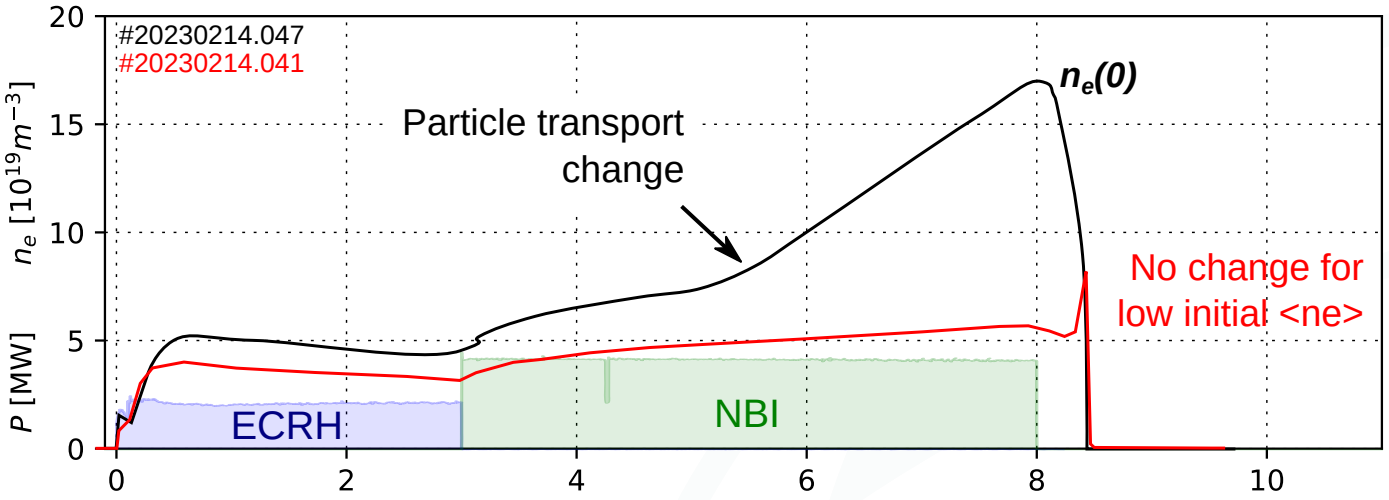

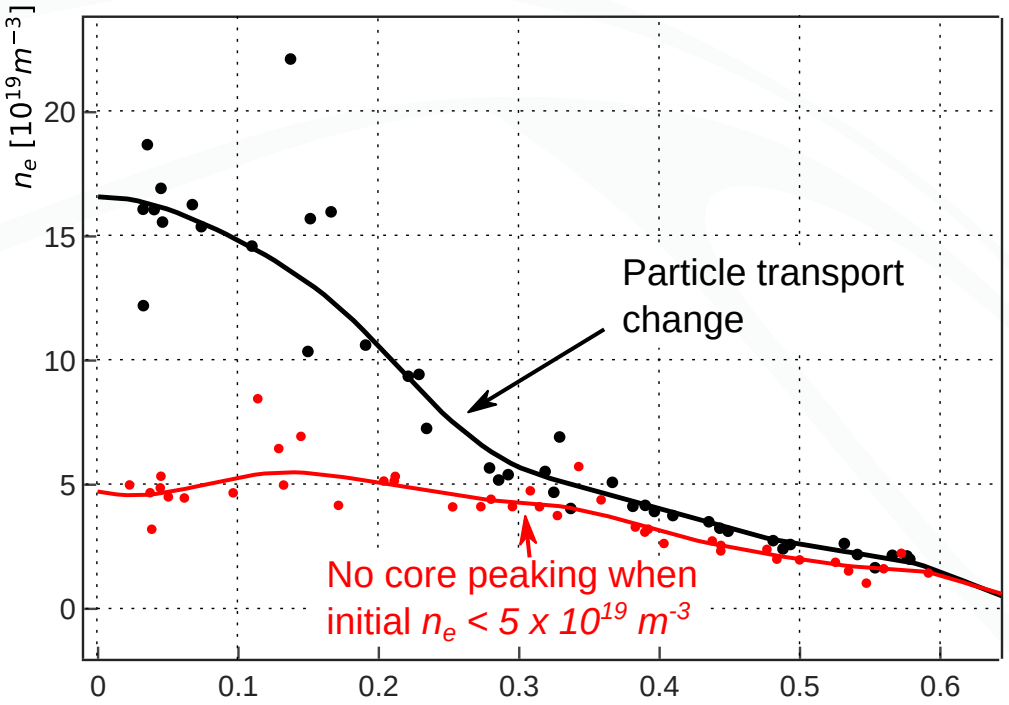

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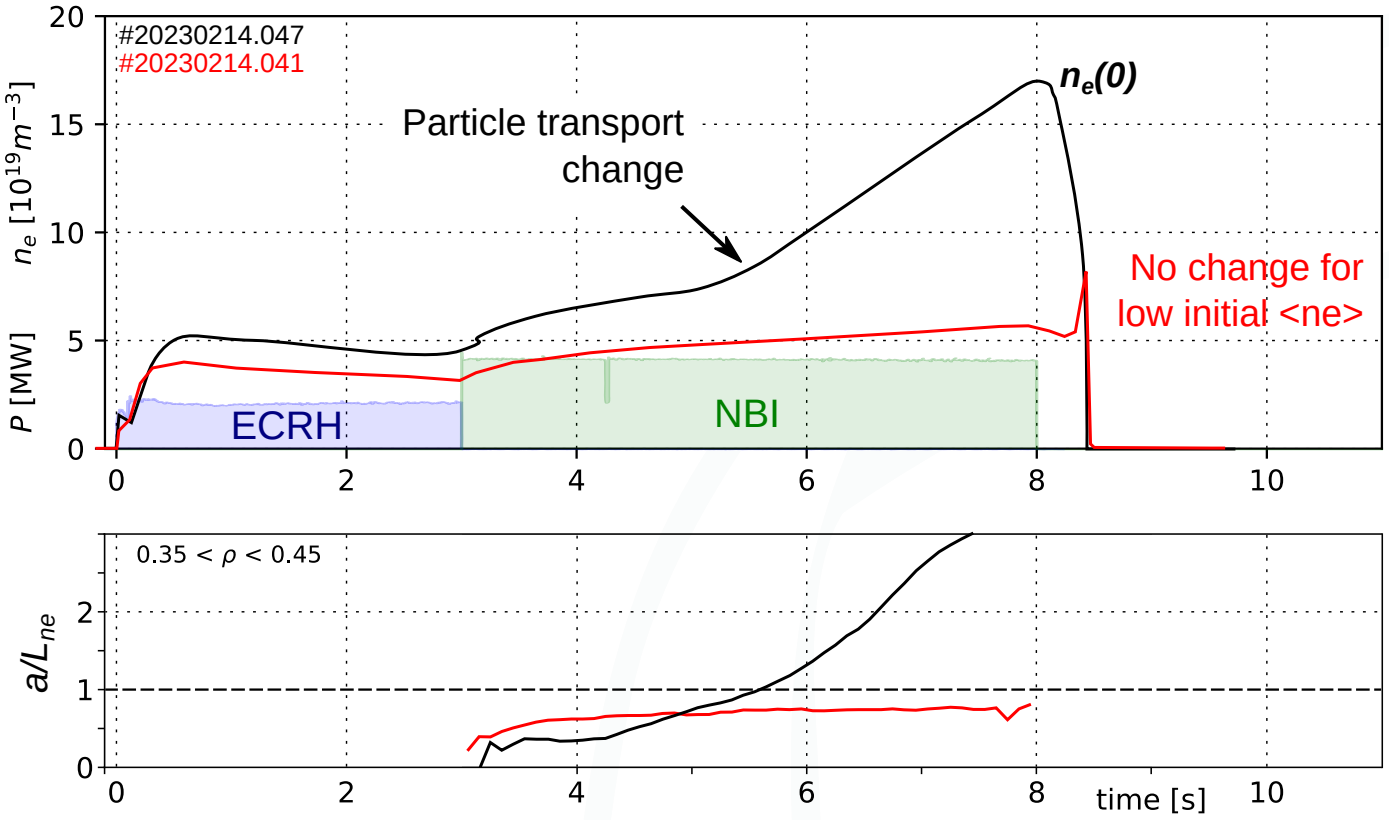

