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

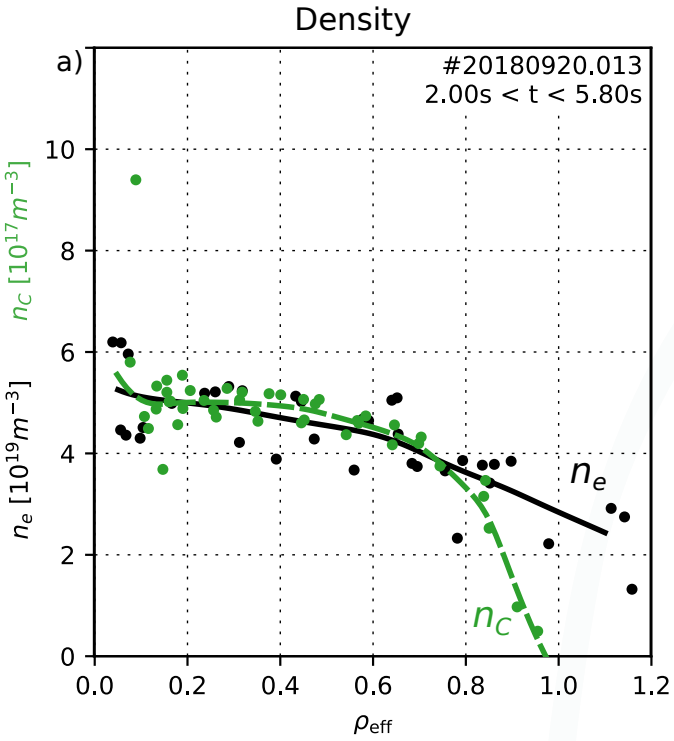
*24th International Stellarator Heliotron Workshop, Hiroshima, Japan*

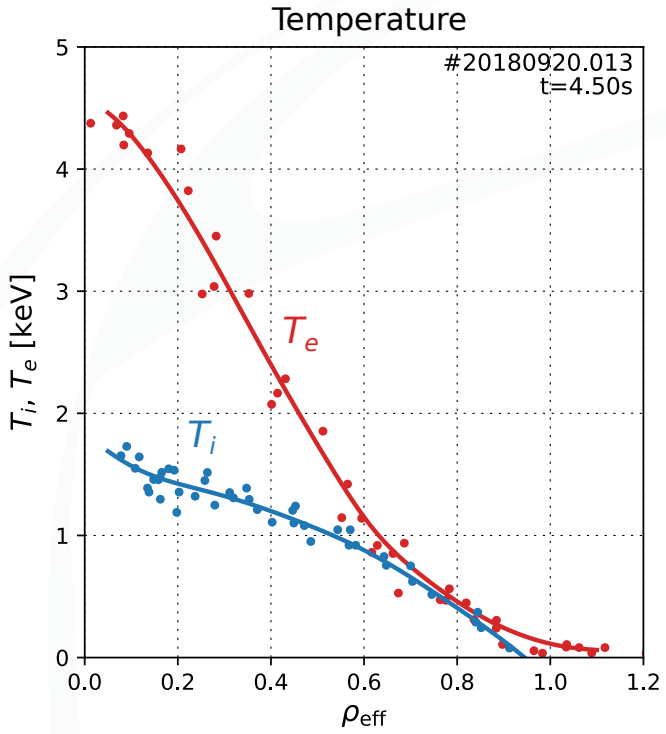


# Gas-fuelled ECRH discharges

In W7-X, typical scenario for long pulse, divertor experiments, parameter scans etc [as shown in talk by D. Gradic].
- Gas/recycling fuelled.
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Result:
- Steady-state
- Flat $n_e$ profiles
- Low, flat impurity density profiles
- Core $T_i \leq 1.5$keV

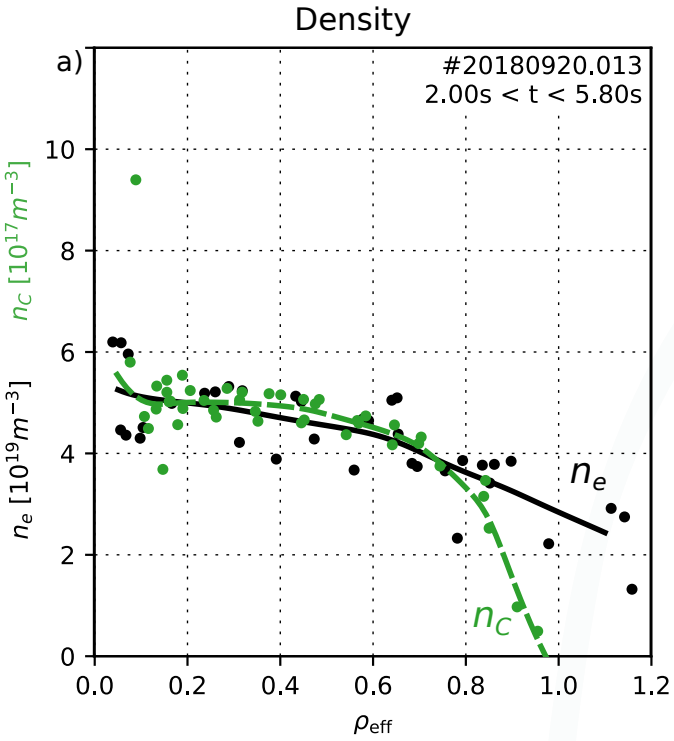


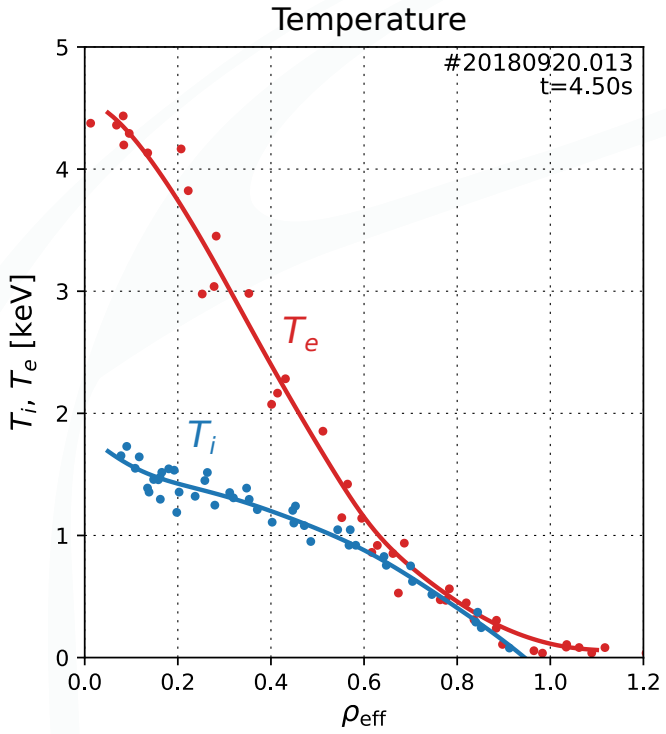



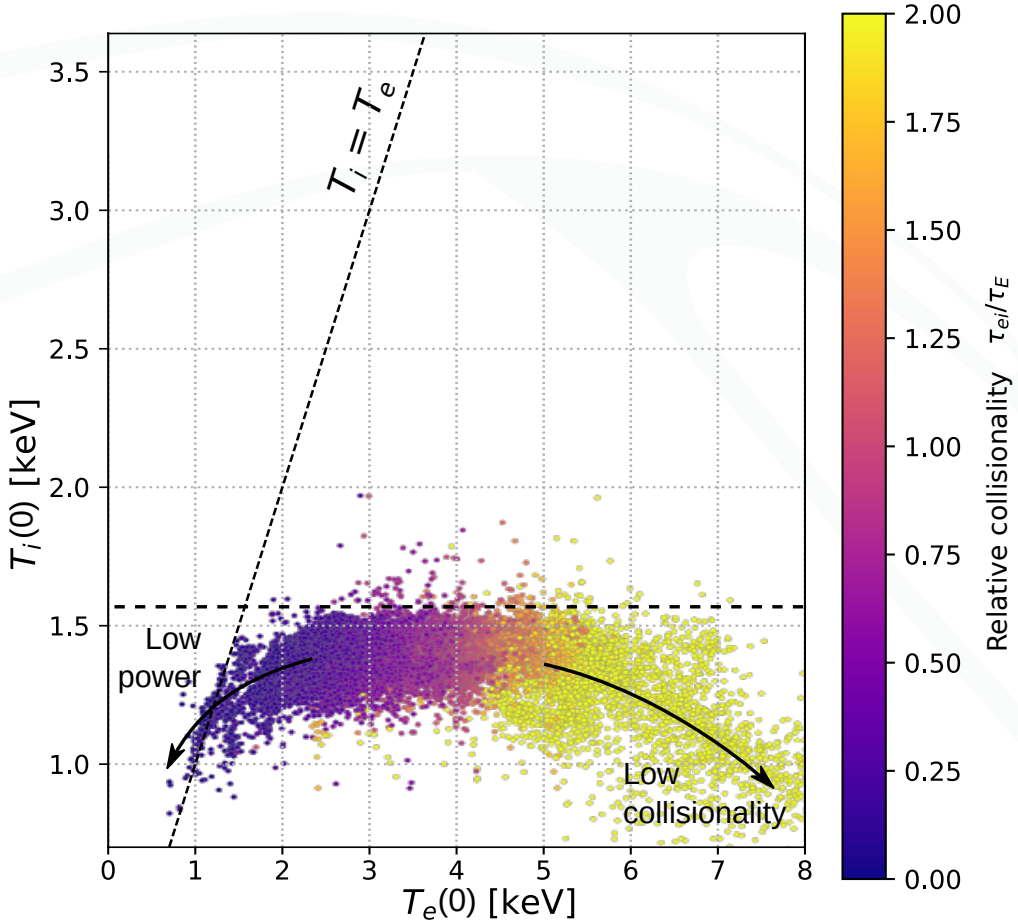
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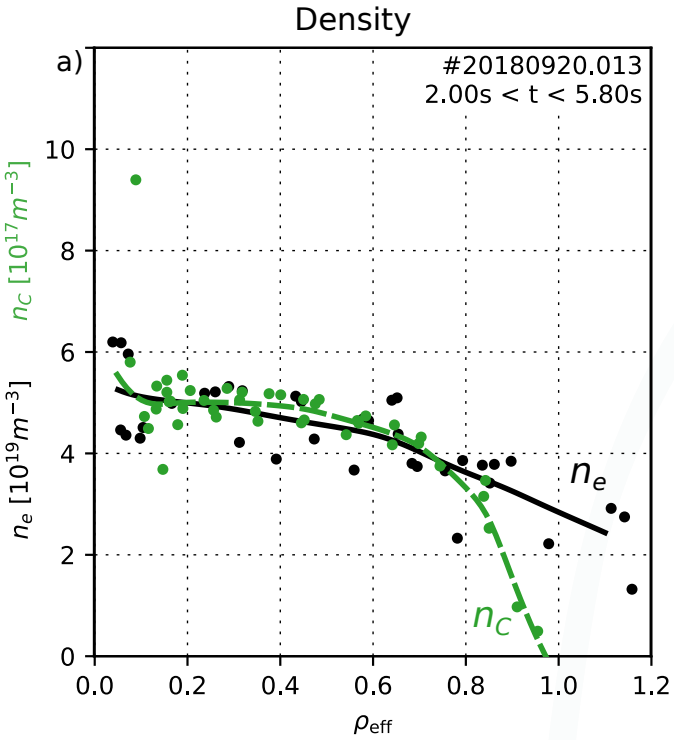



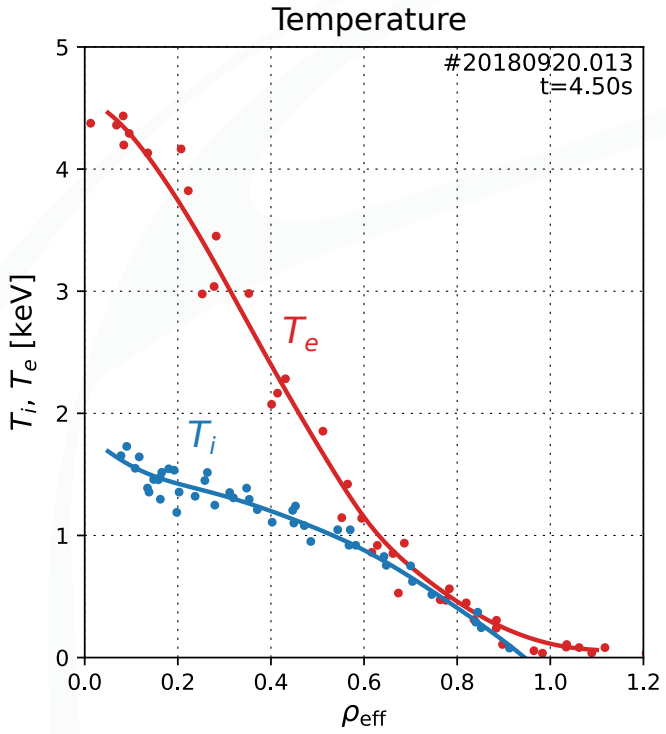



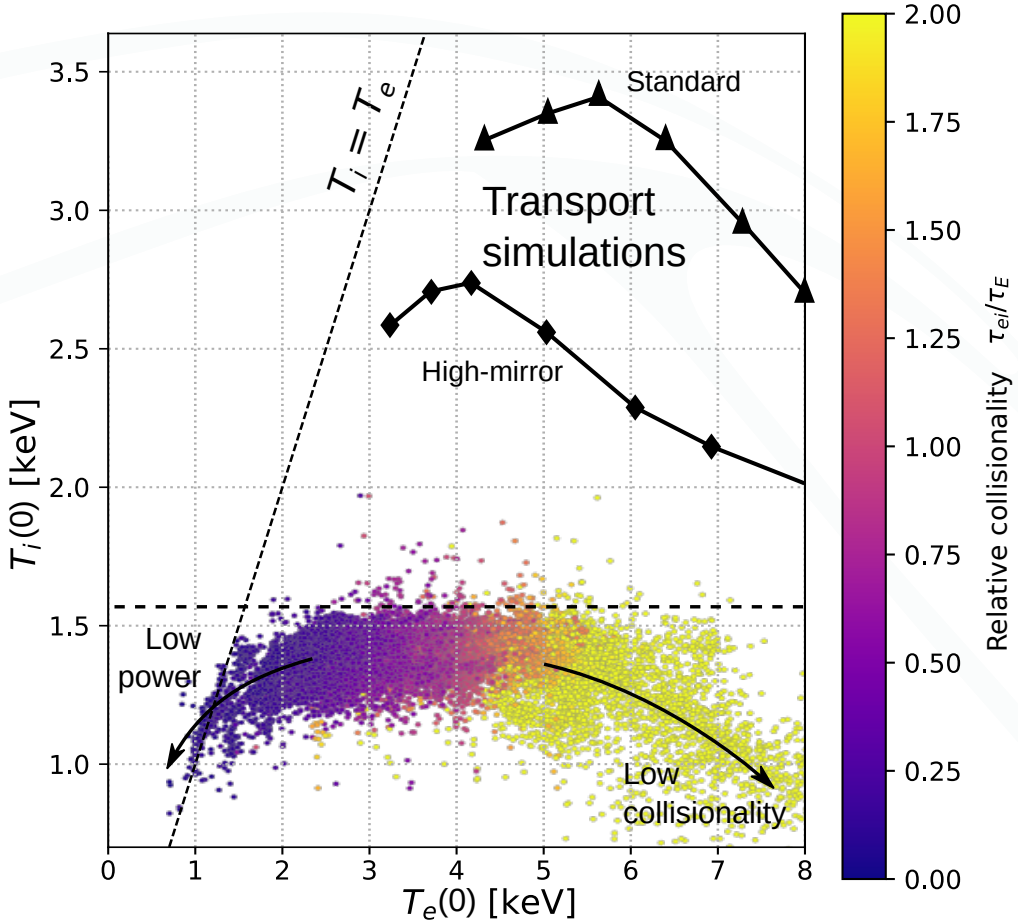
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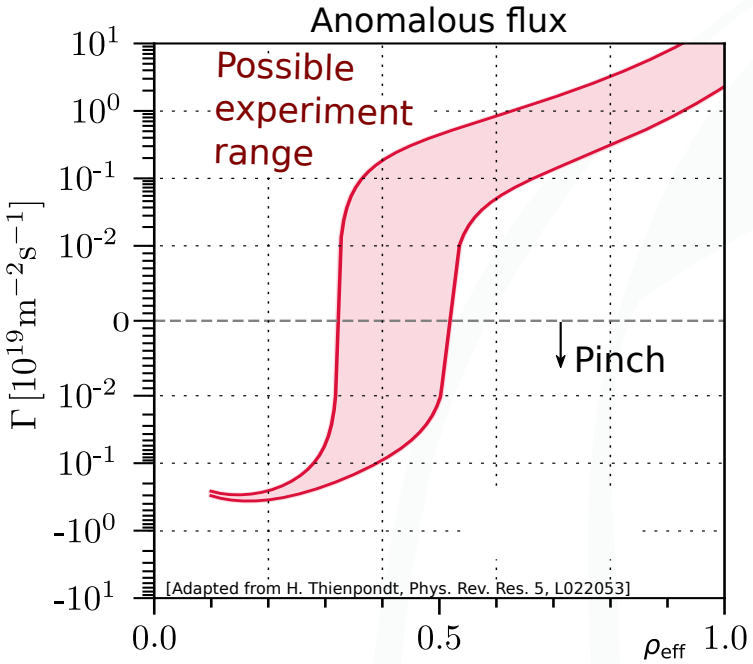