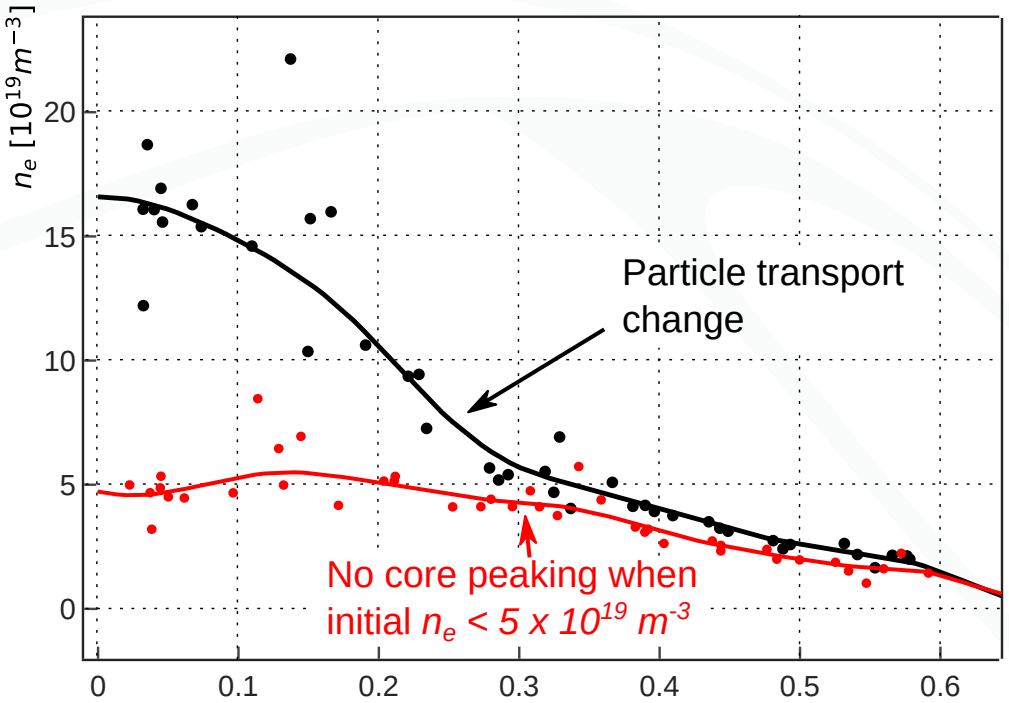

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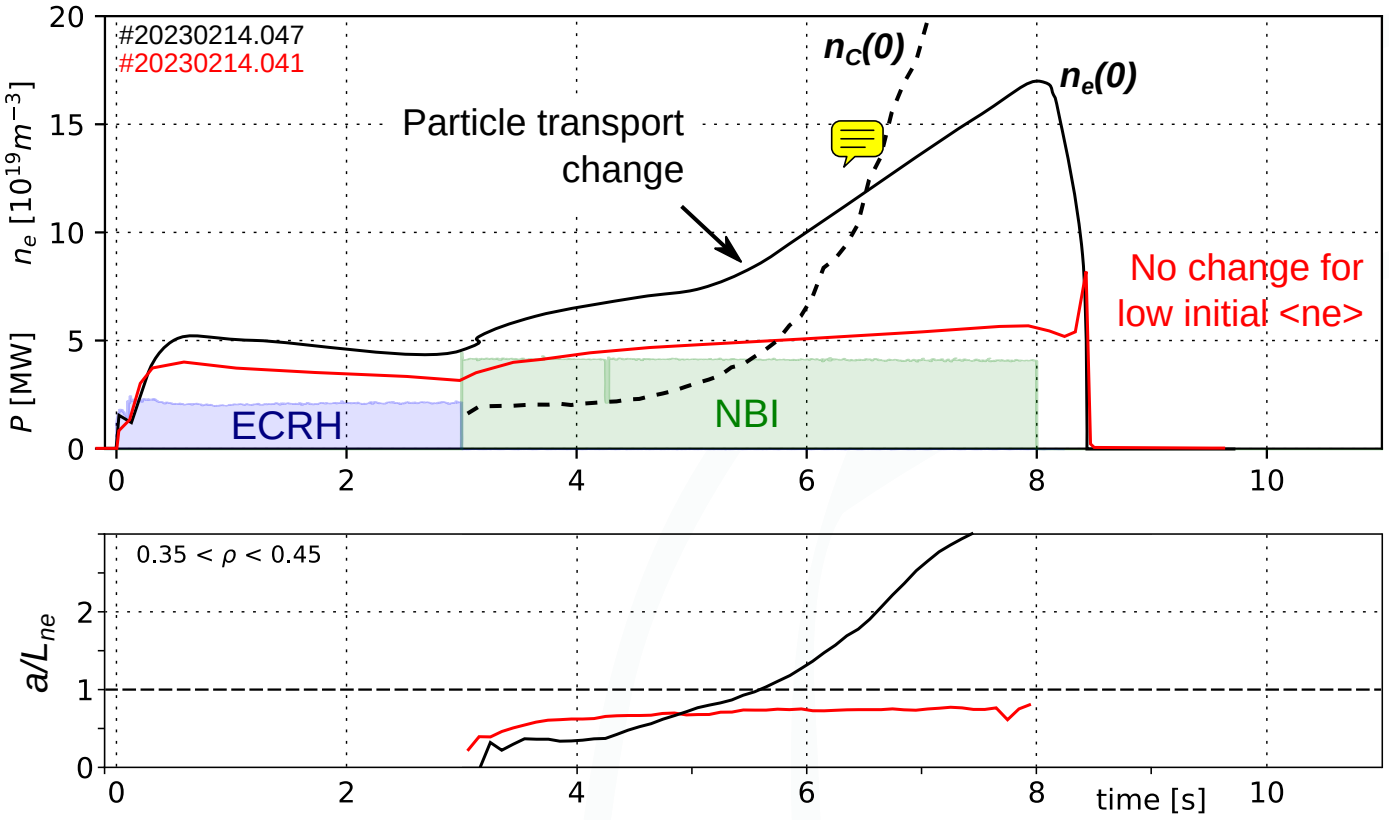

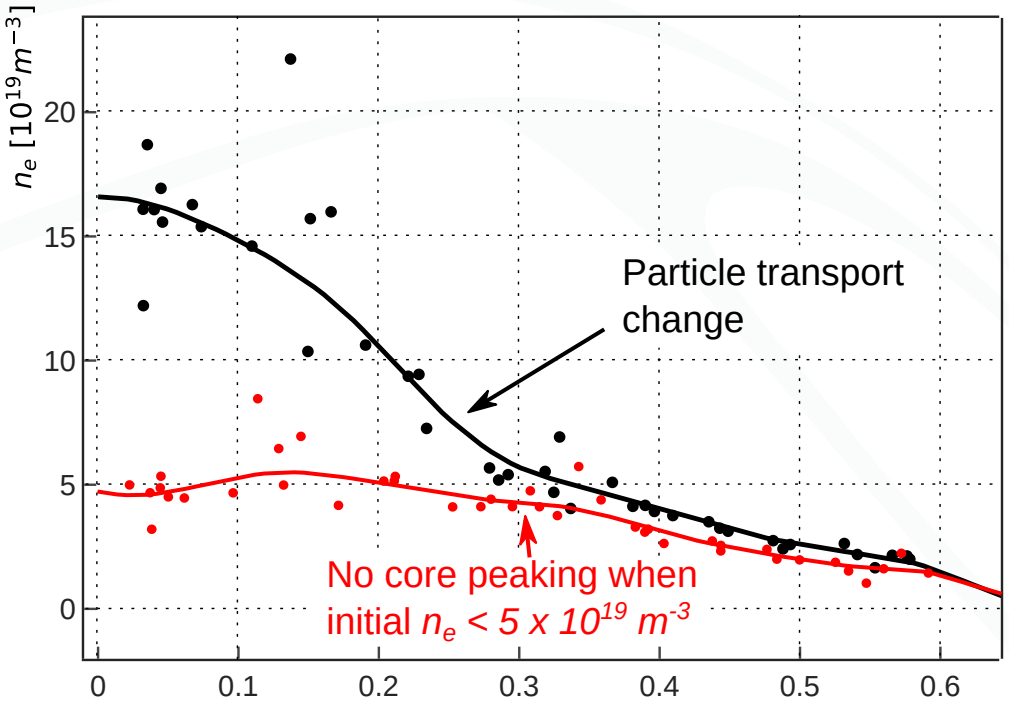

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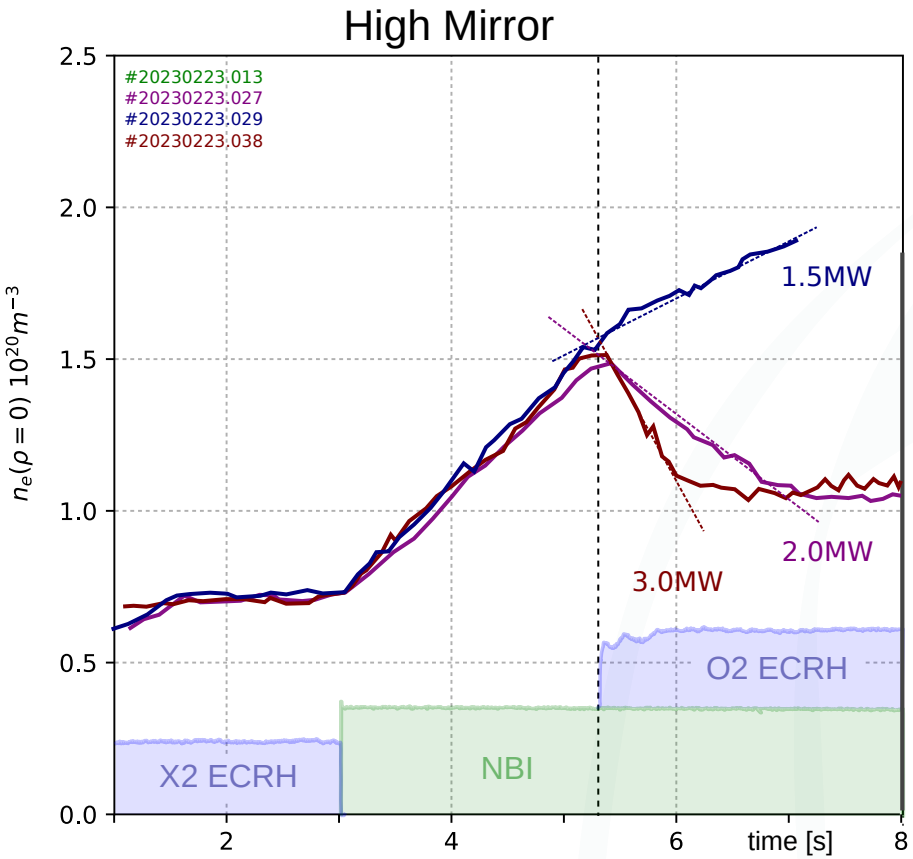

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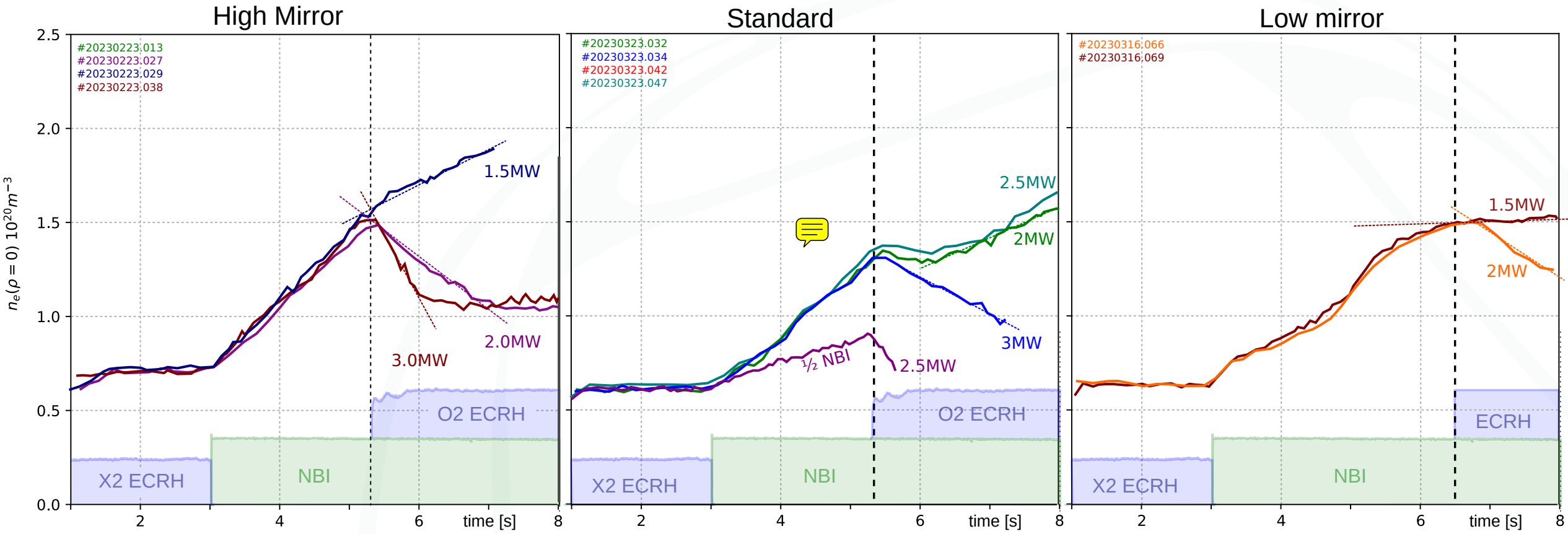

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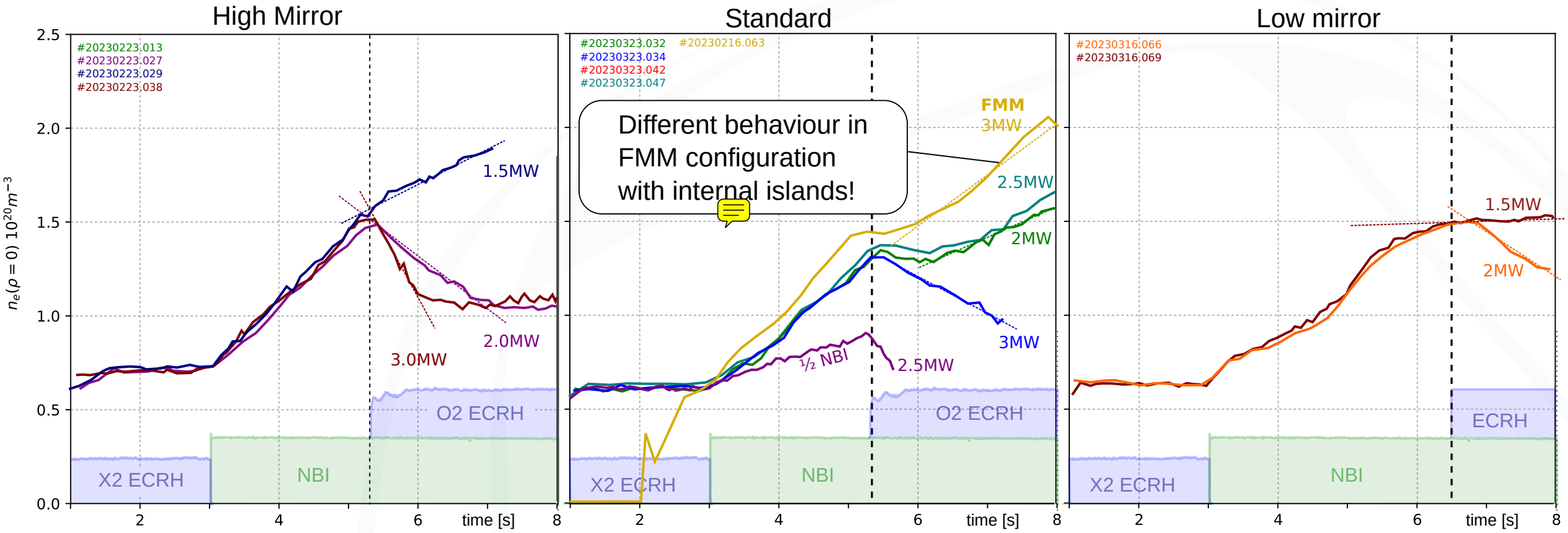
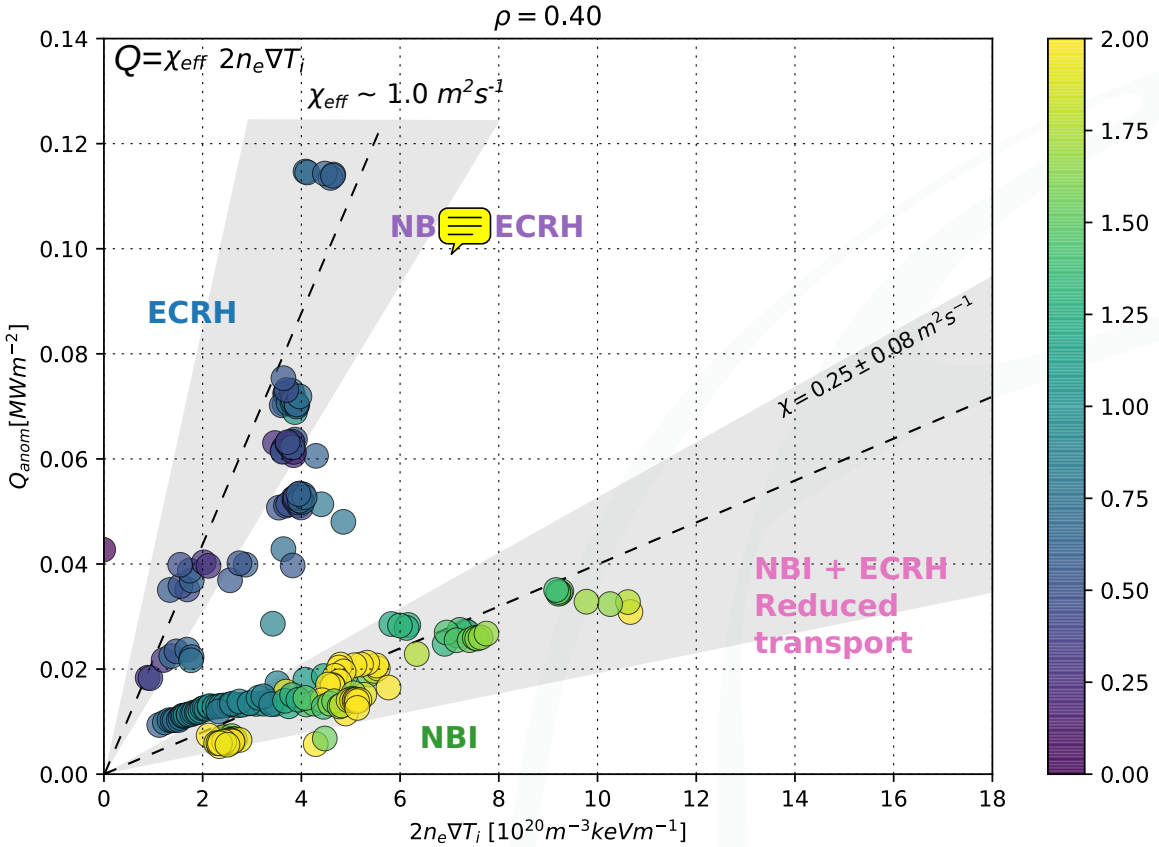


Balancing ECRH power

2023 experiments pushed to higher ECRH power to take advantage of reduced heat diffusivity
- χ_{eff} ~ 0.25 m^2s^{-1} maintained despite x2 higher Q_{anom}. (as high as some turbulent ECRH-only shots)



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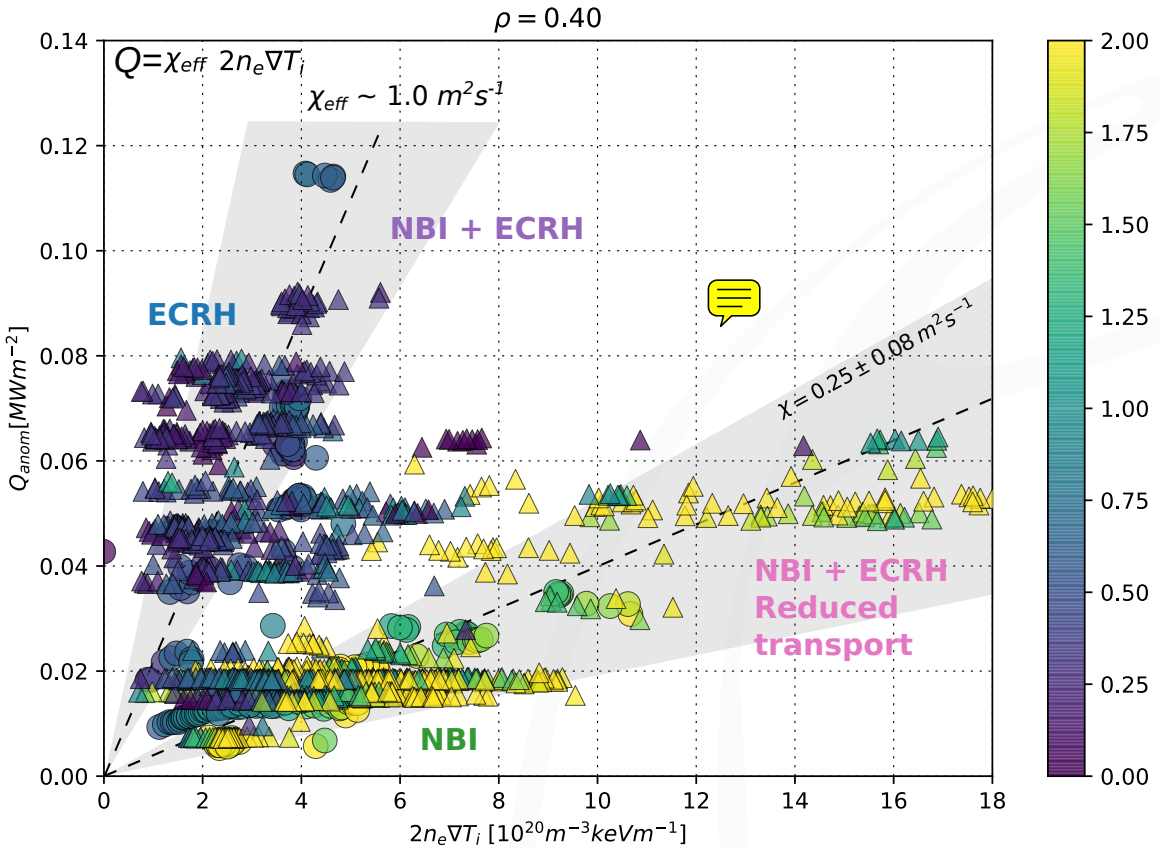