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Main ions:

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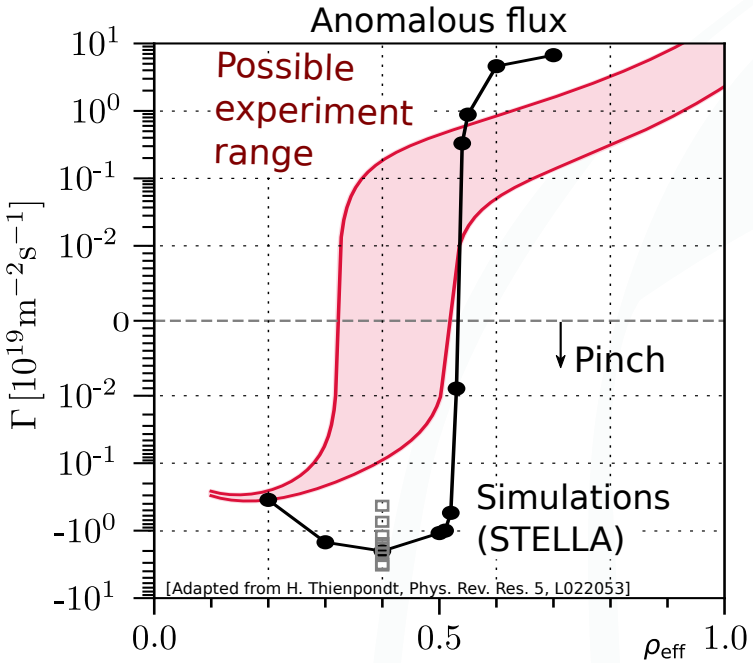
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[Thienpondt, Phys. Rev. Res. **5**, L022053 (2023)]

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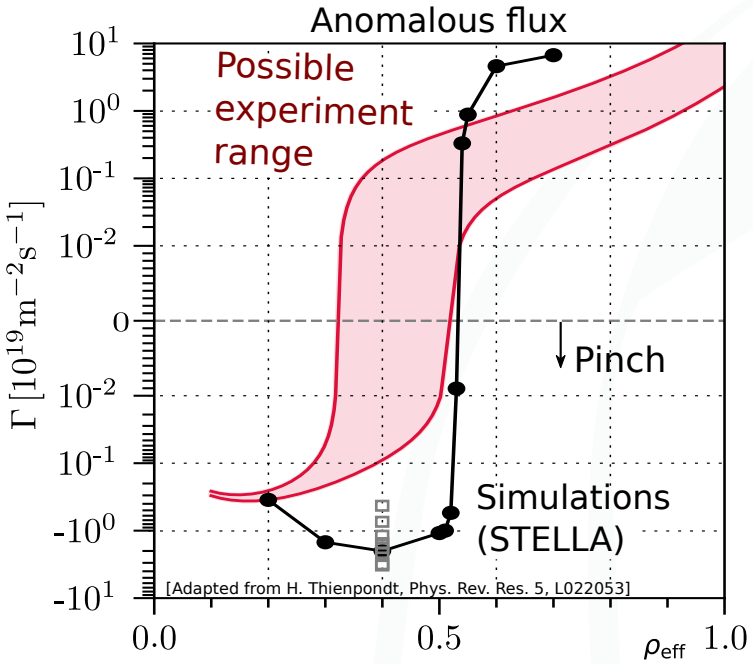
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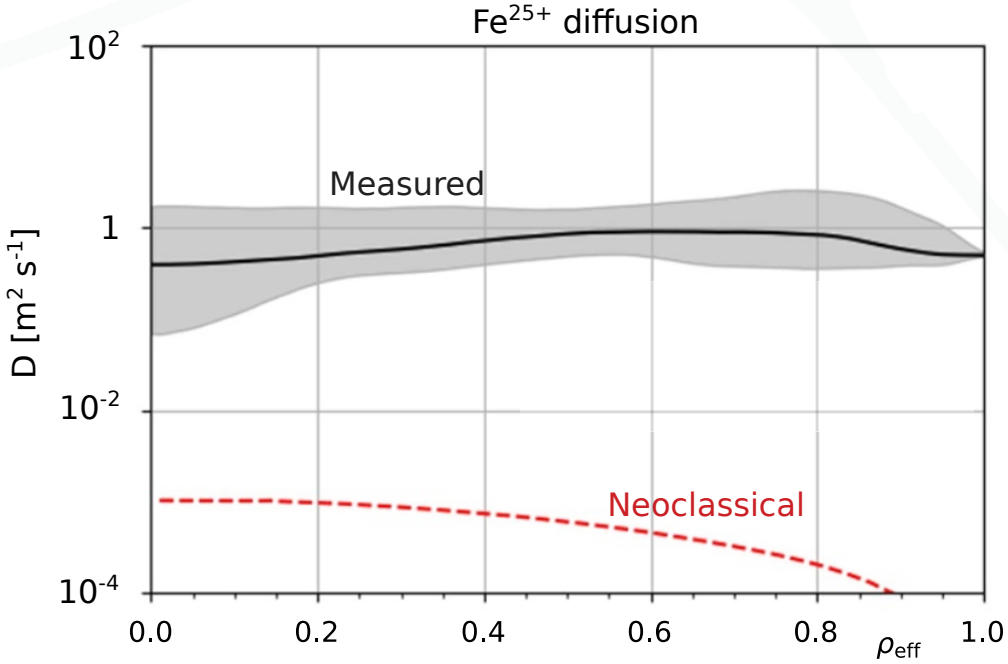
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Impurities:

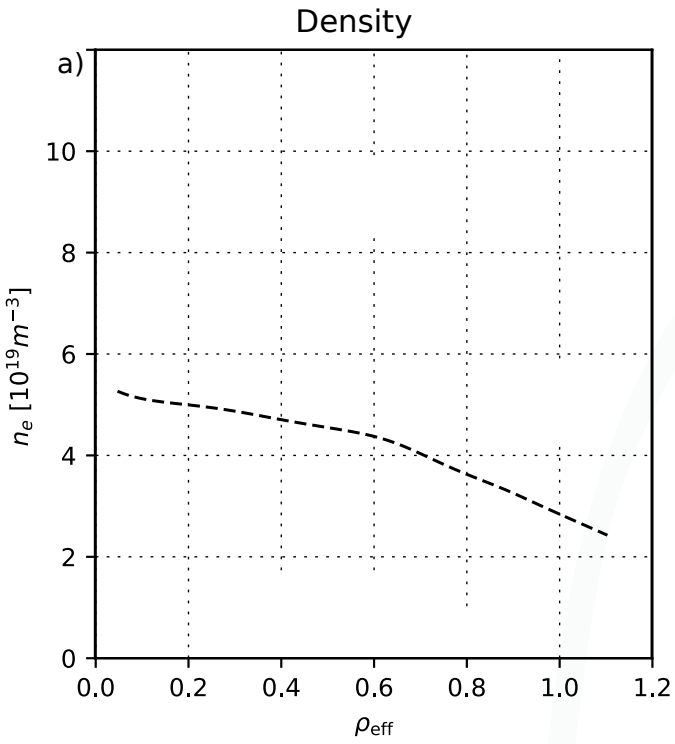
- Neoclassics --> peaked, Experiment = flat
  Require strong anomalous diffusion to flatten the profile ($D > 0.1 m^2 s^{-1}$). [T. Romba PPCF **65** 075011 (2023)]
- Measured *v, D* in LBO injections show strong anomalous diffusion [Swee Nucl. Fus. **64** 086062 (2024), B. Geiger Nucl. Fus. **59** 046009 (2019)]
- Gyrokinetic predictions of $D \sim O(1)\ m^2 s^{-1}$ from TEM+ITG turbulence. [García-Regaña JPP'21]

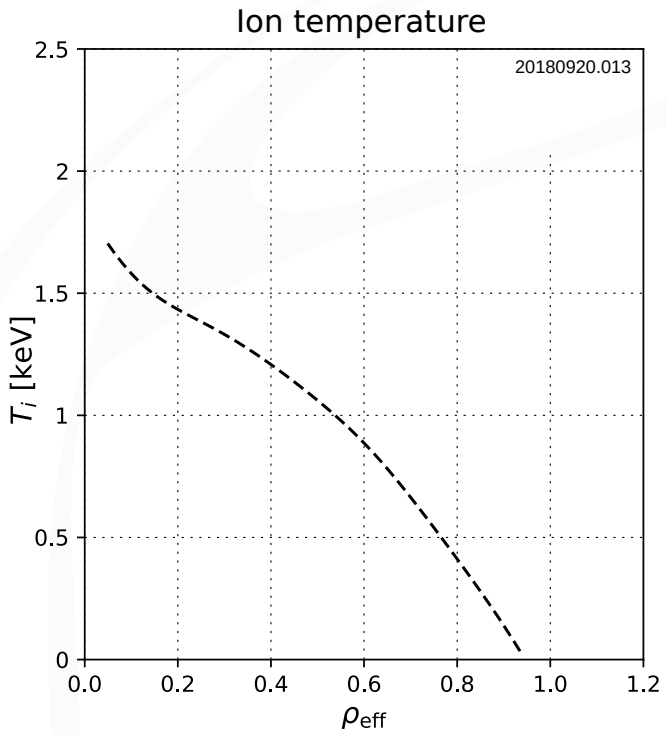


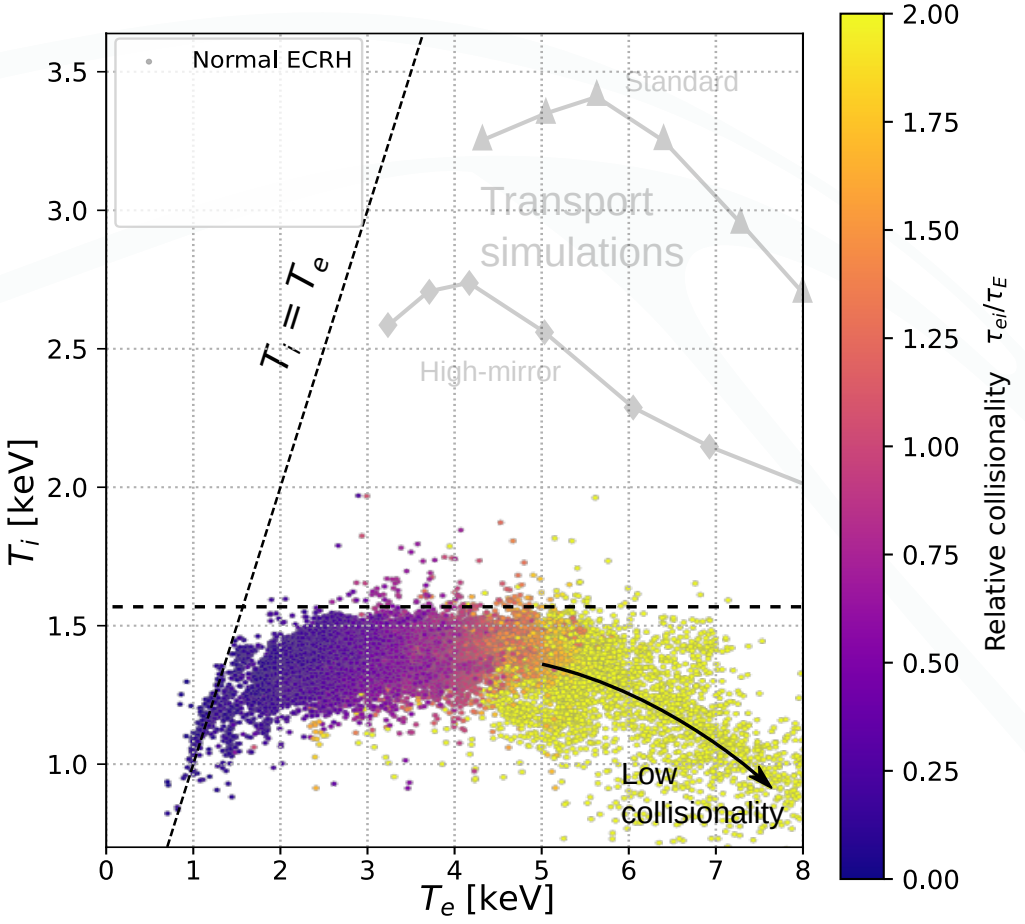
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ECRH + gas --> Turbulence dominated heat and main ion and impurity particle transport.

Various plasma scenarios show effects of reduced turbulence:



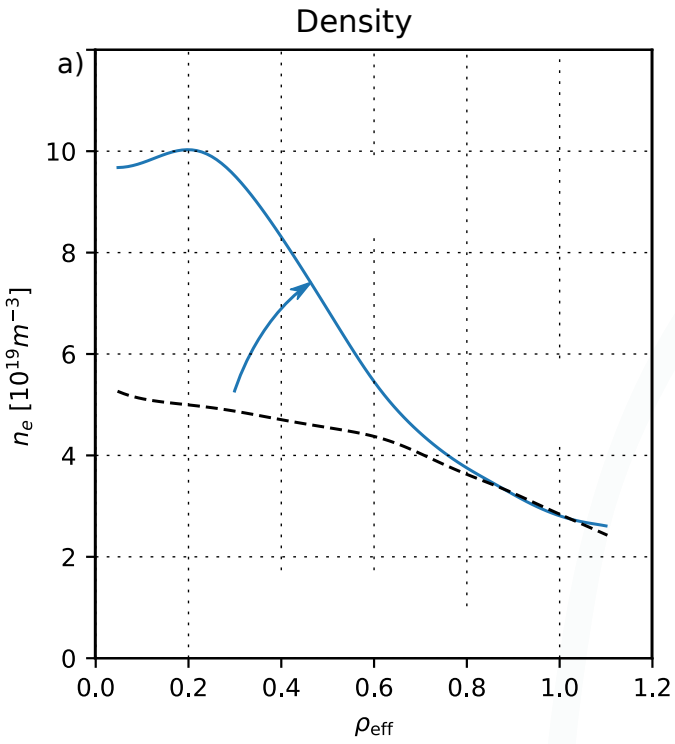



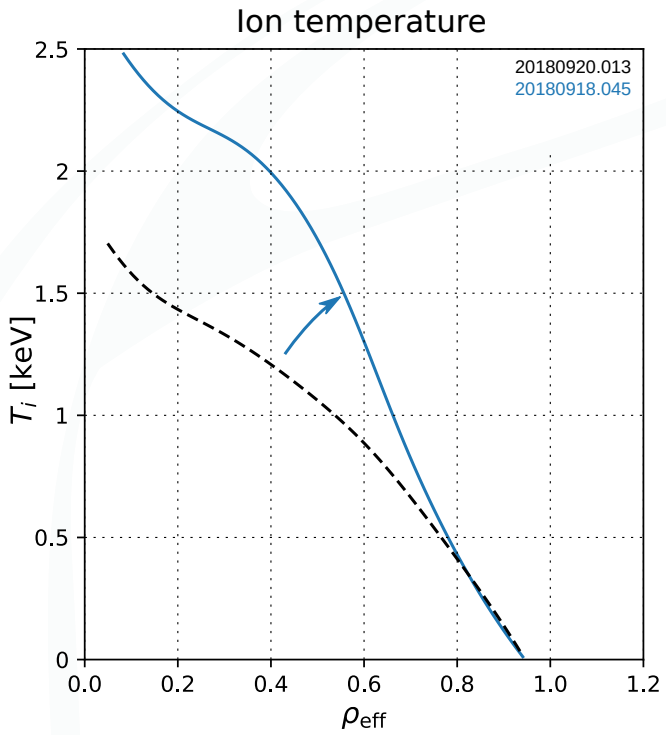
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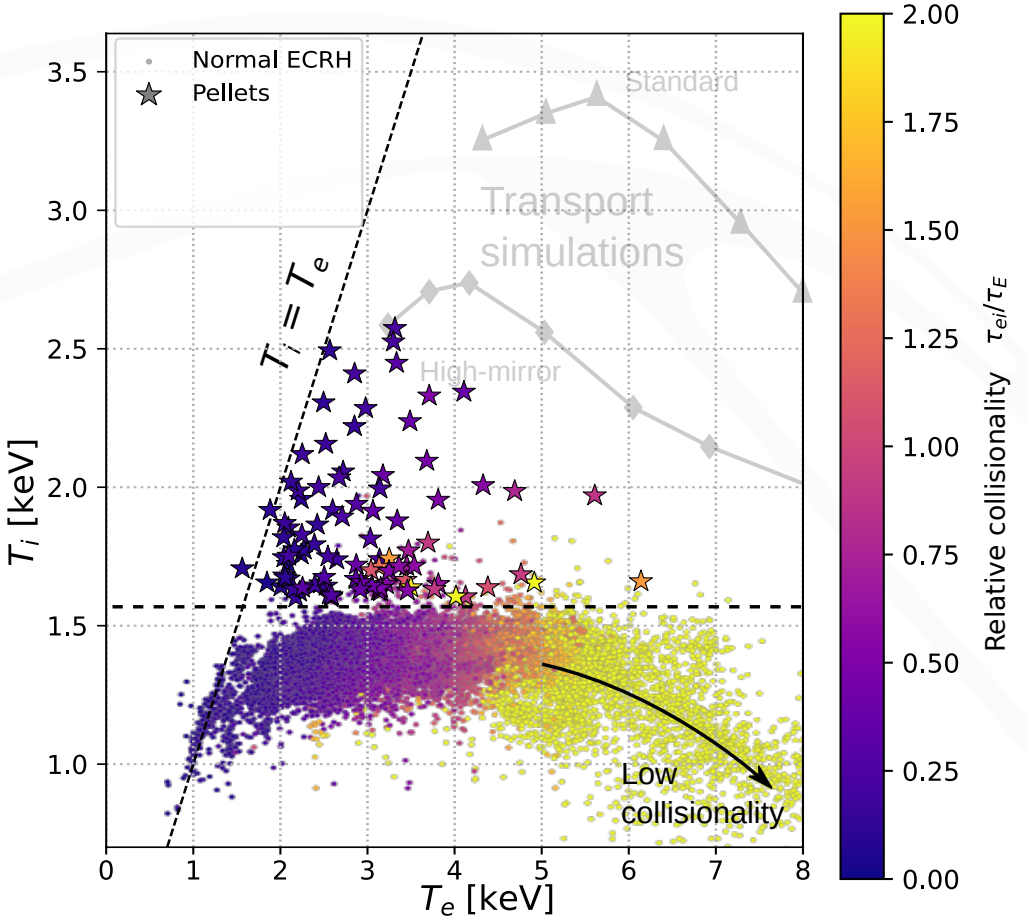
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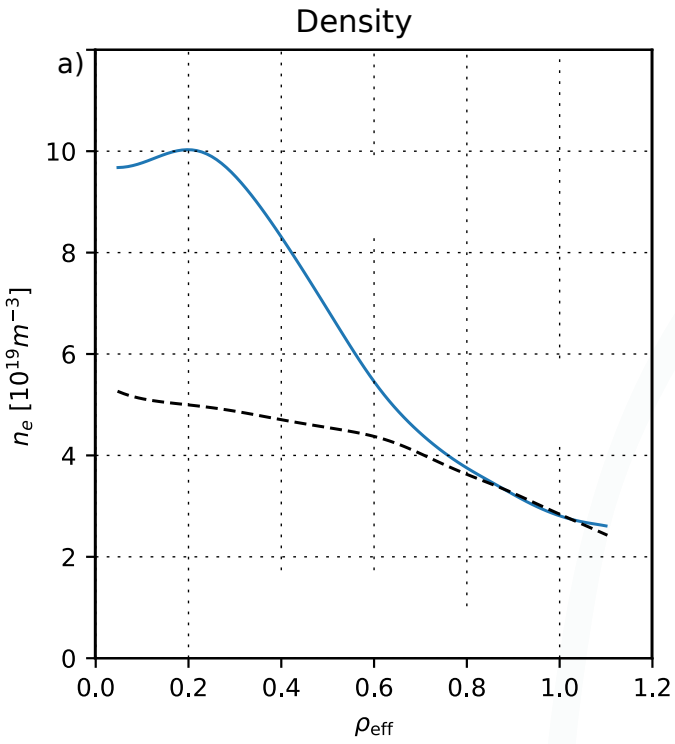



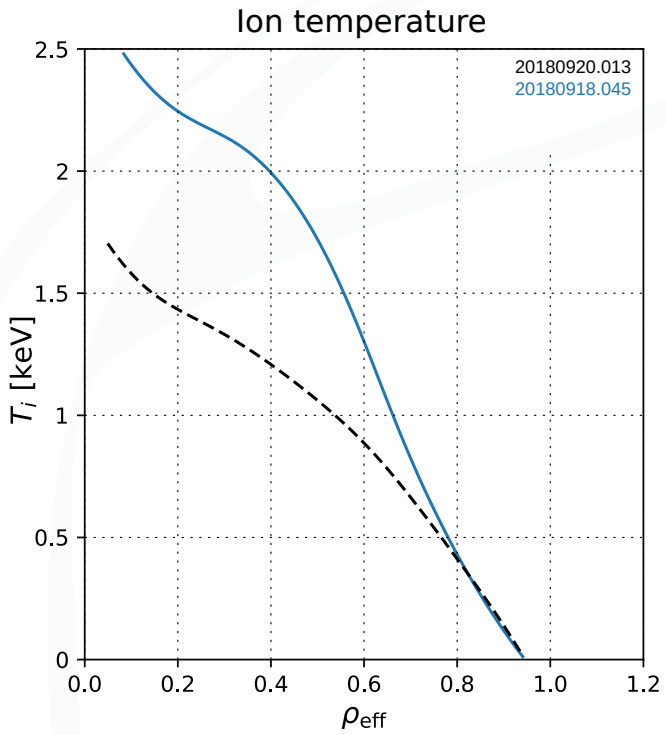
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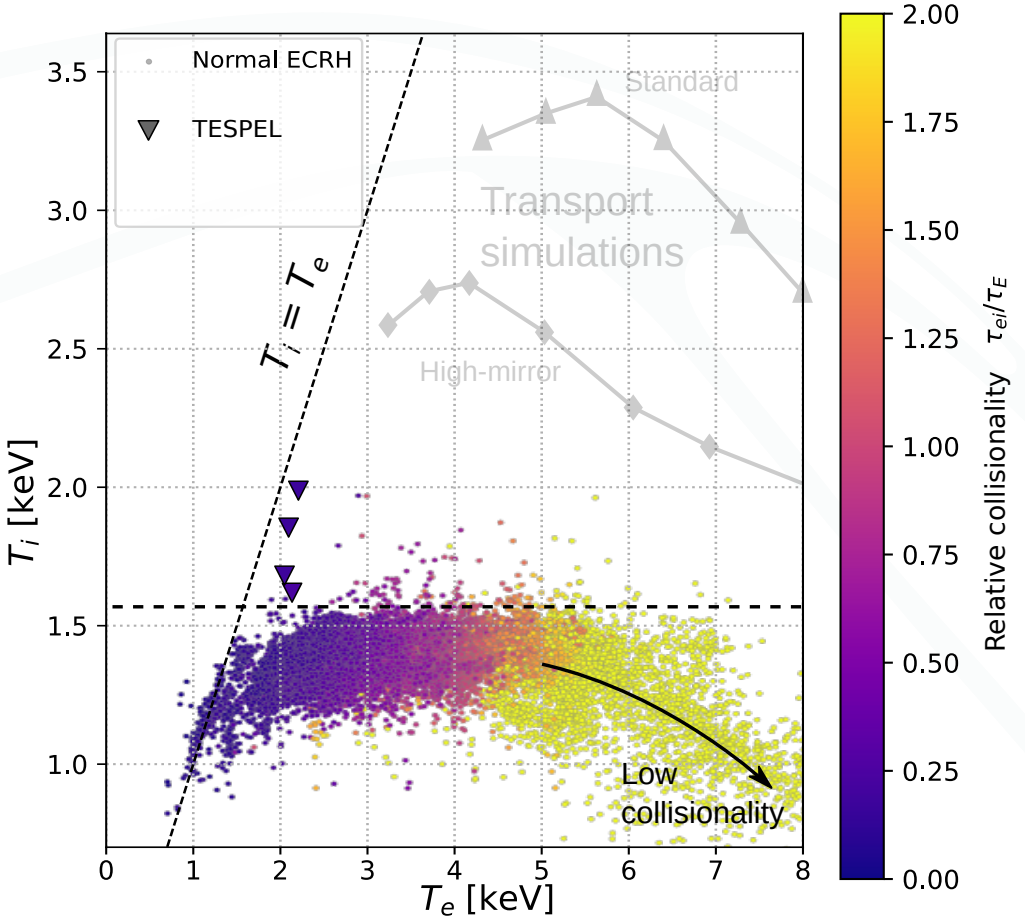
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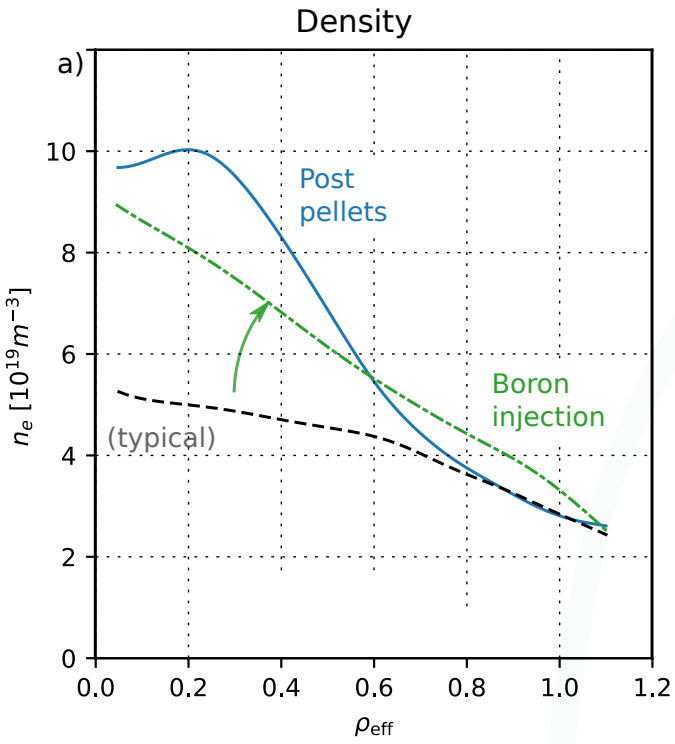



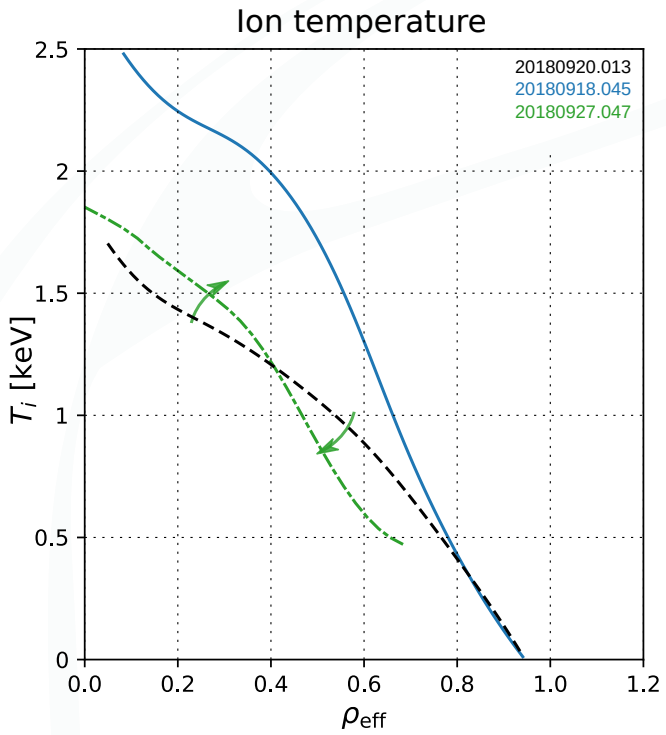
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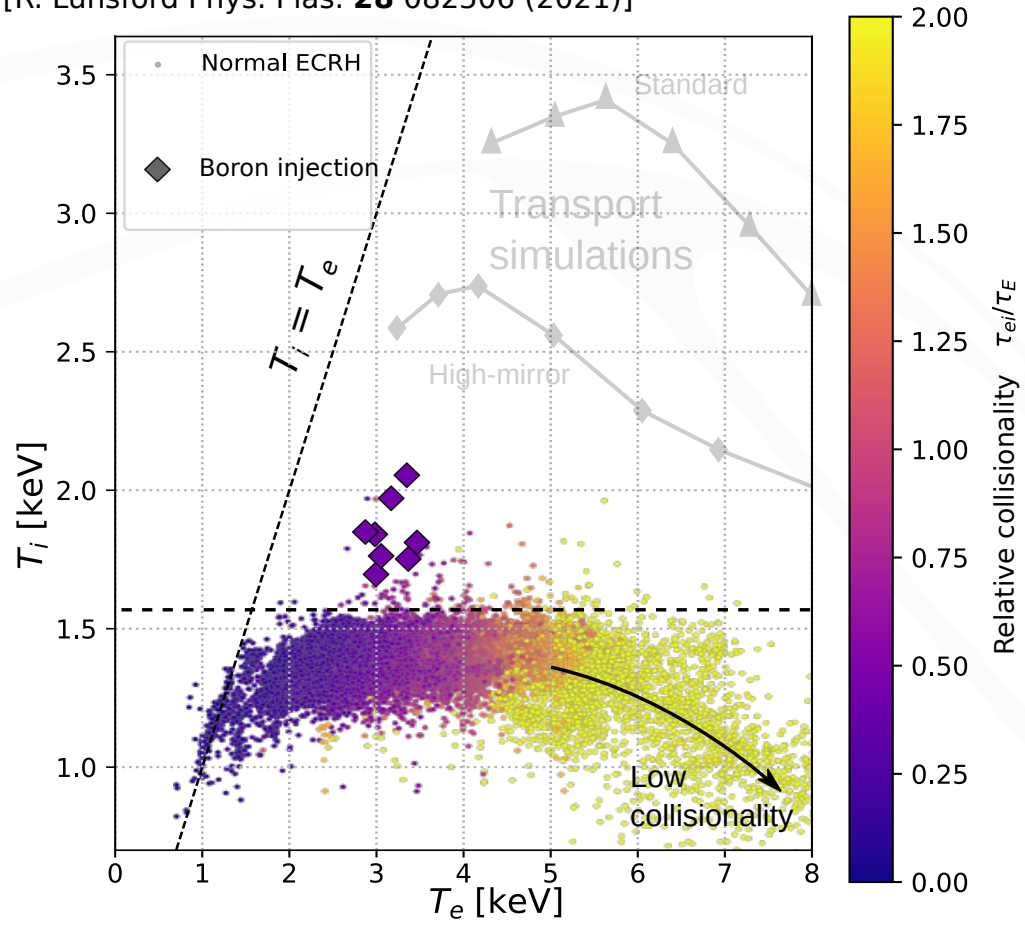
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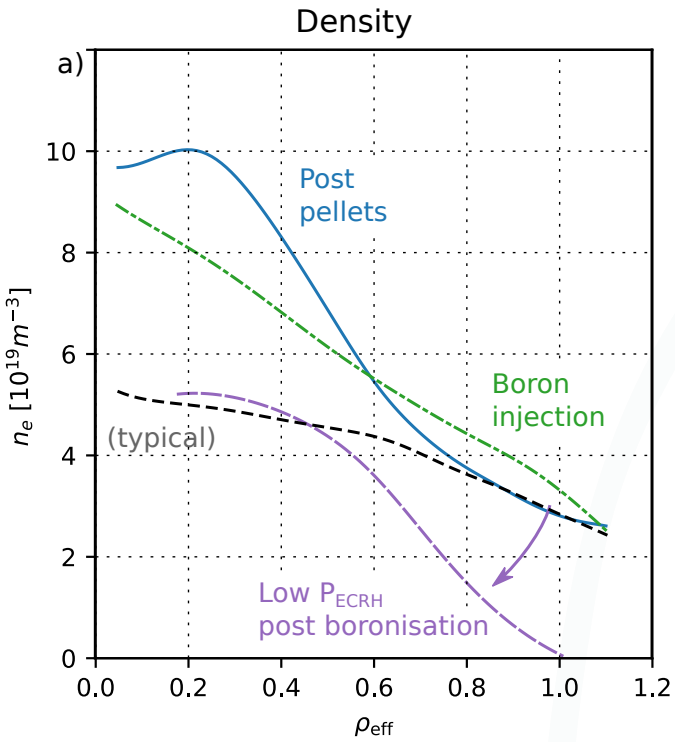