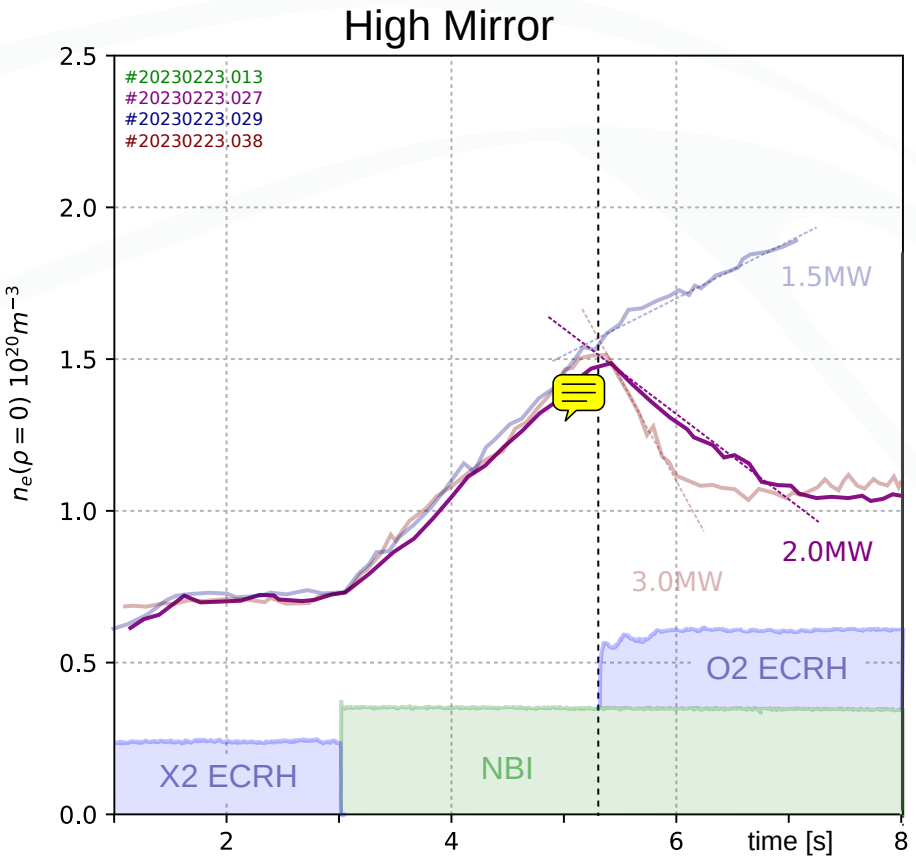

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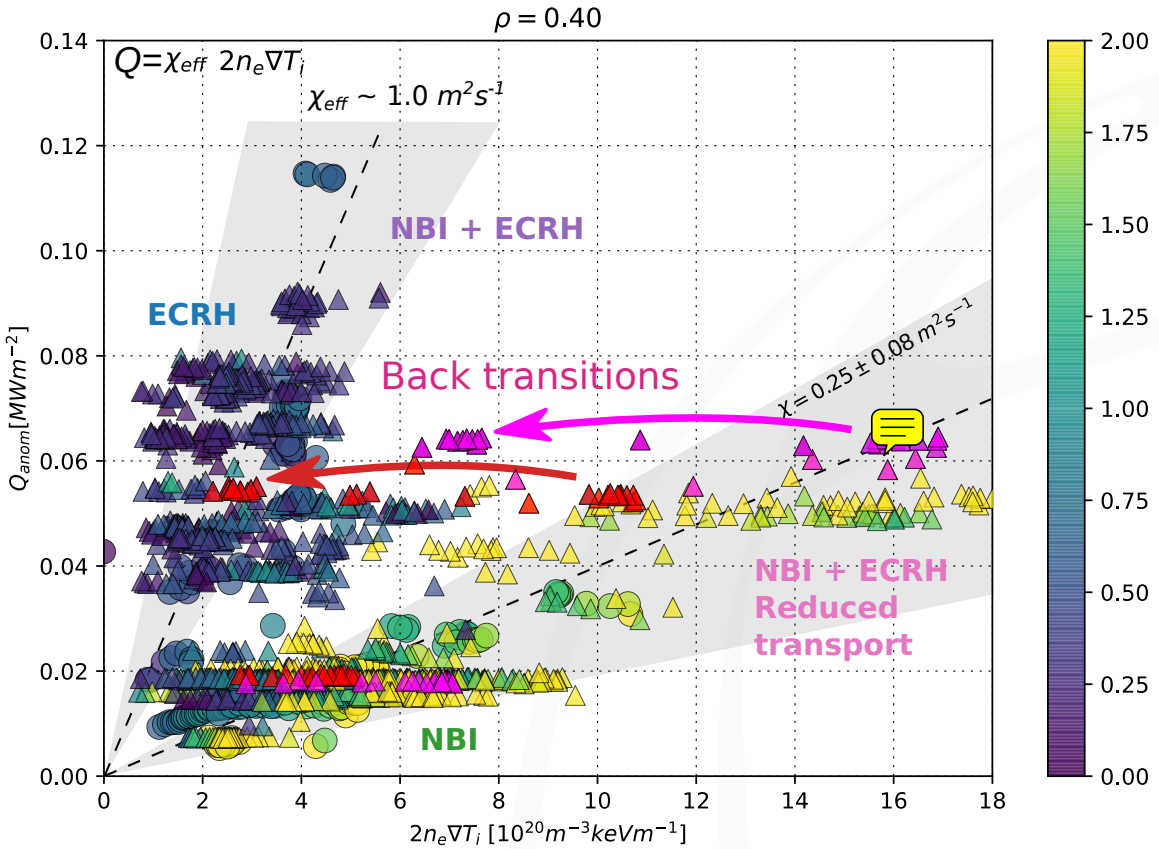
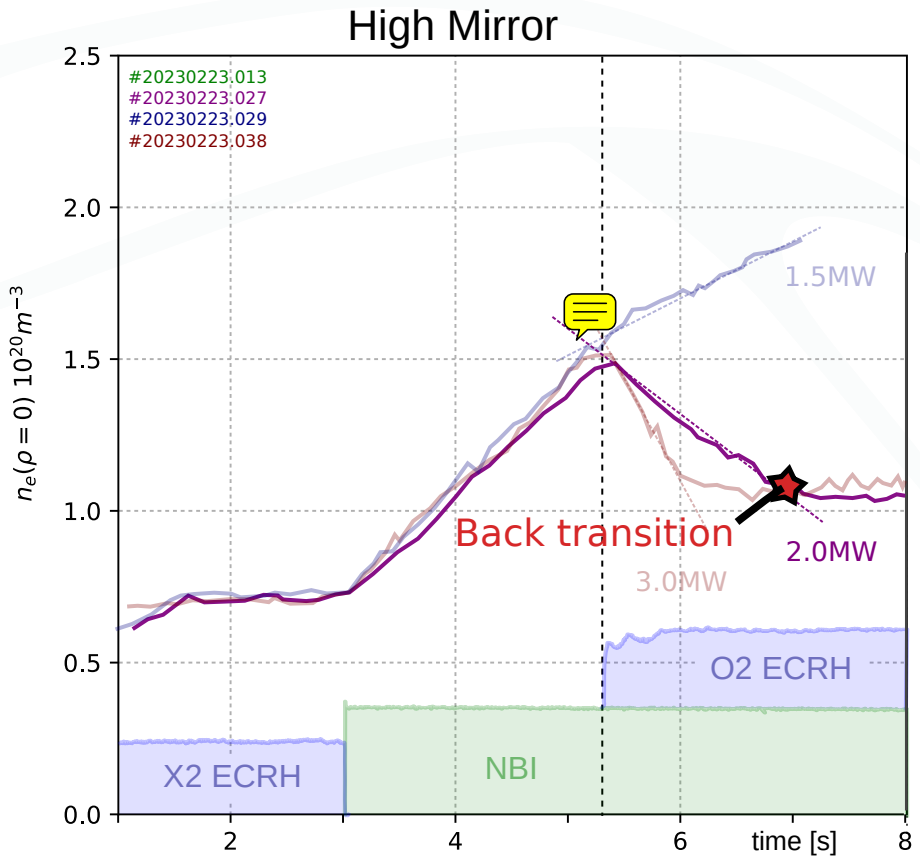
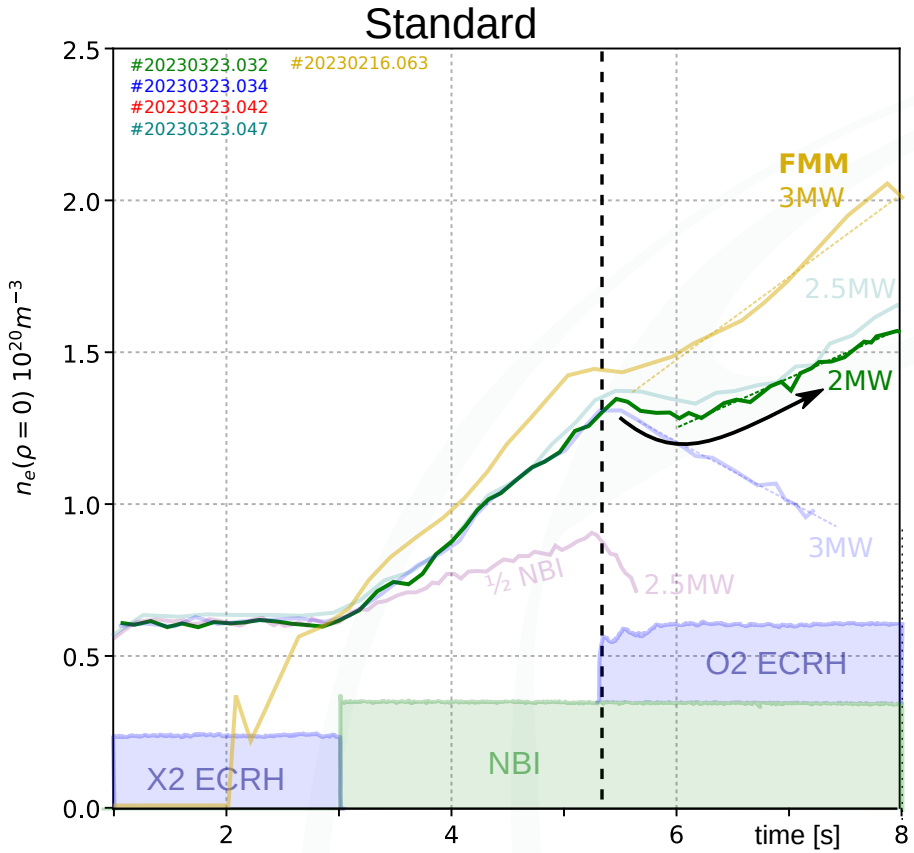
- Spontaneous back-transition to high transport observed as ECRH reduces density gradient.





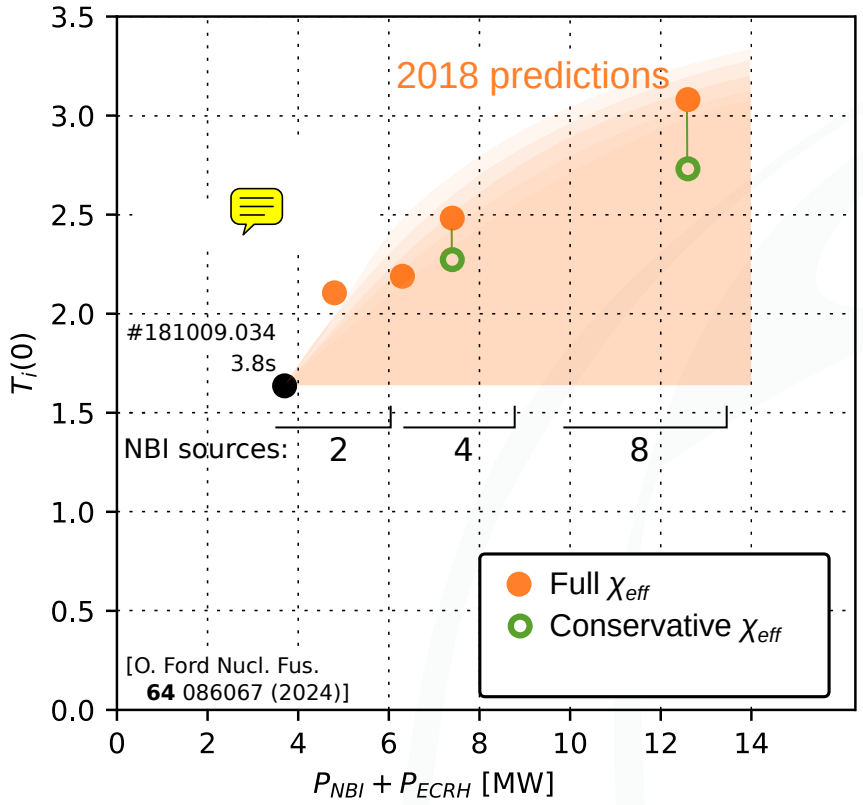
ECRH control

Challenge: Needs dynamic active control of ECRH level:
- Too much --> Loss of density gradient --> back-transition
- Too little --> Too high density, low P/n, impurity accumulation --> radiation collapse.



Achieved performance

- Predictions made from 2018 data using transport simulation (NTSS)



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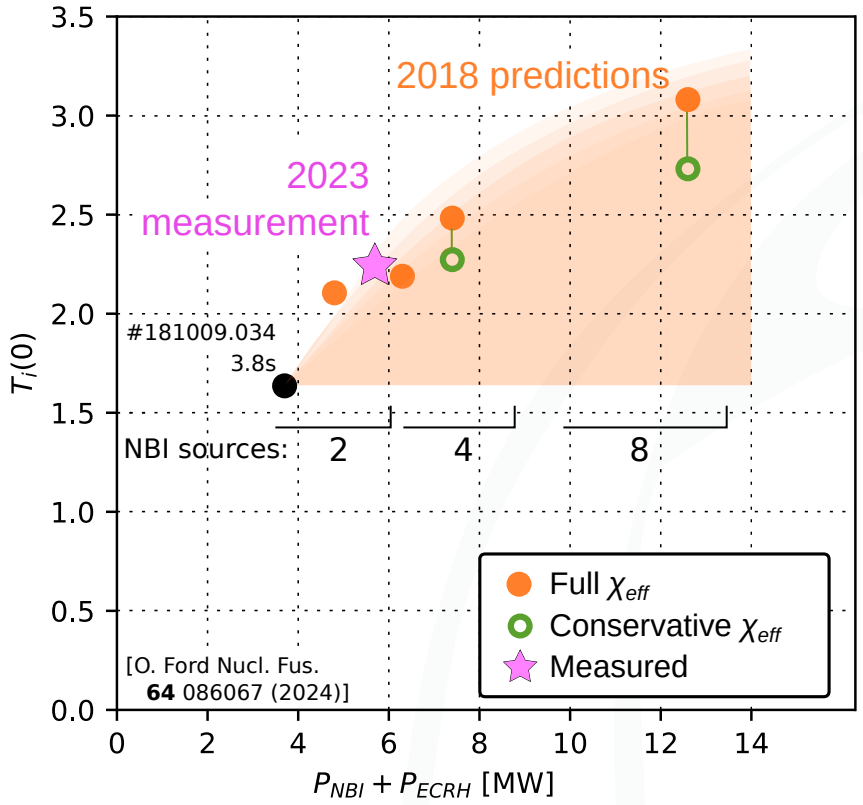