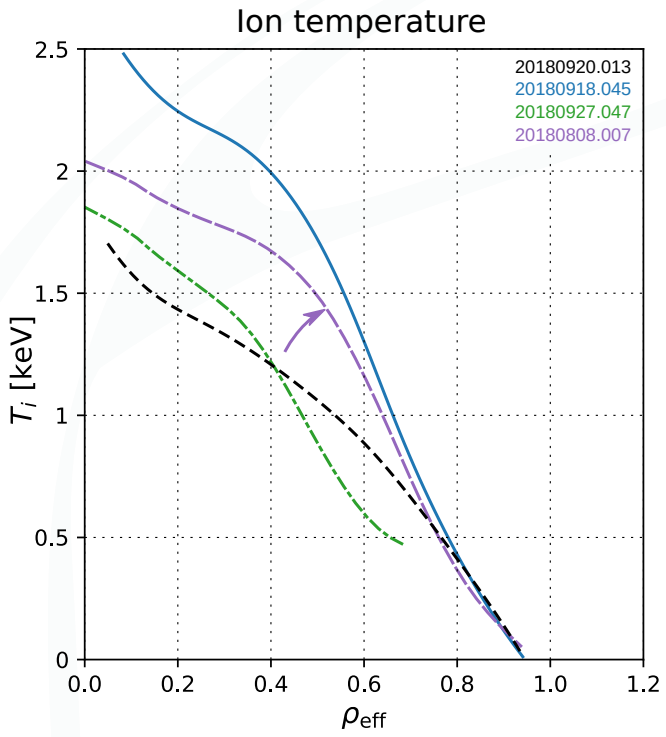
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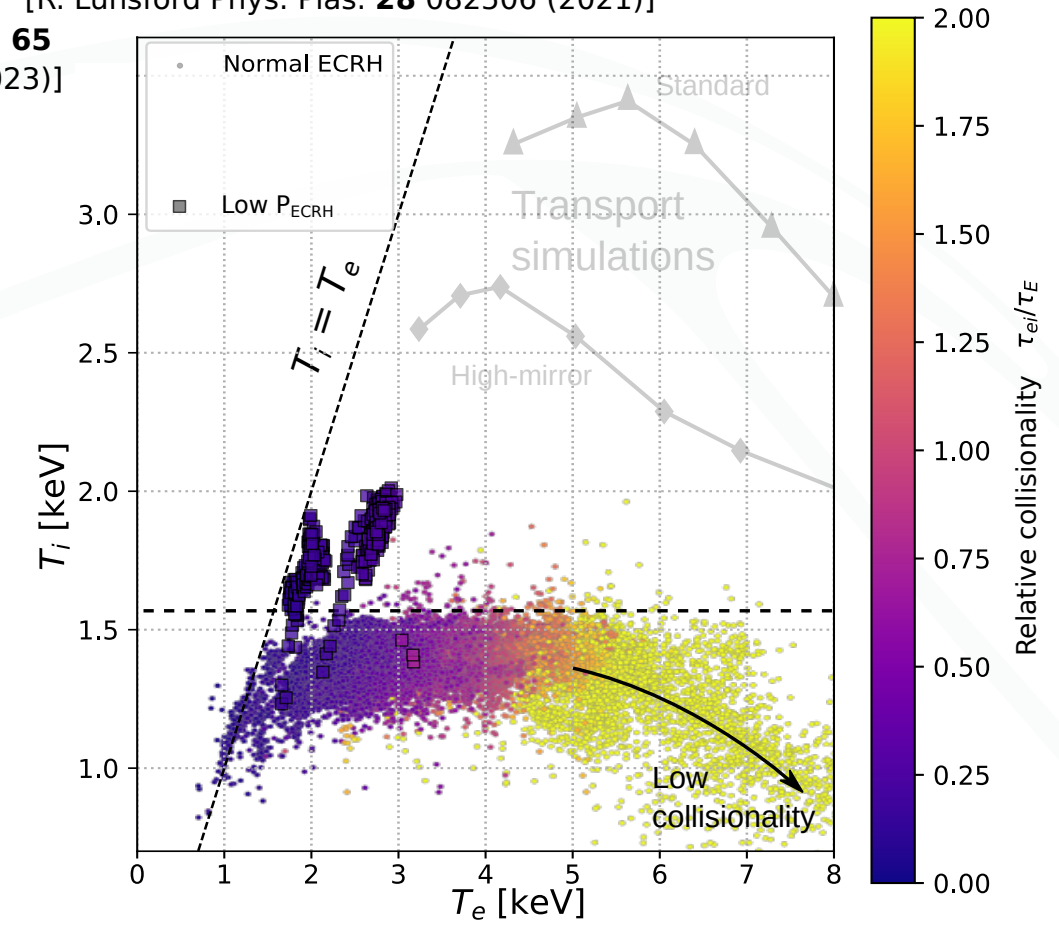
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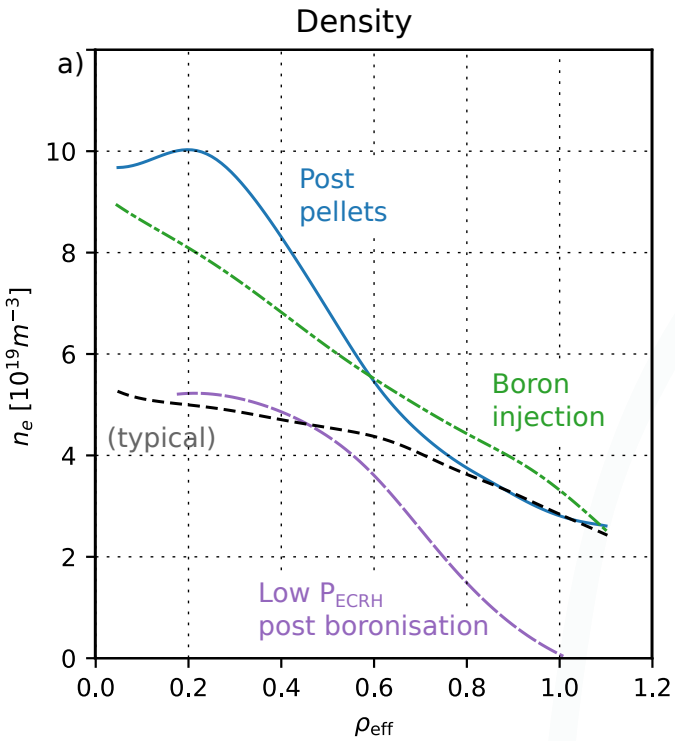
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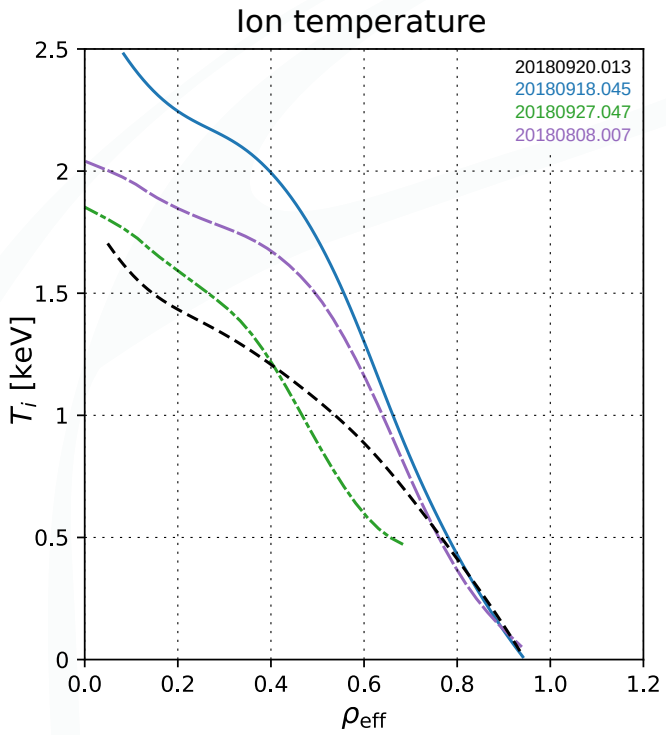
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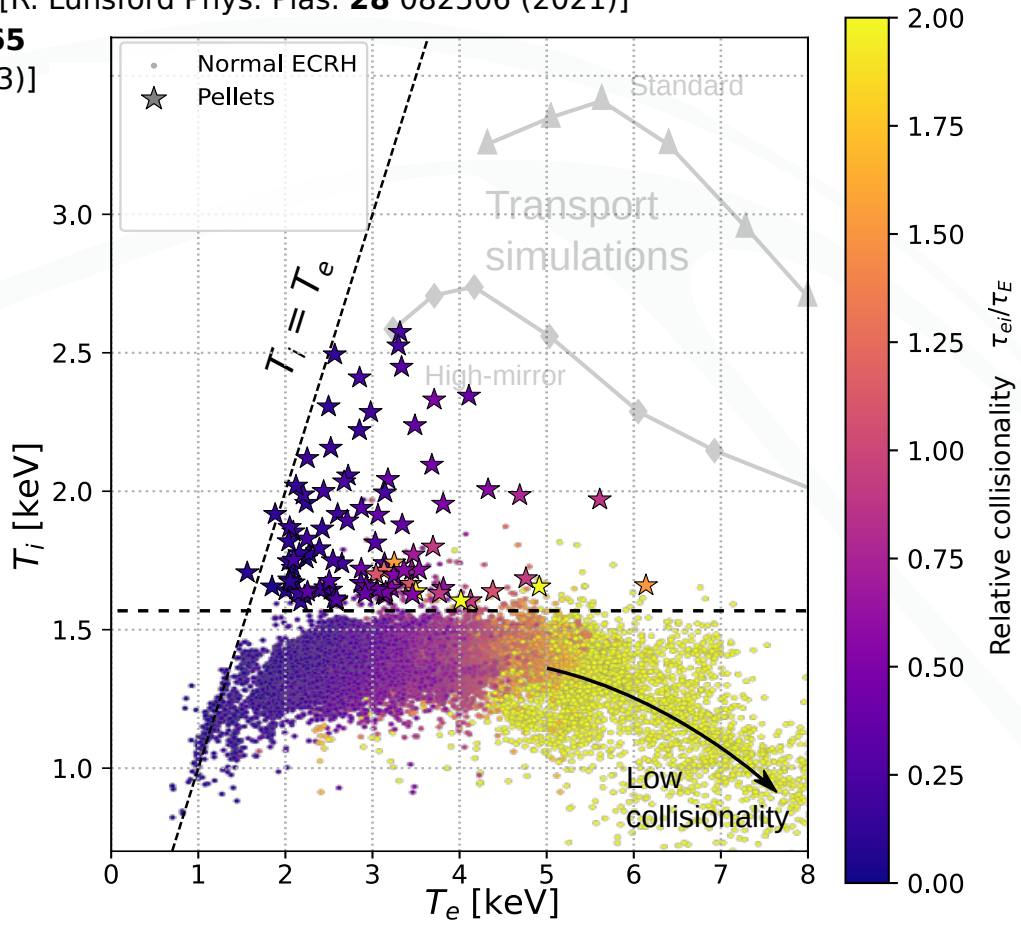
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$\nabla n_e$ --> ITG suppression [Xanthopoulos, PRL **125** 075001 (2020)]
--> reduced $\chi_i$ --> higher $\nabla T_i$ *(poster by M. Wappl, today)*