Achieved performance

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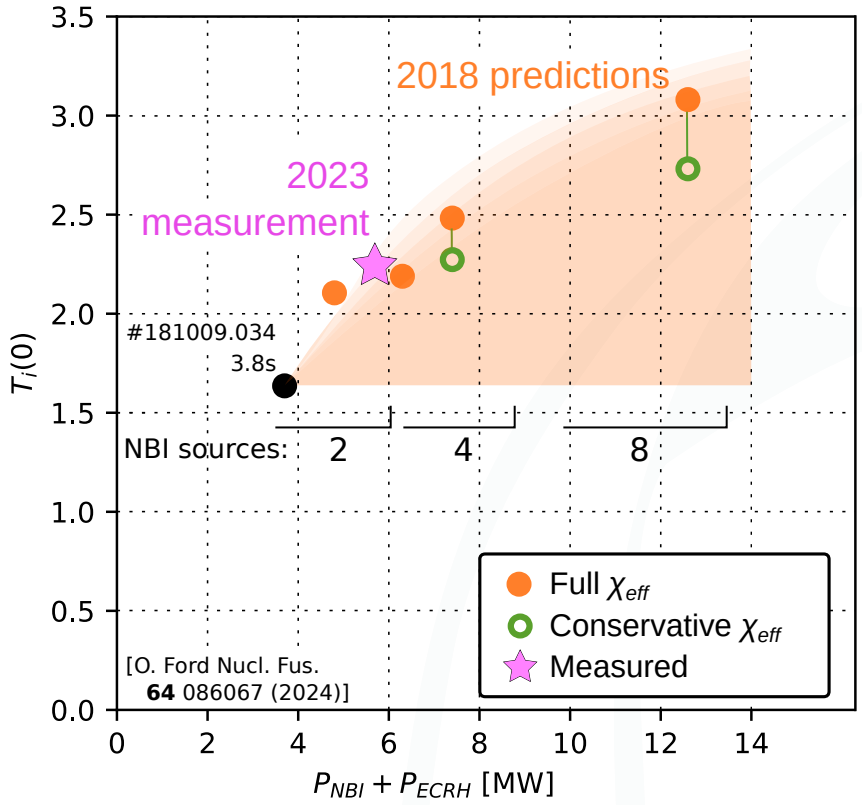
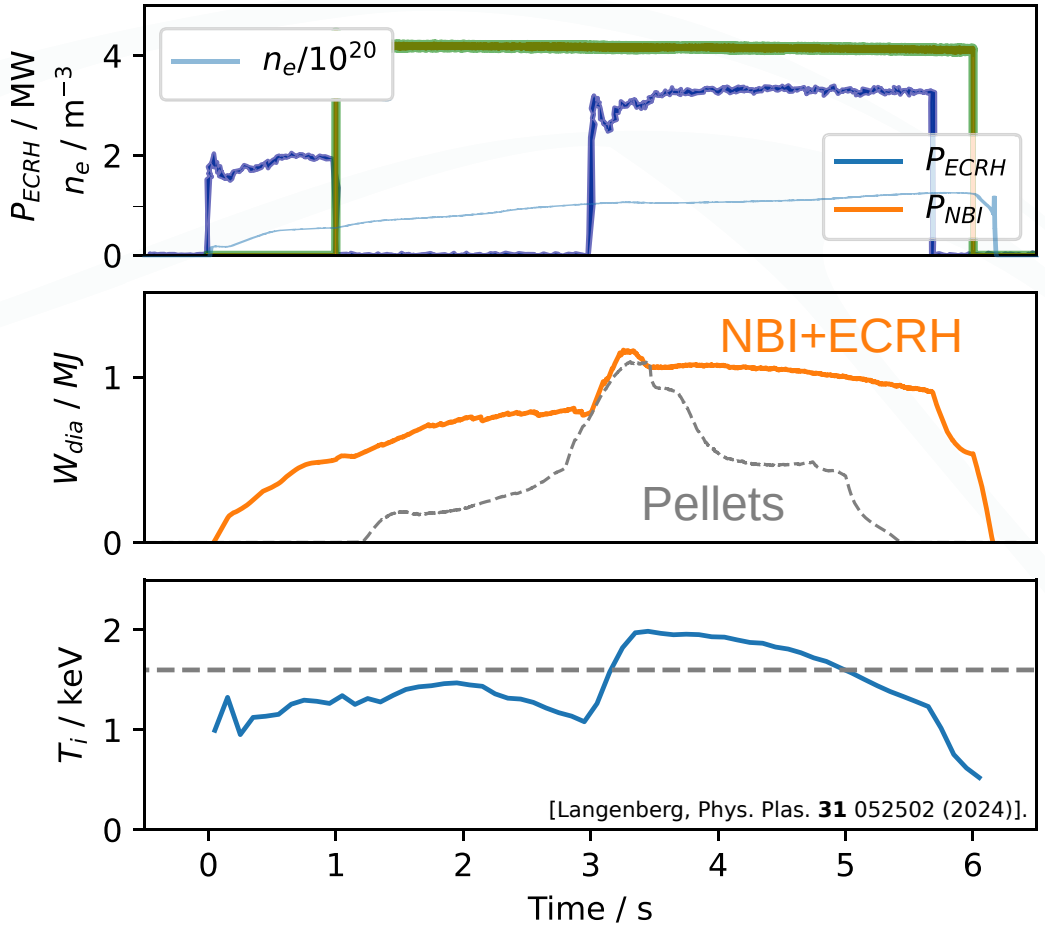
- Highest ECRH power in FMM configuration still does flush out density --> Higher n_e --> high W_{dia}
  --> Matches record stored energy (W_{dia}) for W7-X, but for $t >> \tau_E$

  [Langenberg, Phys. Plas. **31** 052502 (2024)].





Summary

- ECRH+Gas fuelling: Turbulence dominated heat transport, main ion and impurity transport.

- Various scenarious with peaked density profile --> reduced heat transport.

- Dominant NBI plasmas show $\chi_{eff} \sim 0.25\ m^2 s^{-1}$, 4 times lower than dominant ECRH.

- D_{anom} of main ions drops spontaneously at $a/L_{n_e} \sim 1.3$ during pure NBI, leading to accelerated peaking. Impurity transport is fully neoclassical from this point on.

- Reduced heat diffusivity can be exploided by reintroducing a low ECRH power at high a/L_n.

- Reintroduction scenario reproduced and refined in 2023 expeiments.
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  - Density pump-out by too-high ECRH leads to back-transition to high χ_{eff}.
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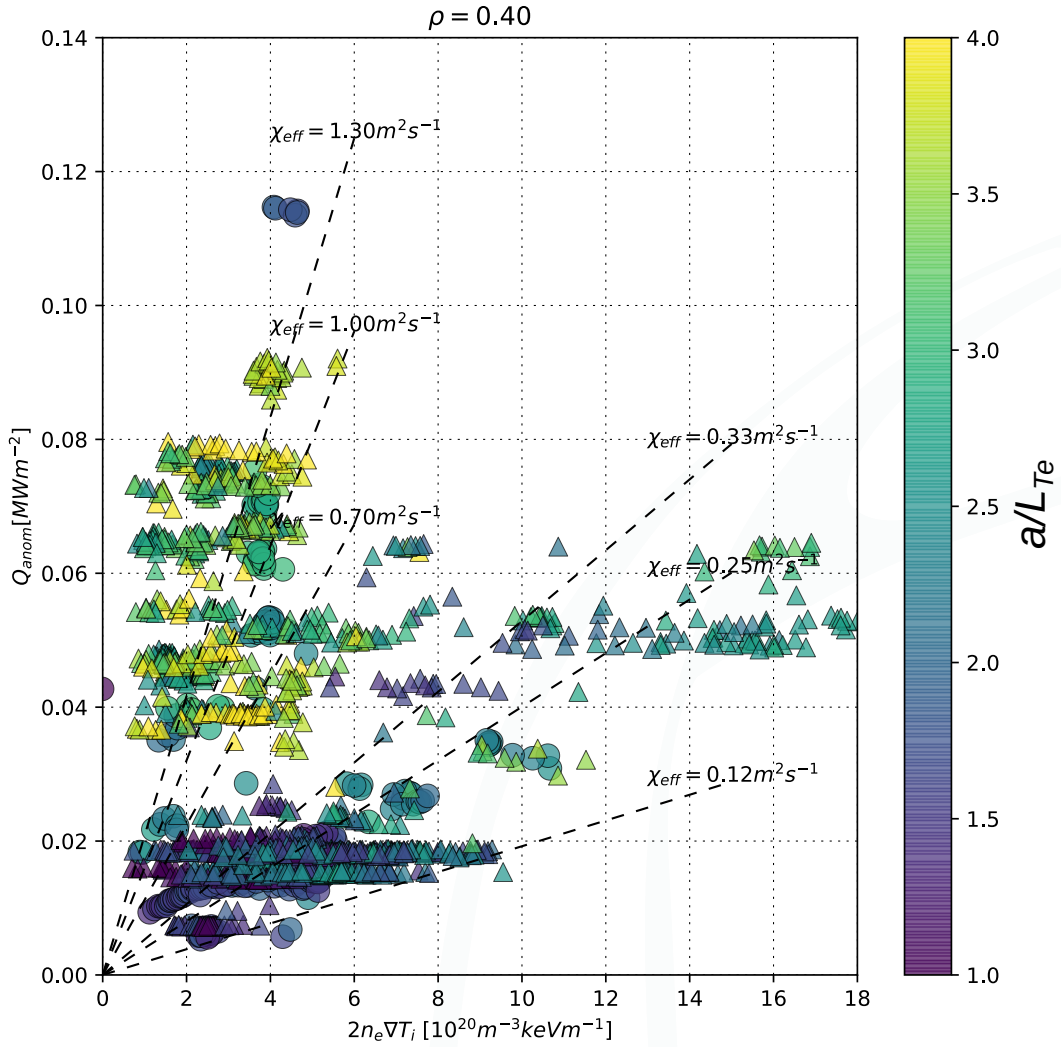
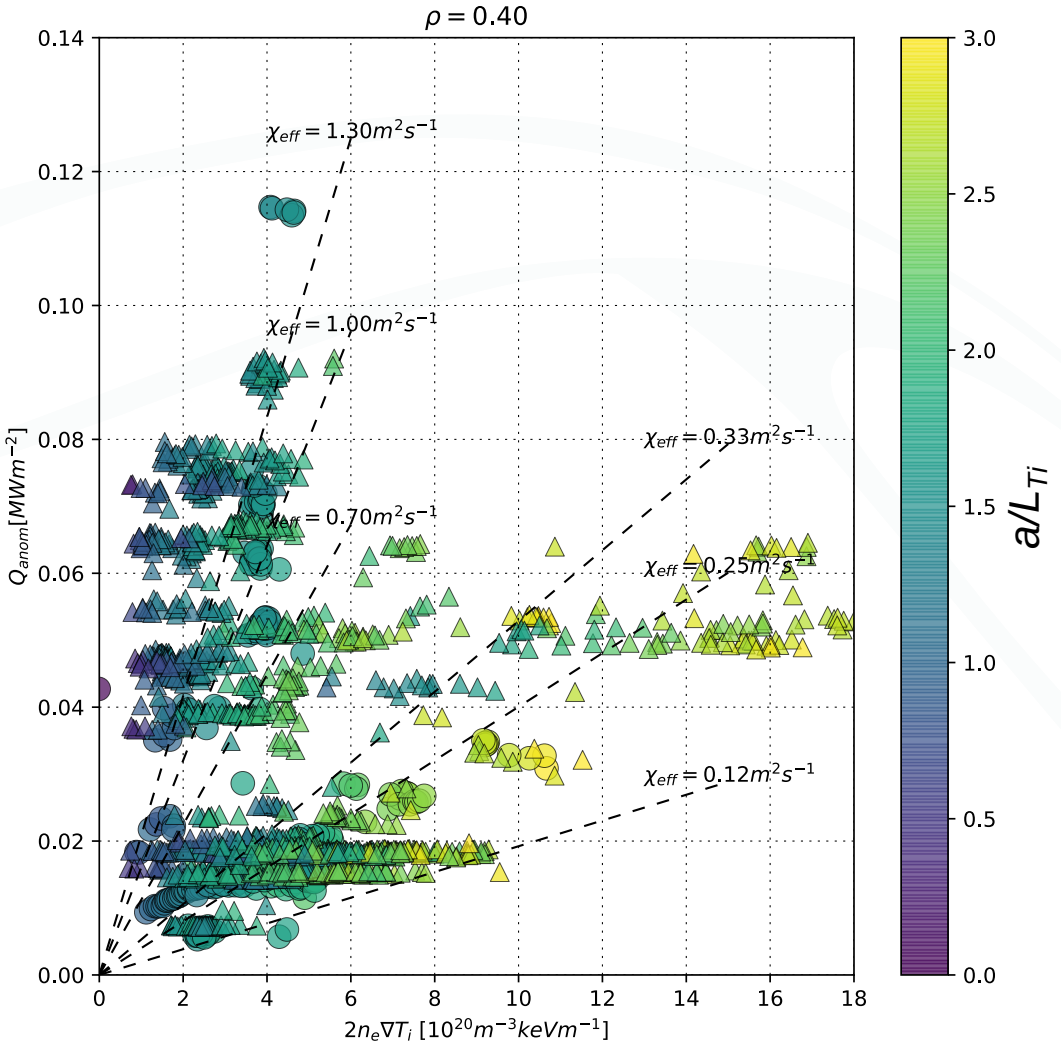
Diffusivity vs temperature gradients