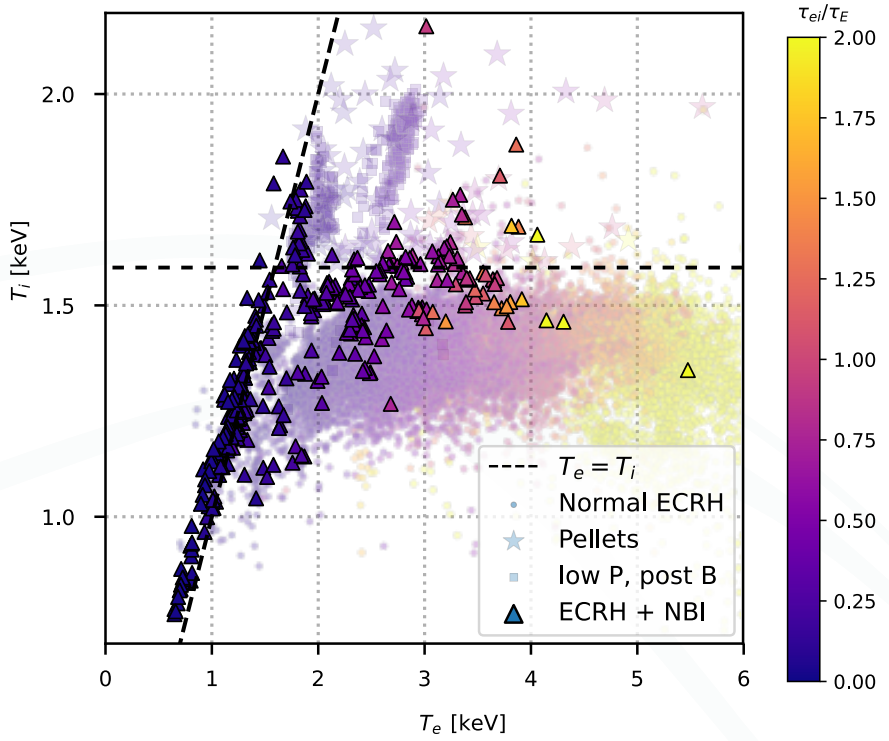


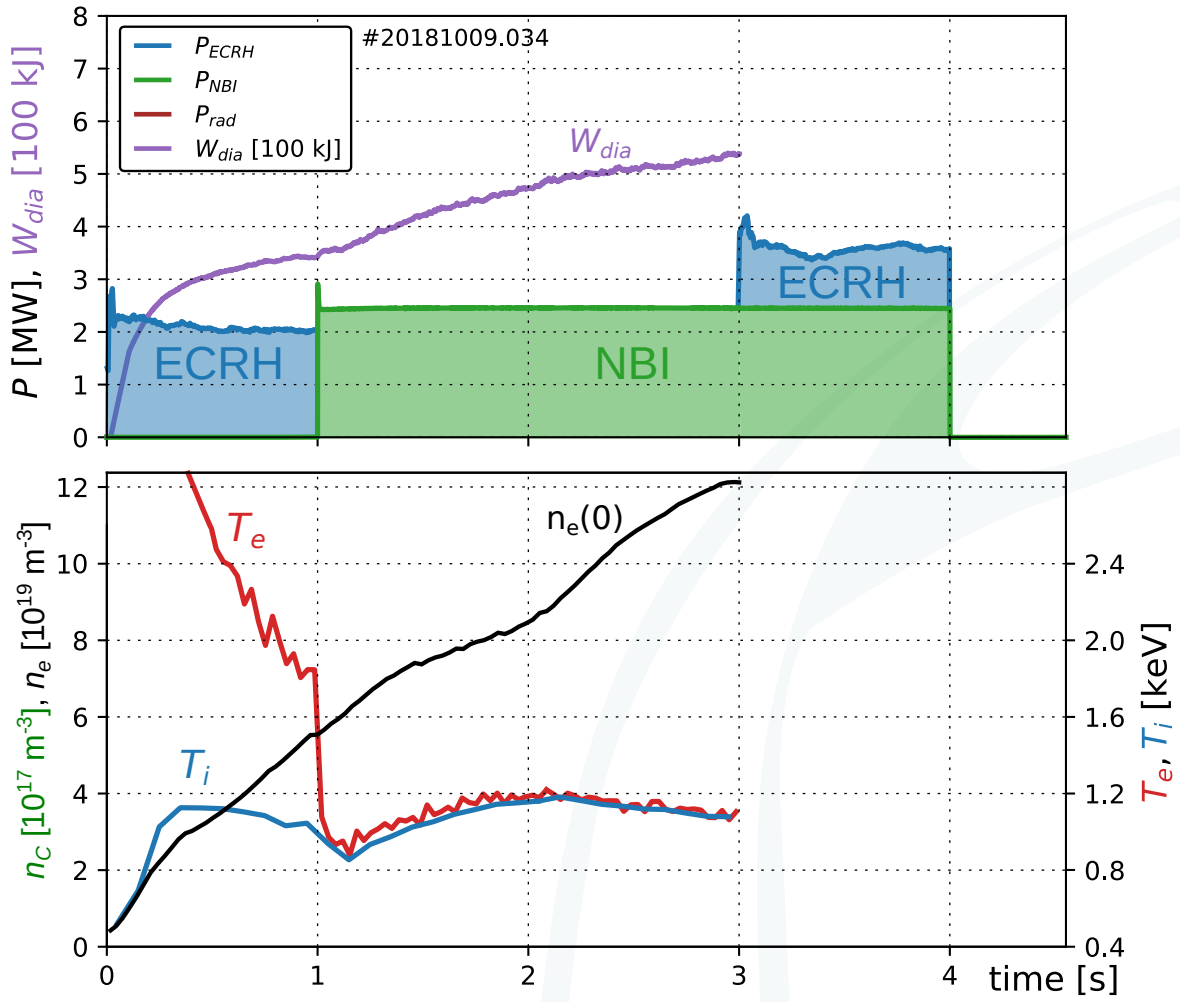
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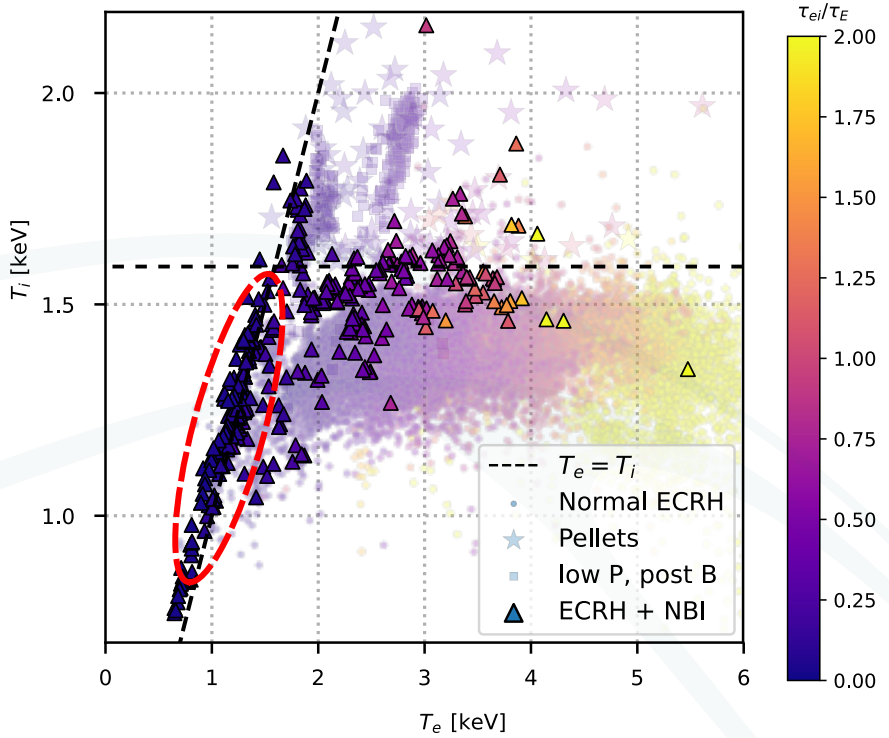
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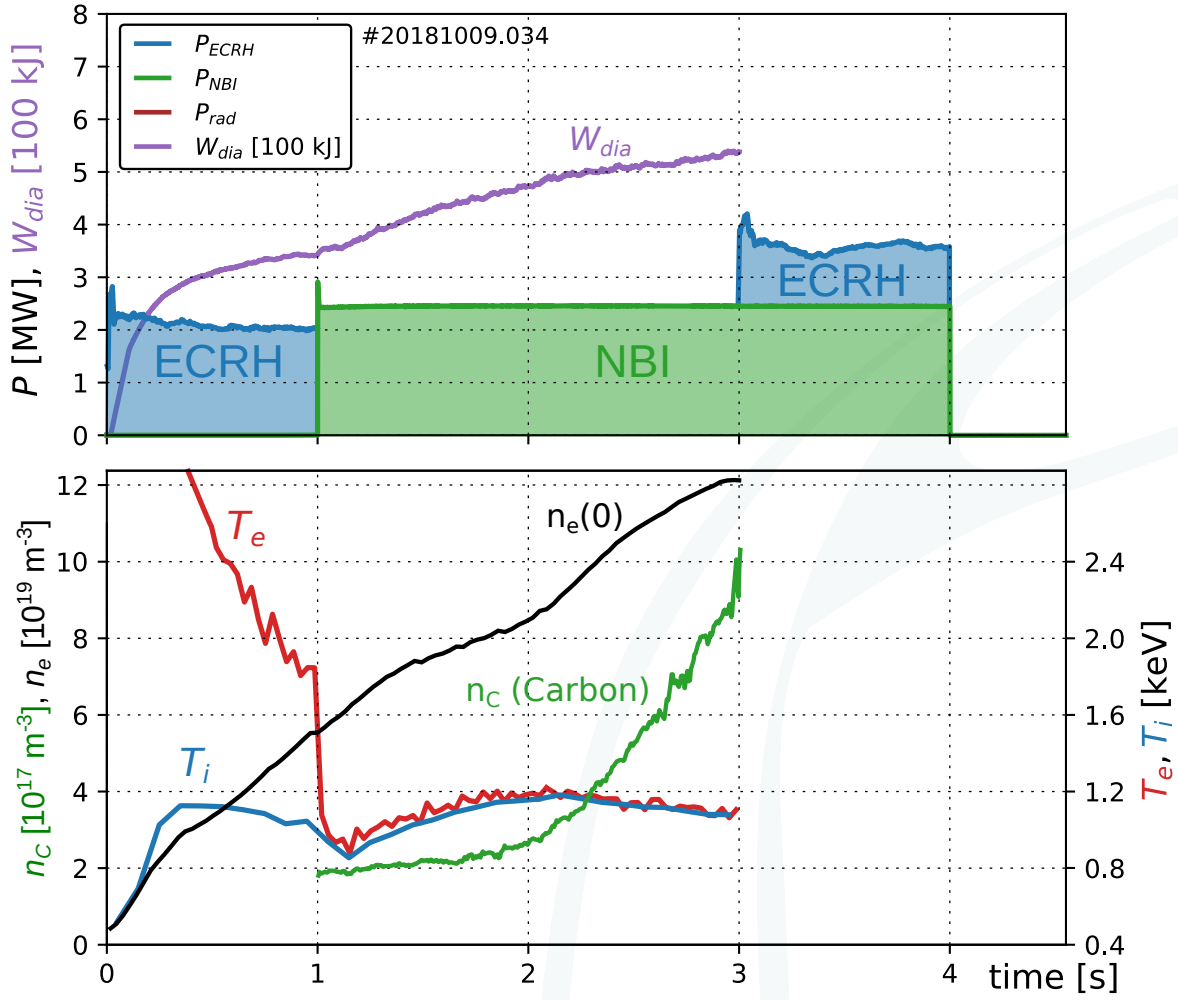


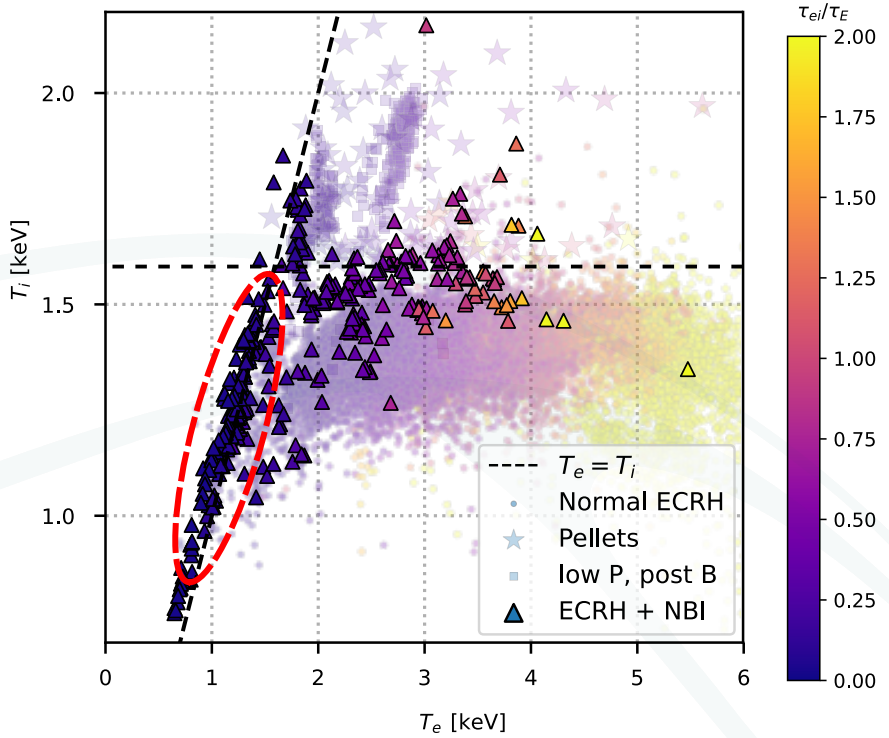




[O. Ford Nucl. Fus. 64 086067 (2024)]

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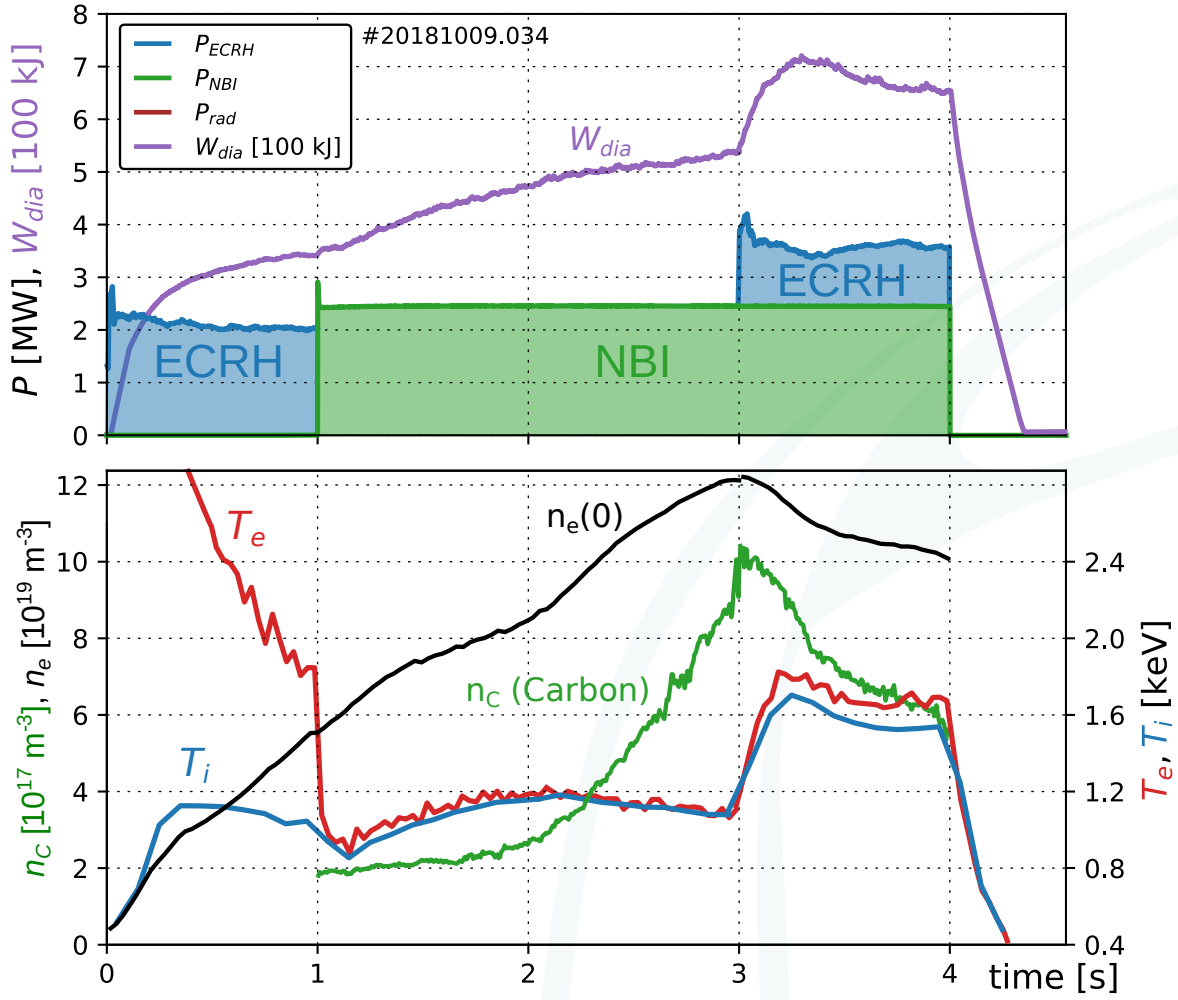



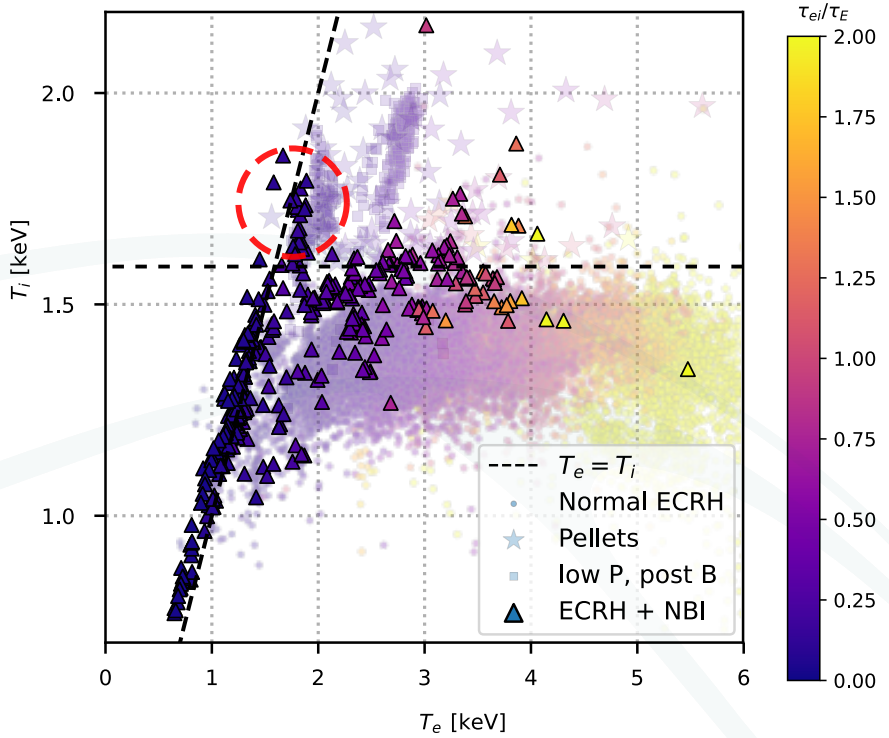

- Impurities accumulate from the middle of NBI phase, almost entirely determined by neoclassical transport.
  [T.Romba Nucl. Fus. **63** 076023 (2023)] (talk by T. Romba - Monday)

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

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- NBI *sometimes* gives density gradients. In some cases cleary $T_i > 1.5$
- Strong density peaking during pure NBI but low $T_i$.
- Higher $T_i$ after reintroduction of ECRH.



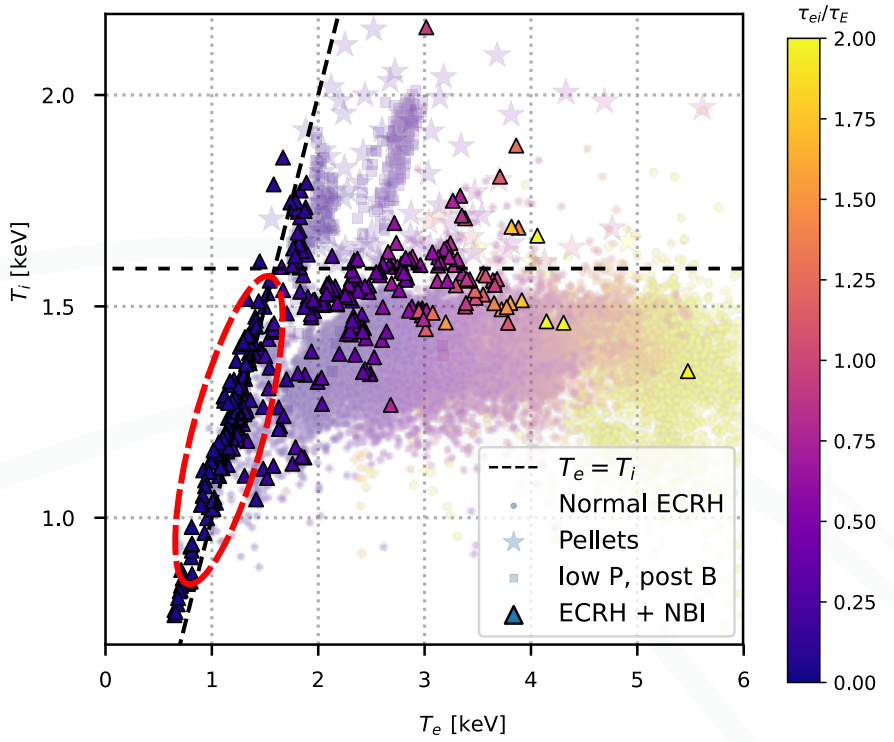




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- Reintroduced ECRH stops density peaking or reduces it, and flushes out impurities.

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

# Electron/ion energy fluxes in NBI plasmas

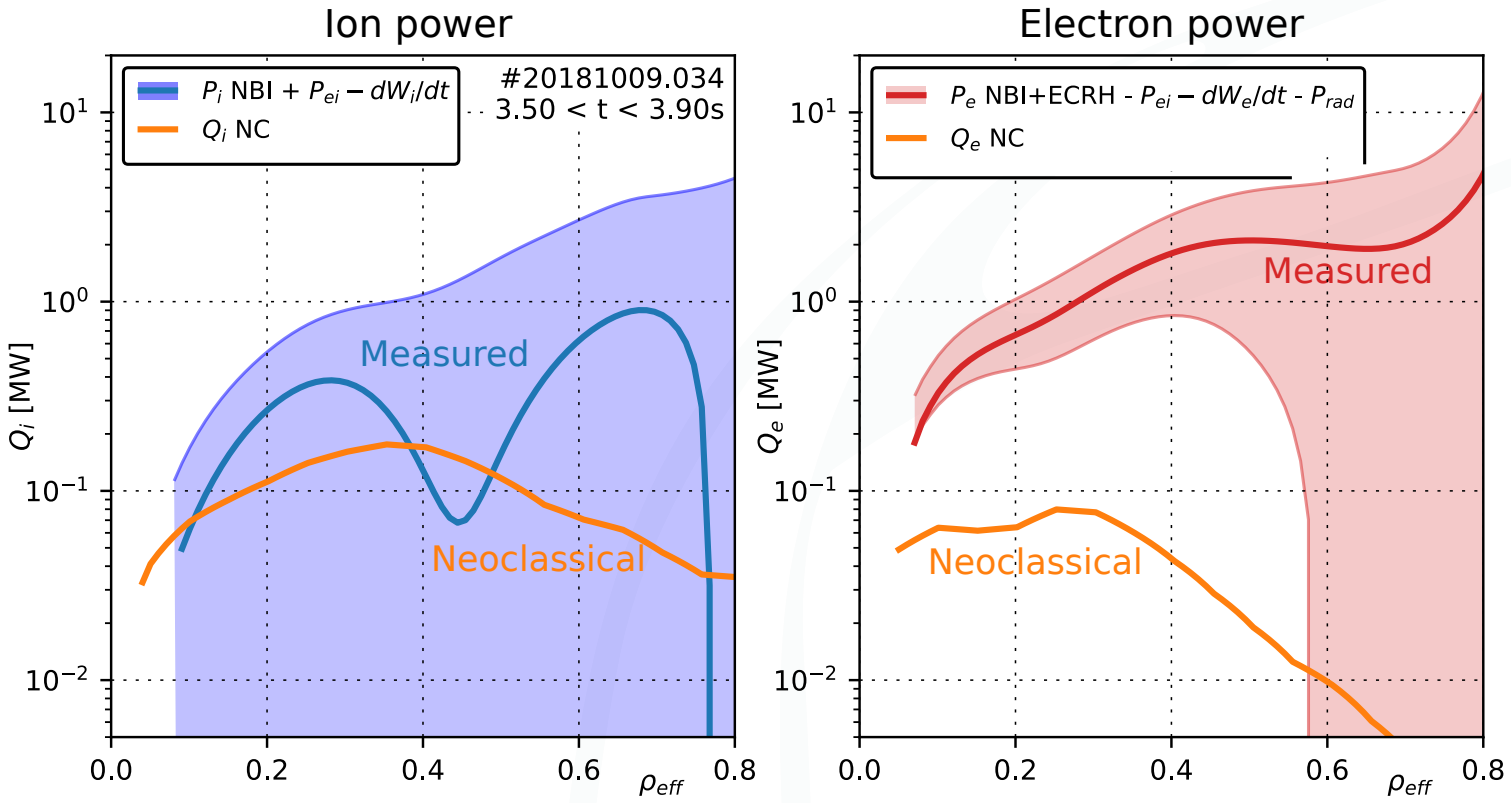
Energy fluxes:
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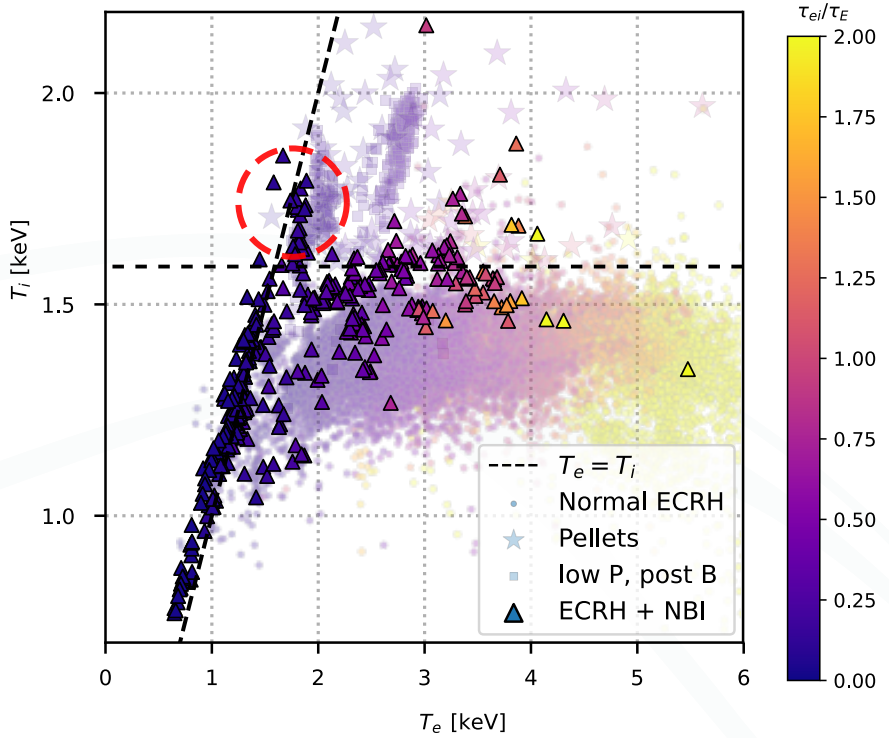


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- Some NBI+ECRH plasmas hint at **possibility** of $Q_i$ near neoclassical levels, e.g.:

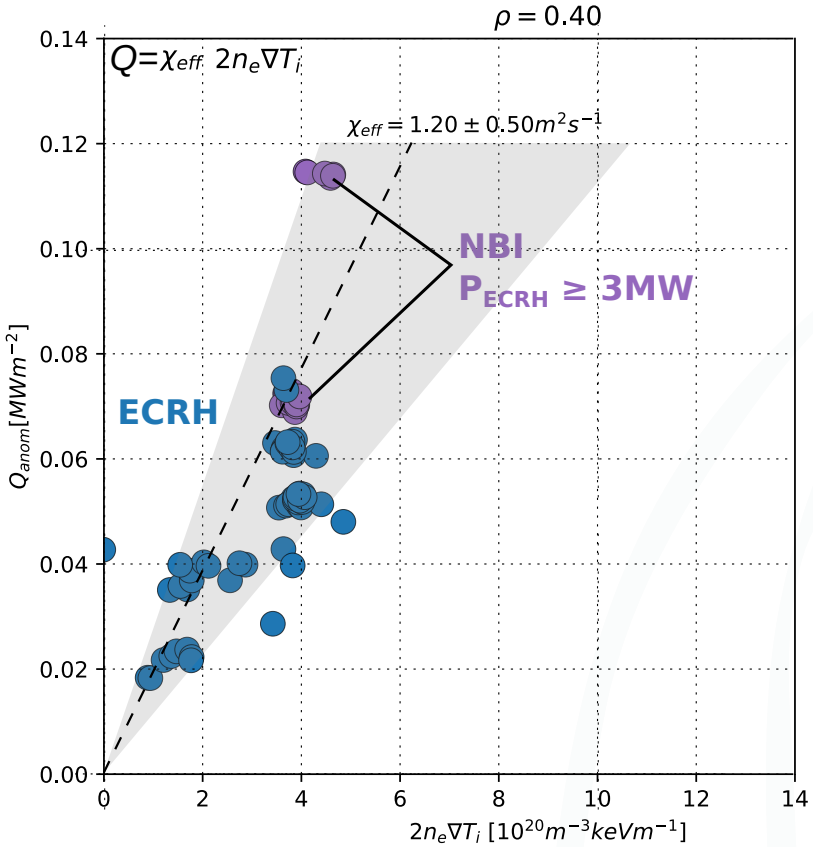



[O. Ford Nucl. Fus. 64 086067 (2024)]
[D. Carralero et al. Nucl. Fus. 61 096015 (2021)]

# NBI (±ECRH) - Anomalous heat diffusivity

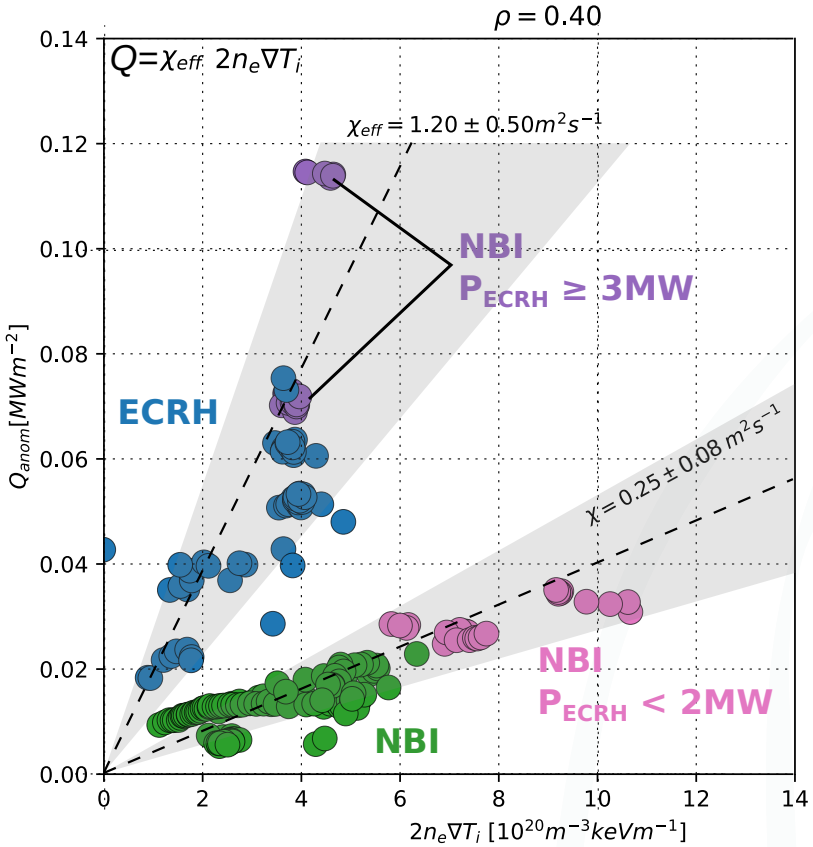
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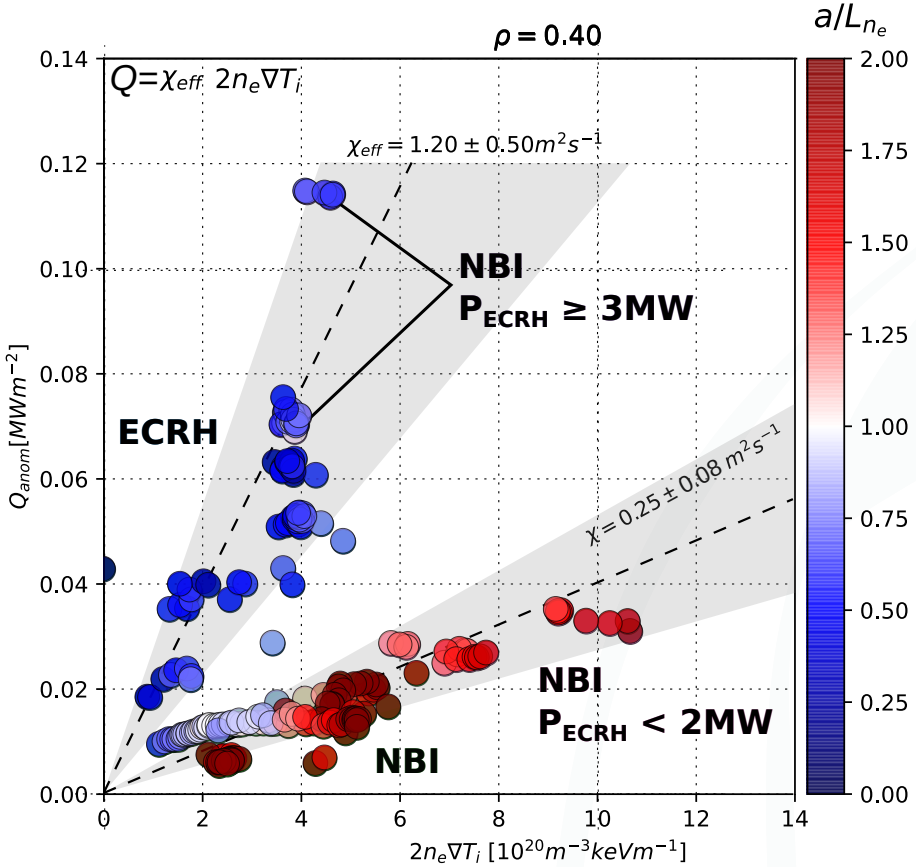
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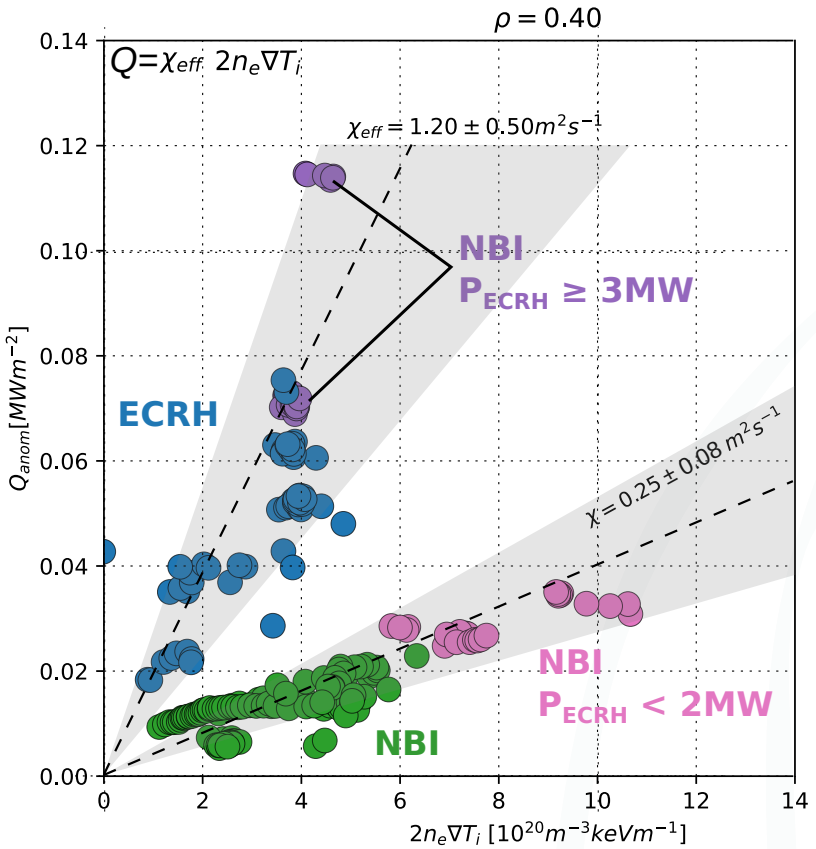
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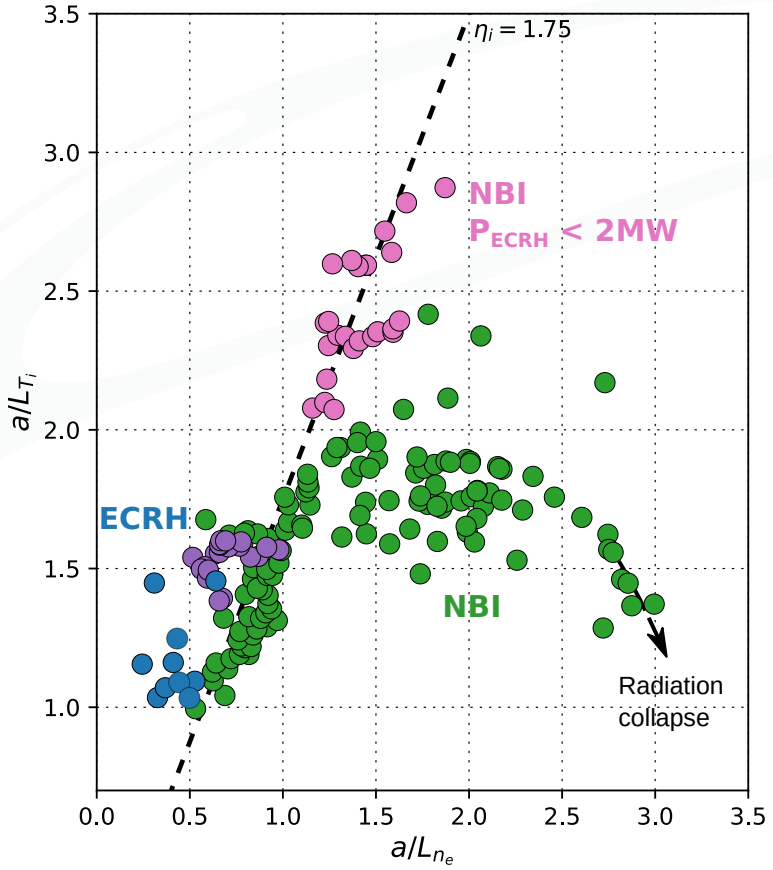