No obvious dependence of χ_{eff} on a/L_{Te} - at least not clear as a/L_n. (a/L_{T_i} is the dependant variable)

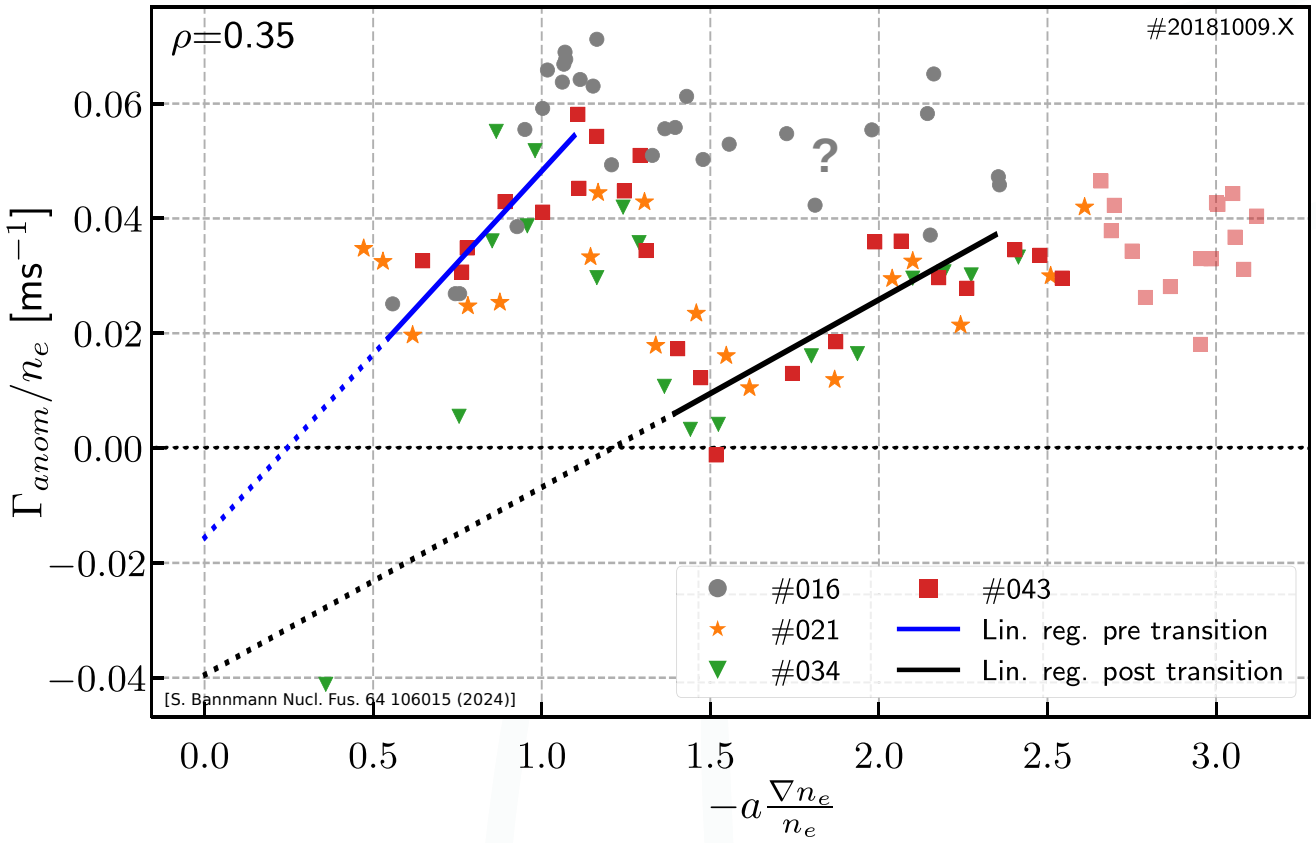




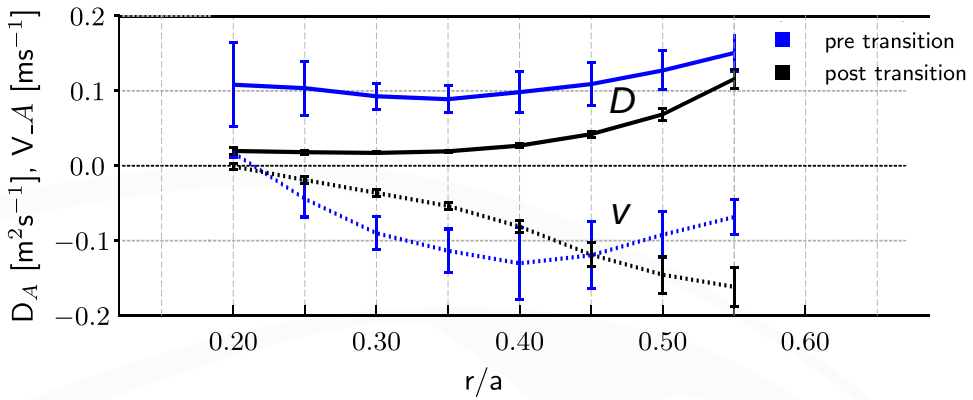
Pure NBI - Particle transport

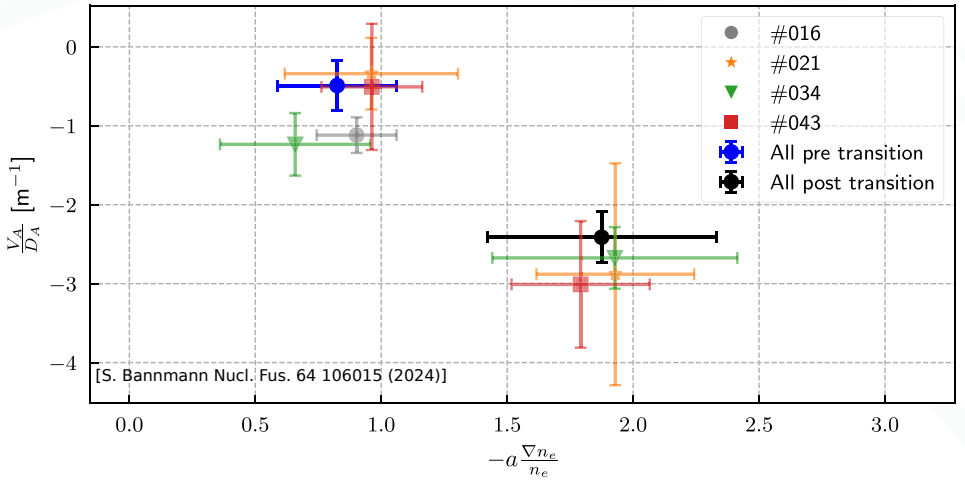
∇n_e is changing. What is just an 'expected' reponse to this?
--> Decompose into diffusive D and convective v.
- Indicates two phases of ~consistent v, D, with significant drop of D at a/L_n ~ 1.3.

$$\frac{\Gamma_{\text{anom}}}{n} = -D_A \frac{\nabla n}{n} + V_A$$



[S. Bannmann Nucl. Fus. 64 106015 (2024)]

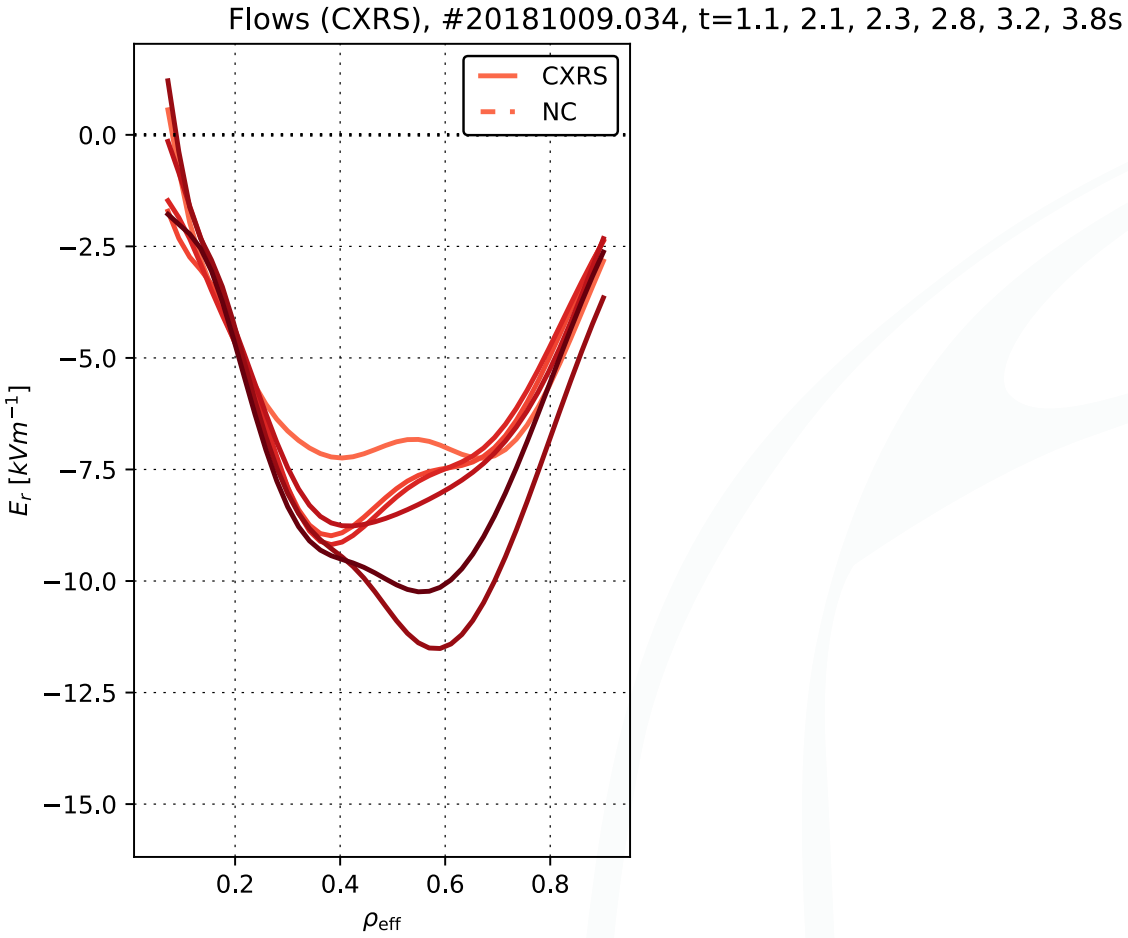




- Threshold not yet reproduced in modelling.
(Range not covered by original STELLA study [H. Thienpondt, Phys. Rev. Res. 5, L022053 (2023)])

port Pure NBI - Radial Electric Field

- E_r or Er can affect anomalous transport and often changes strongly in W7-X. e.g. Ion vs Electorn root.
- NBI discharges all ion root with no significant E_r changes at onset time (measured or NC)