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Normalised gradients at $\rho \sim 0.4$

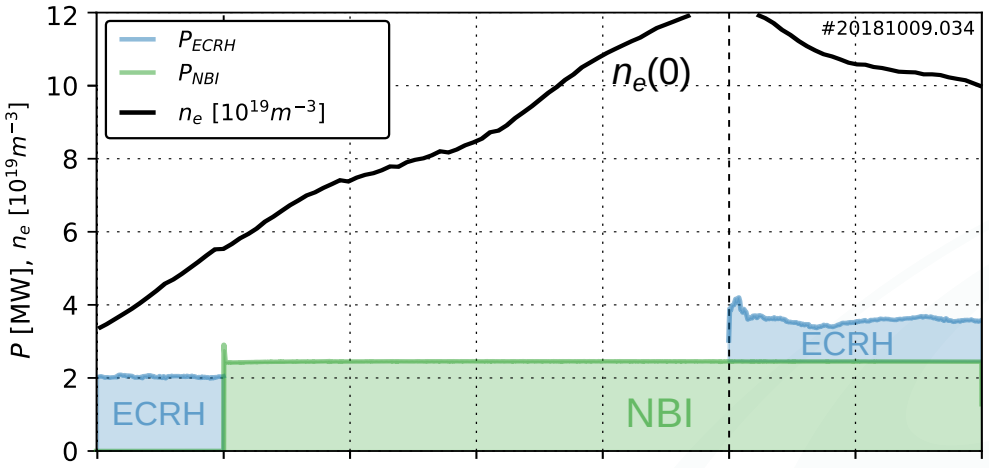



- Pure NBI has reduced $\chi_{eff}$, but much broader power deposition results in similar $\nabla T_i$. (and $T_i(0)$)
- Mixed NBI with low $P_{ECRH}$ maintains $\chi_{eff} \sim 0.25$ and can exploit it for higher $\nabla T_i$.
- All plasmas with $a/L_{ne} > 1.0$ have lower $\chi_{eff}$.
- Without additional ECRH, NBI plasmas can undergo radiation collapse.

[O. Ford Nucl. Fus. 64 086067 (2024)]
[D. Carralero et al. Nucl. Fus. 61 096015 (2021)]

# Pure NBI - Particle flux

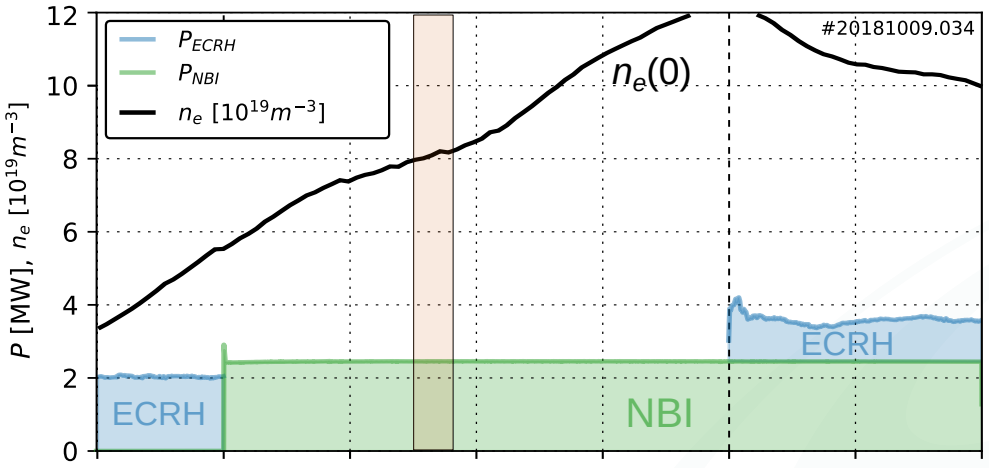
- Particle balance during pure NBI phase shows:
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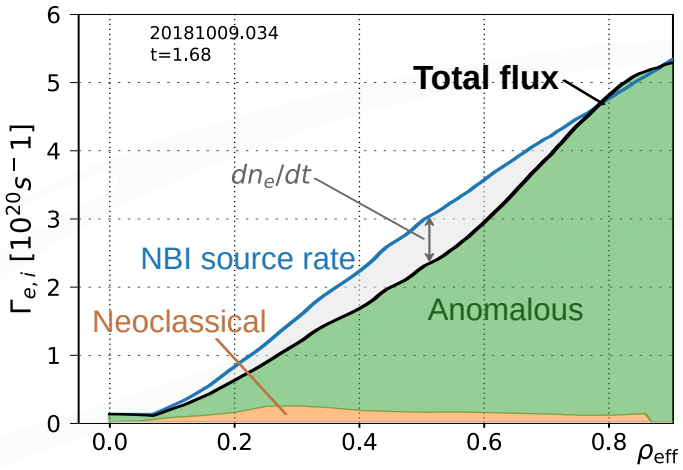



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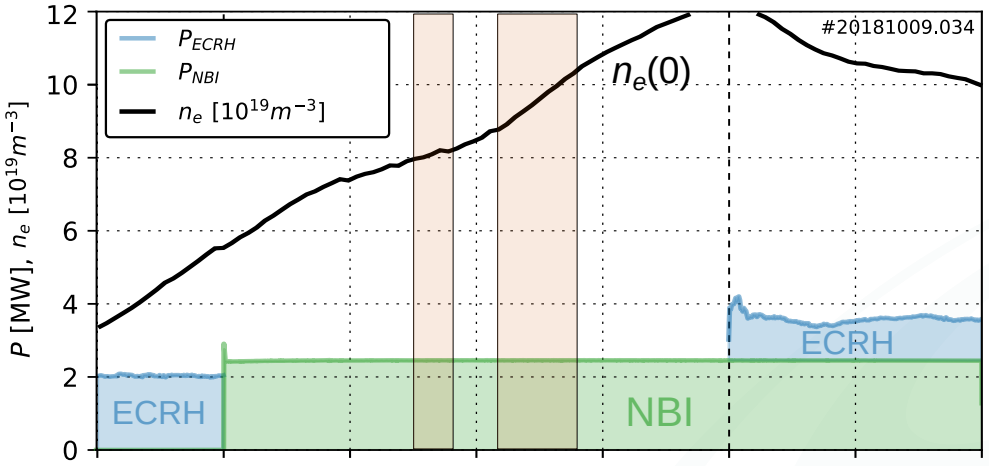


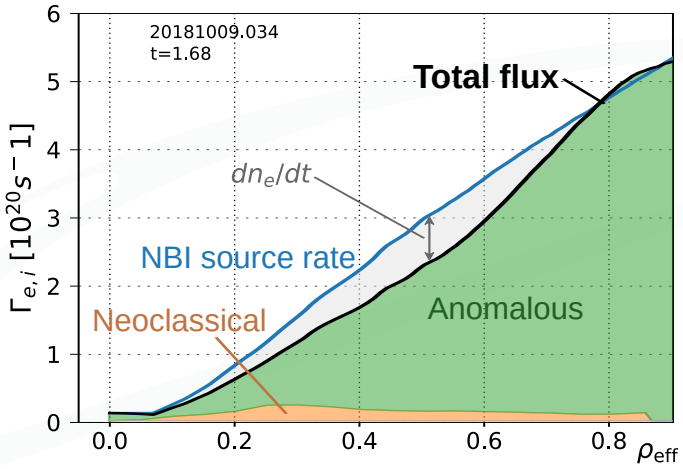



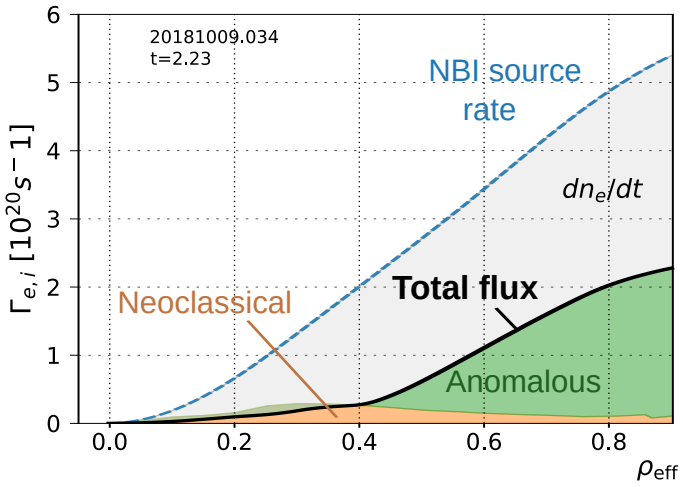

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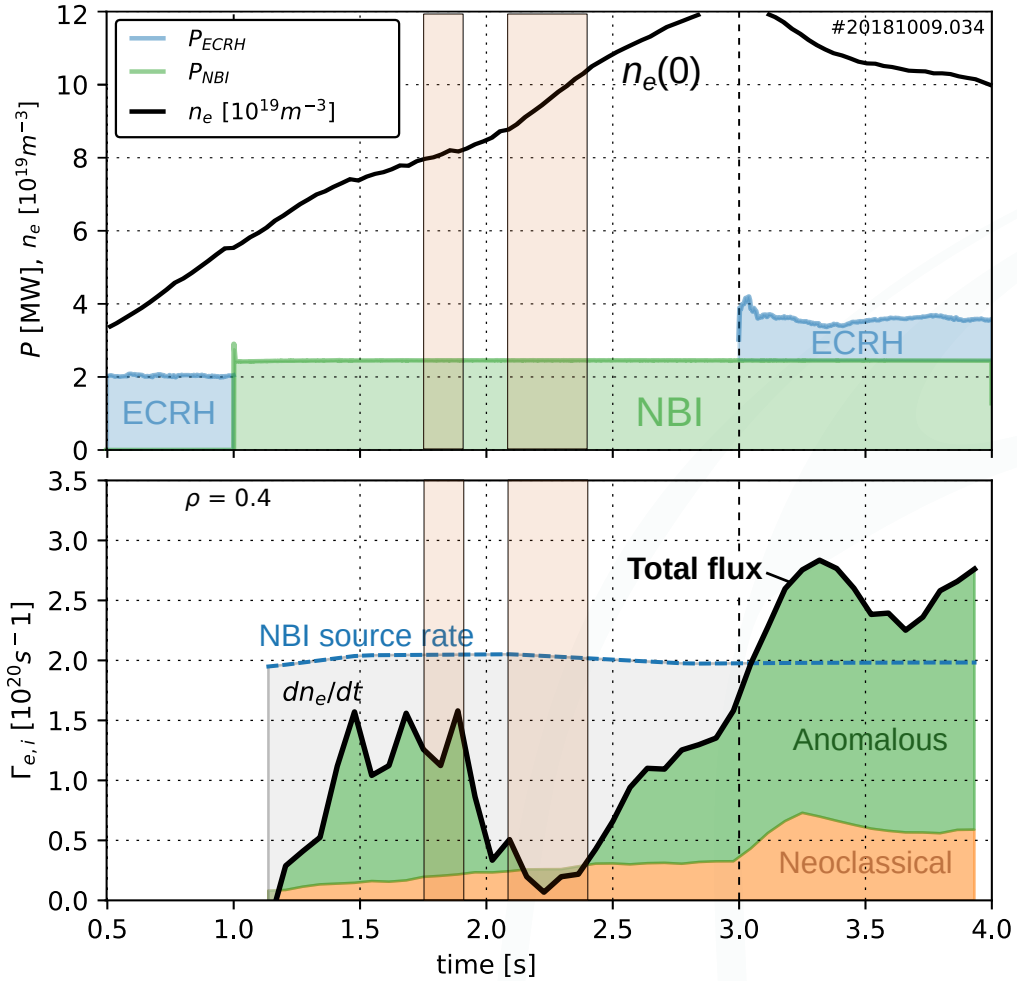



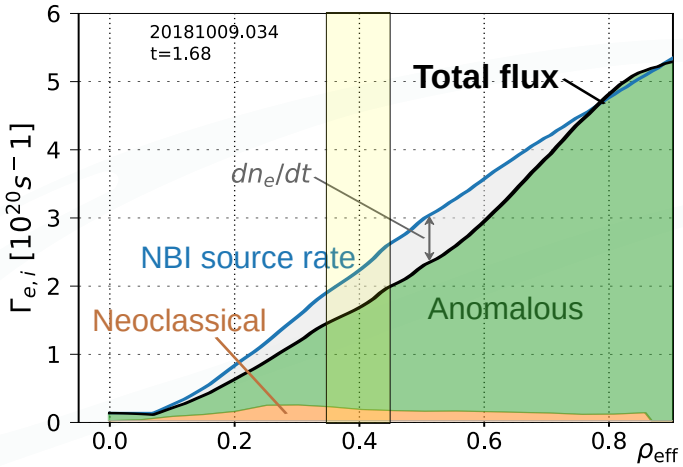

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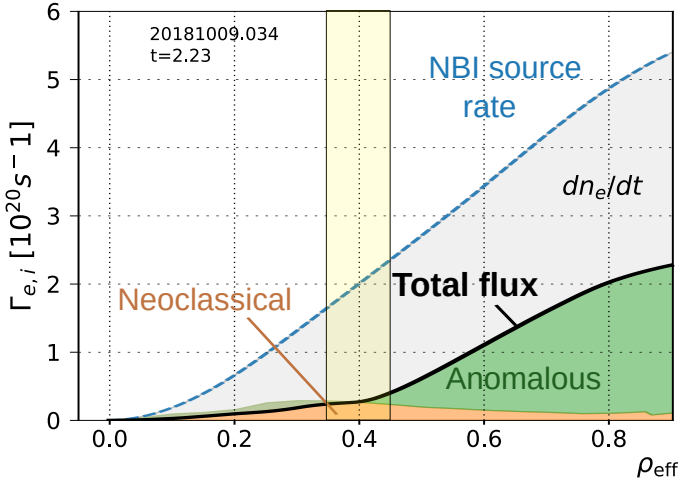
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- Drops to apparently neoclassical flux level.
- Increases again shortly afterwards.
- Increases again at ECRH reinroduction, reducing $n_e$ a little.