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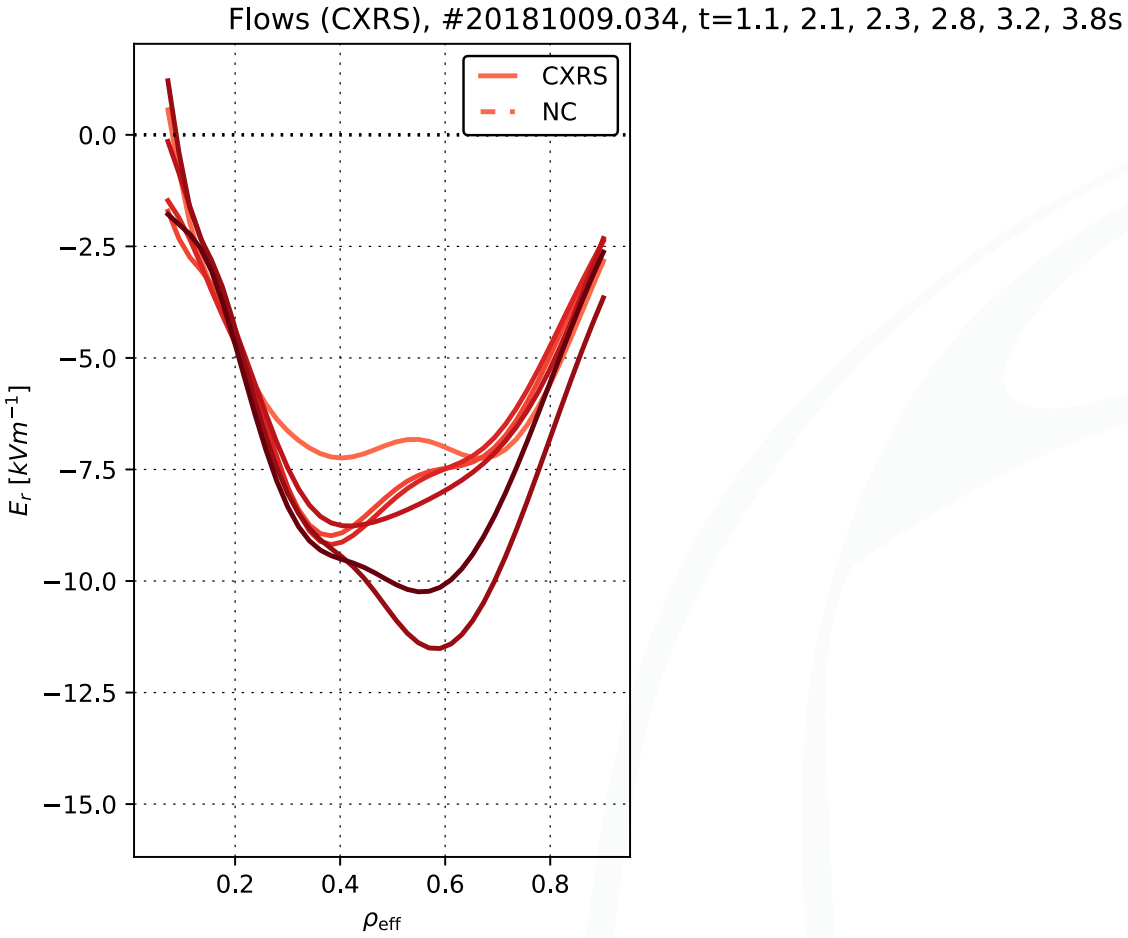

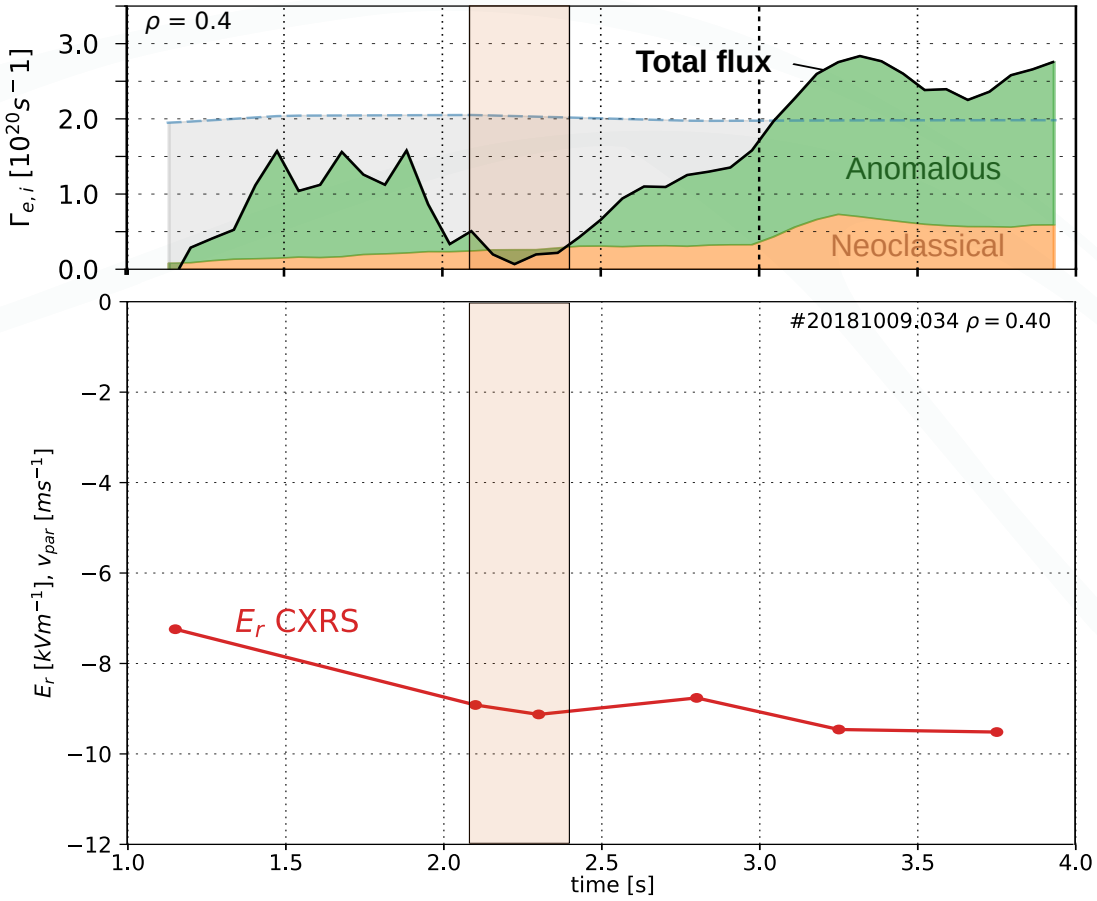

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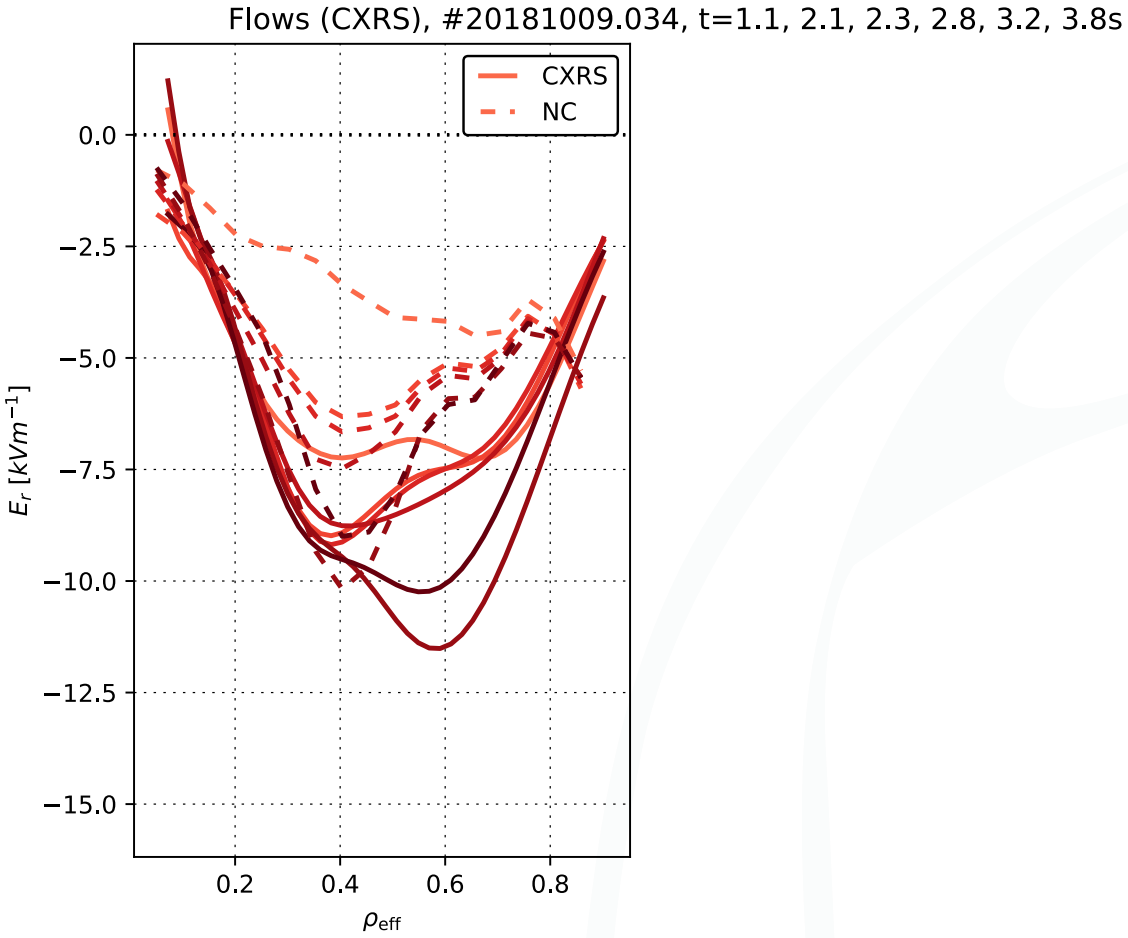

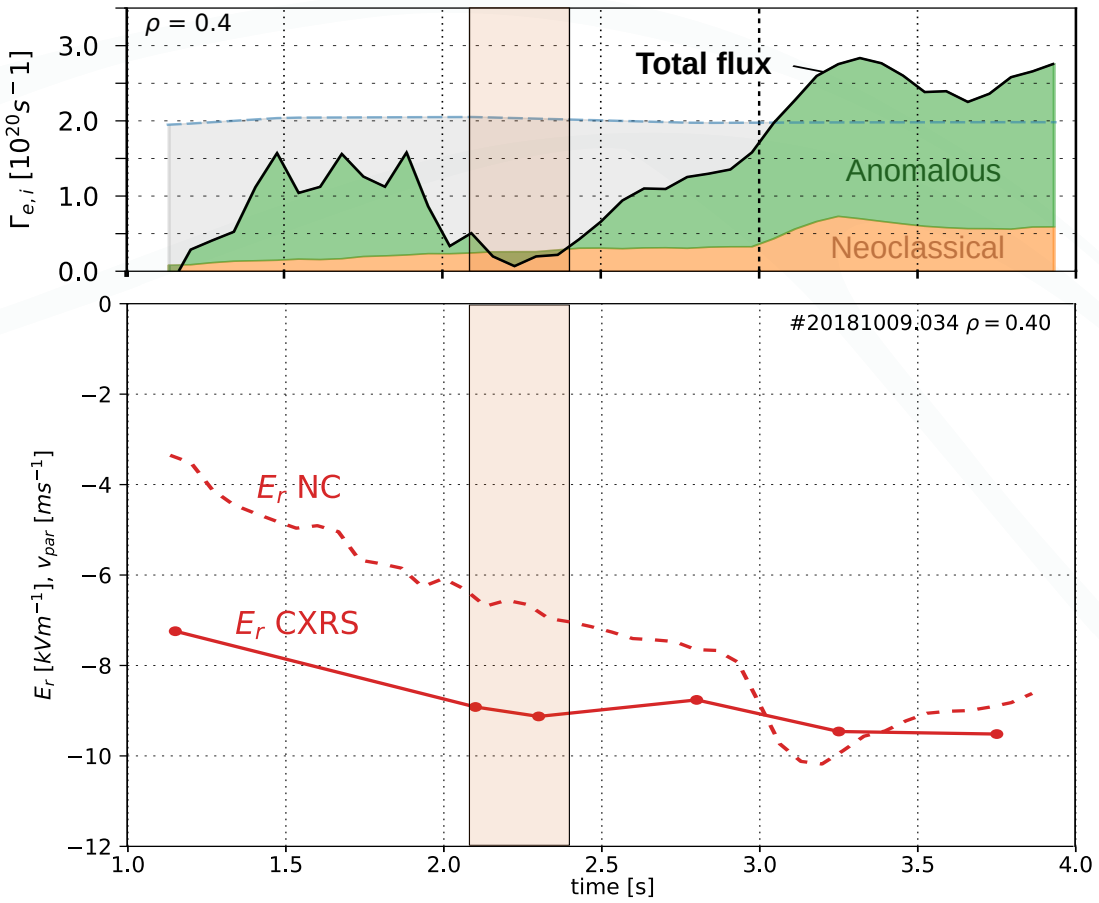

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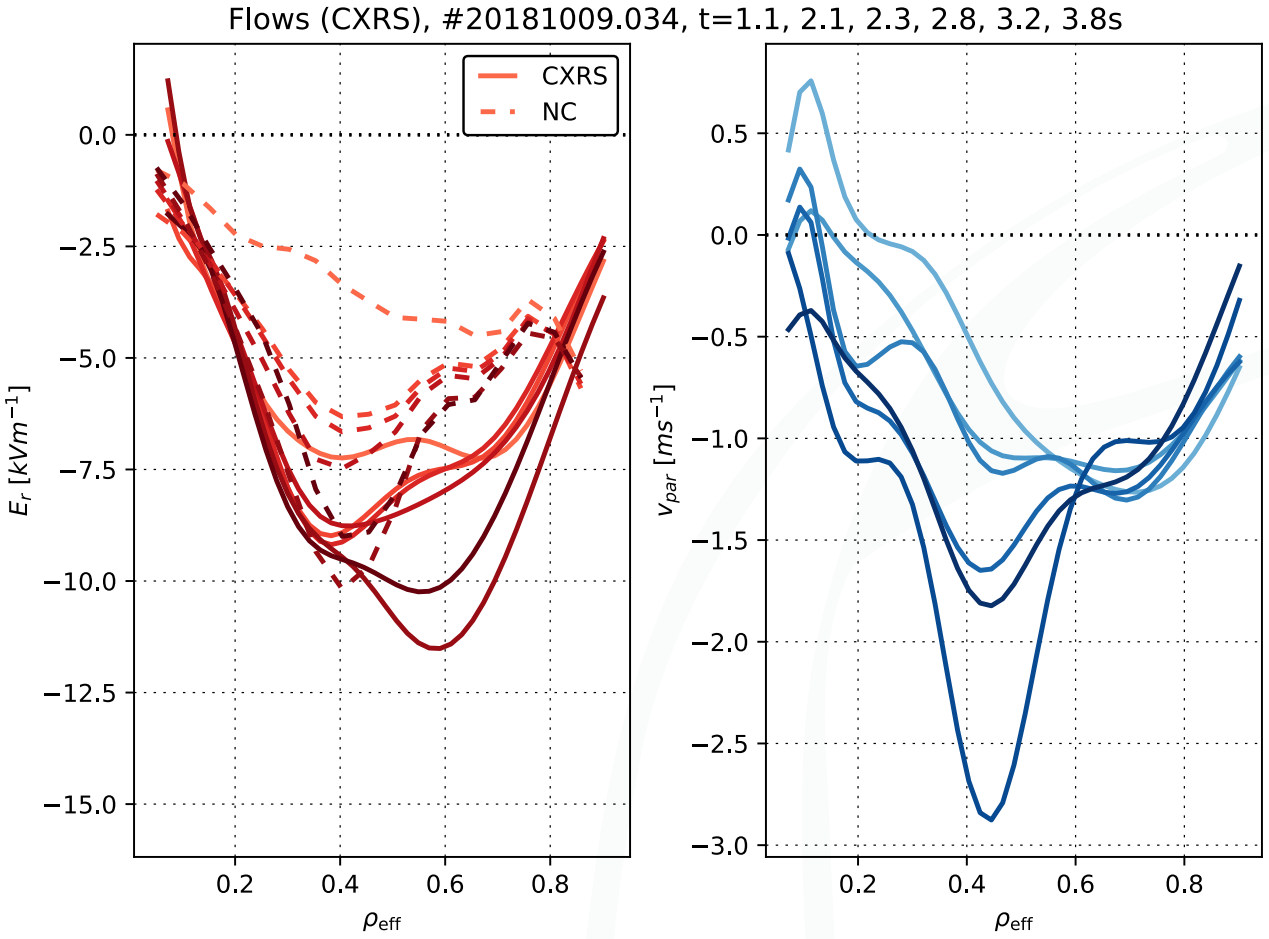
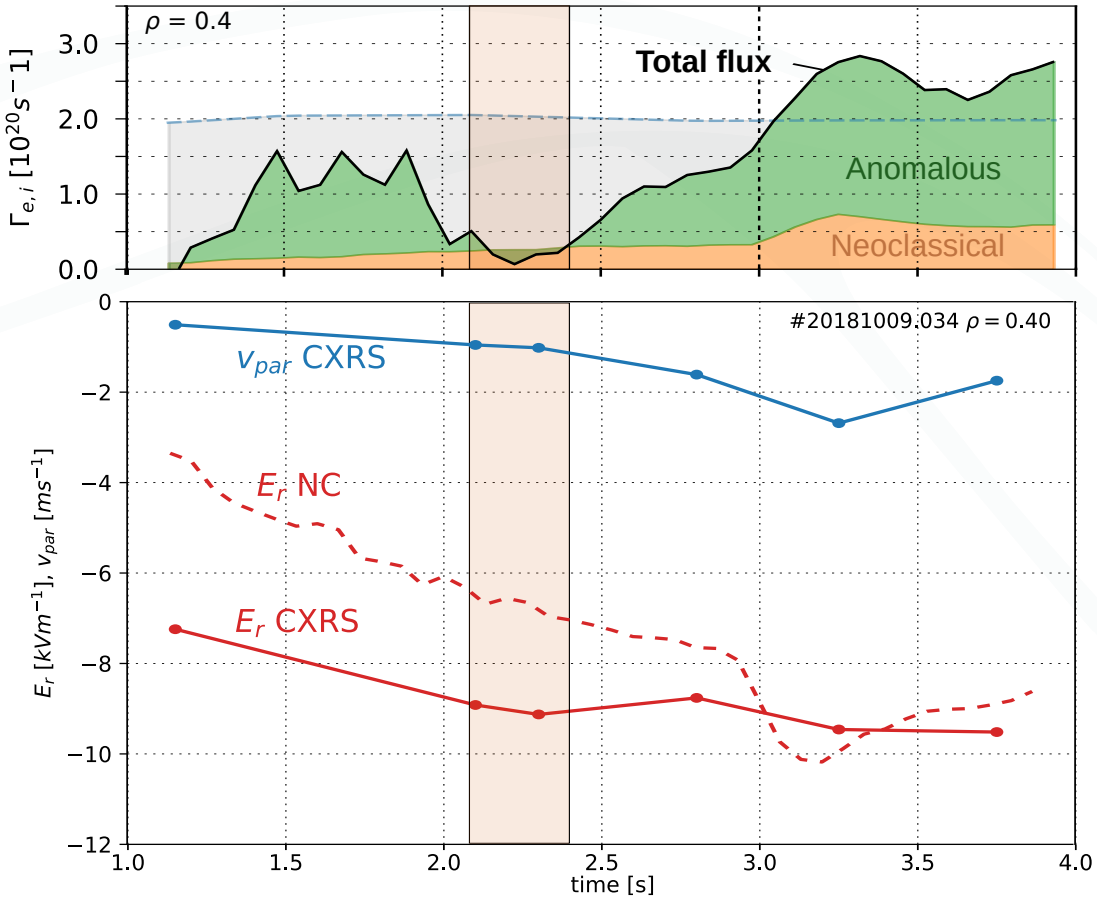


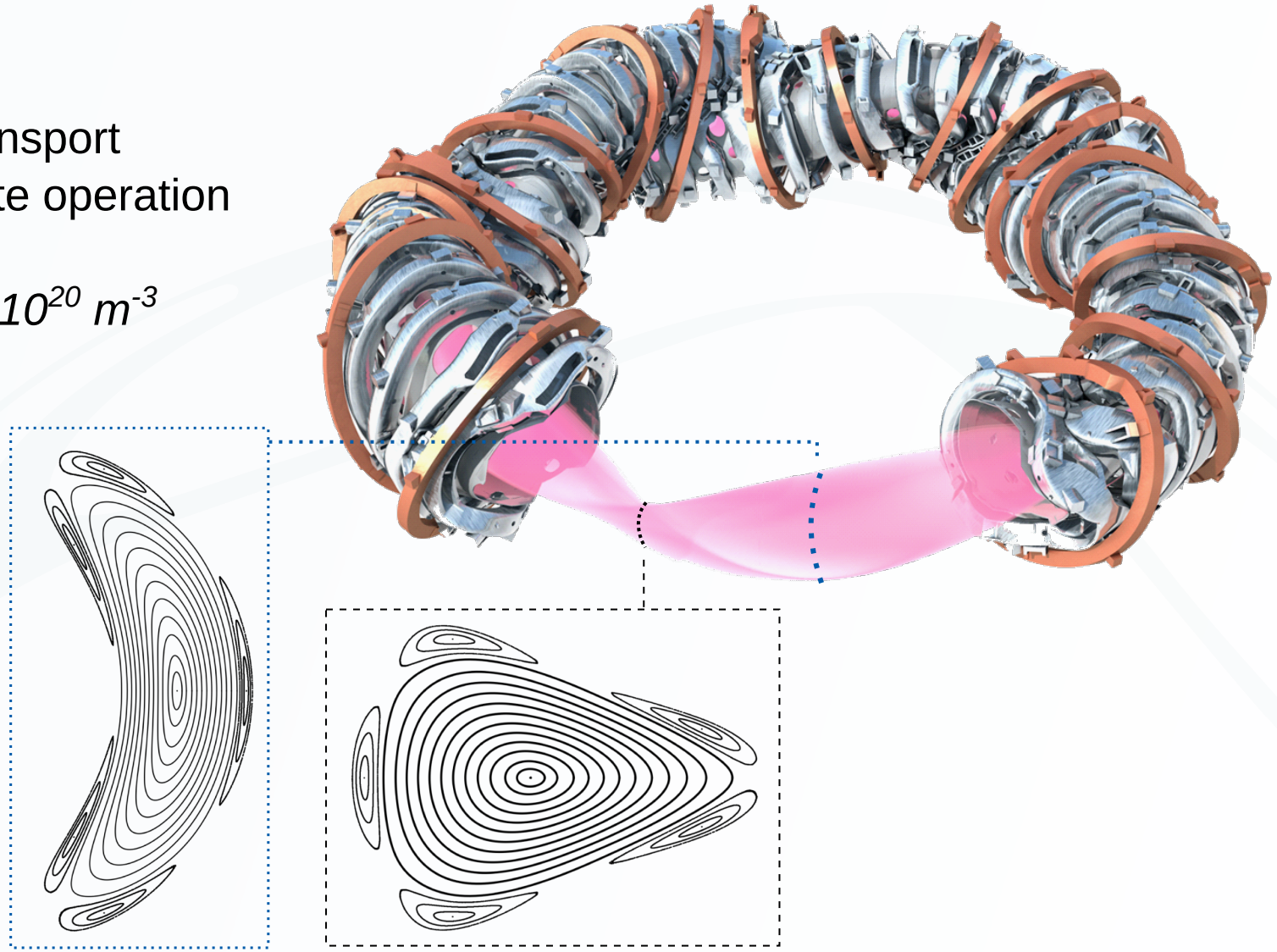


The Wendelstein 7-X Stellarator

Wendelstein 7-X:
- 5 period helixcal axis stellarator
- Optimised to reduce neoclassical transport
- Designed to demonstrate steady-state operation with continuous ECRH heating.
- Operation at high density: $n_e \sim 1.8 \times 10^{20}\ m^{-3}$

R_0	5.5 m
a	0.5 m
V	30 m^3
B_0	⩽ 3 T
ι_a $(\sim q_{95}^{-1})$	5/6 ... 5/4

	2024	2026+
pulse	200s	30 min
ECRH	7.5MW	10 MW
NBI	2.6MW	5.2MW
ICRH	-	1.5MW



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