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

# Pure NBI - Particle transport

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

$\nabla n_e$ is changing. What is just an 'expected' reponse to this?
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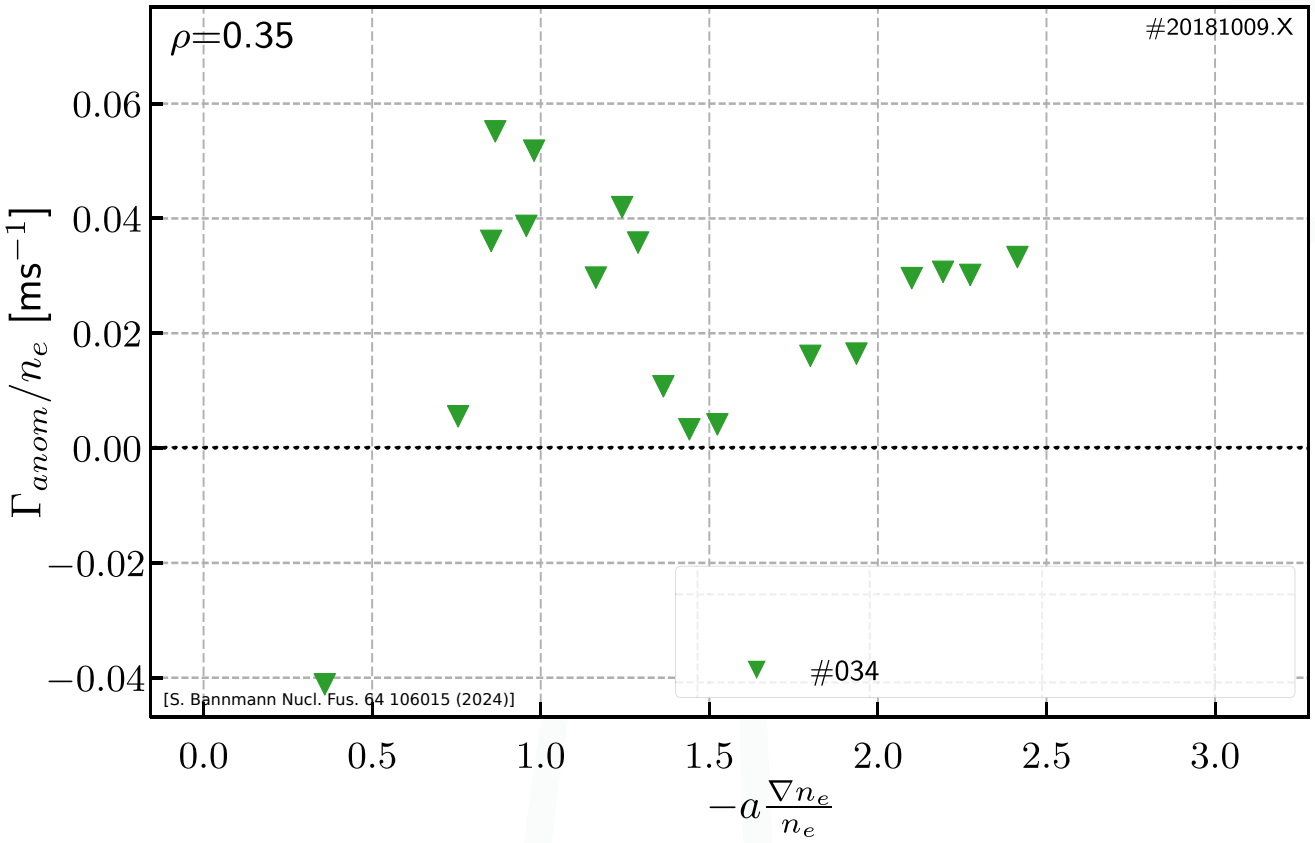
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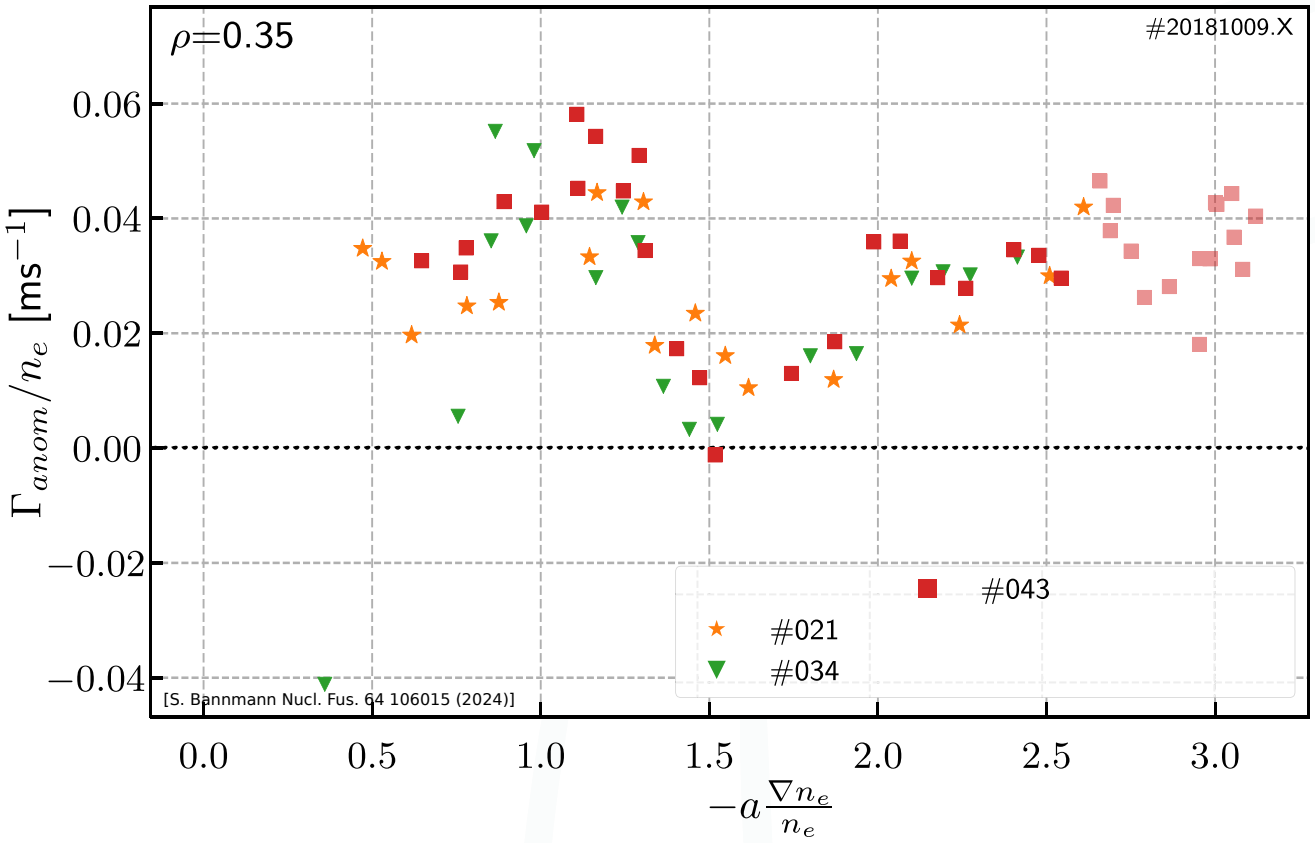
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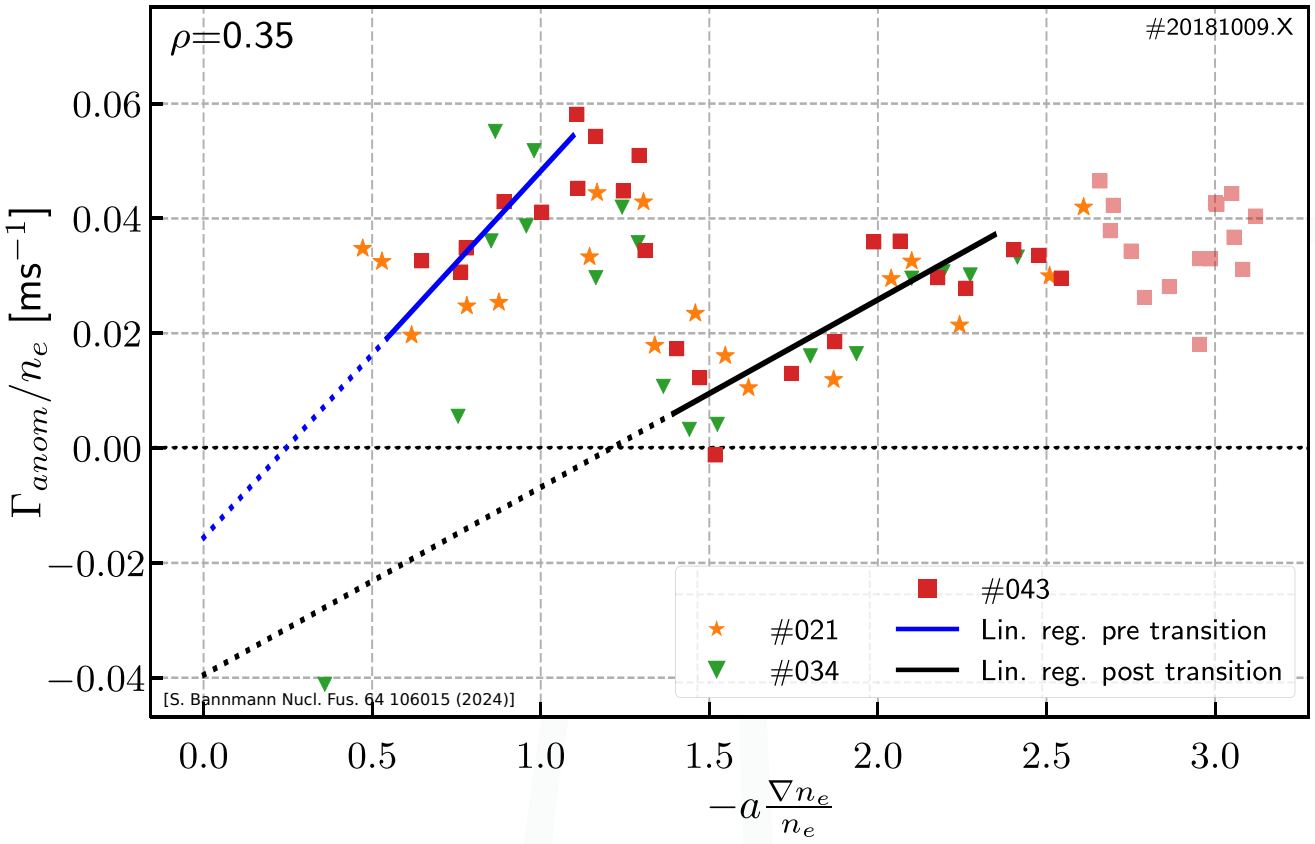
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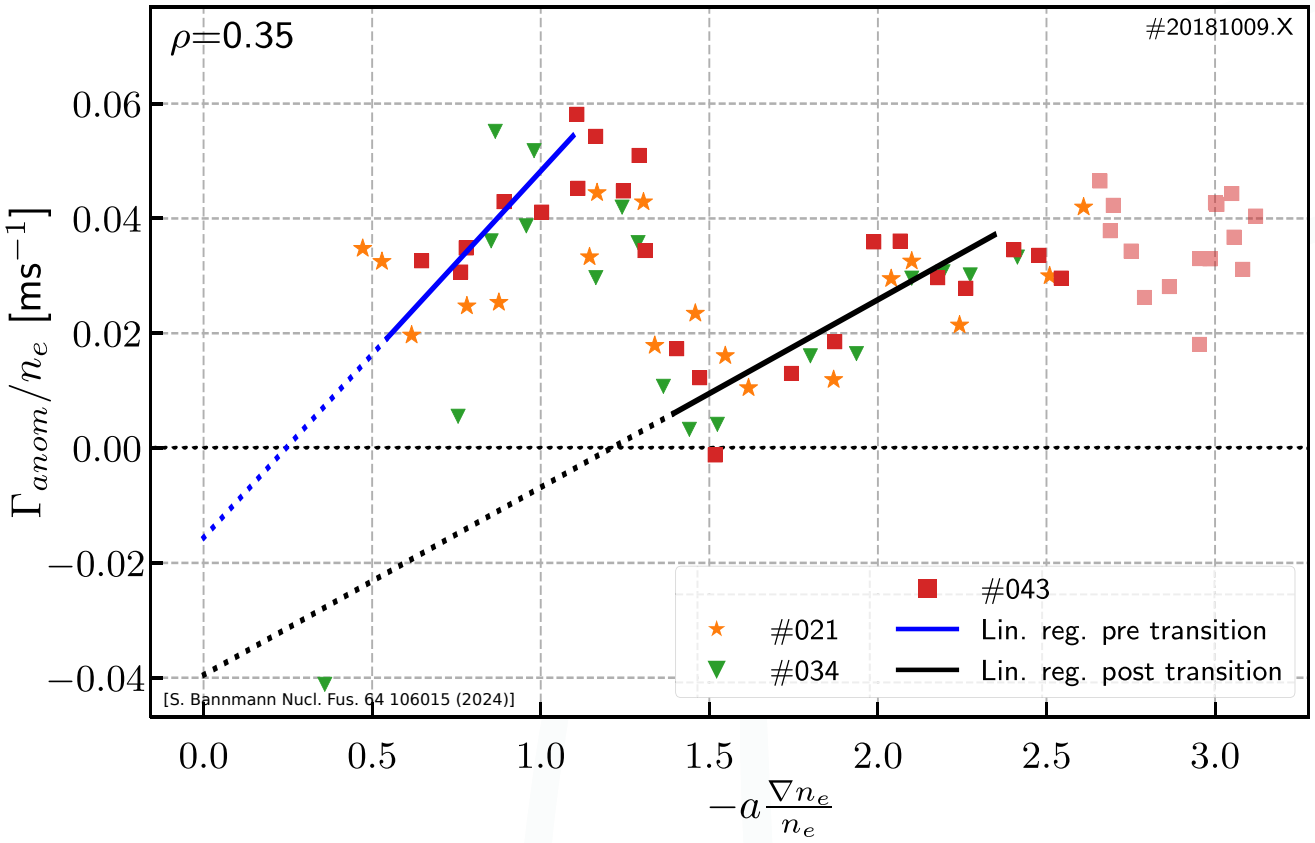


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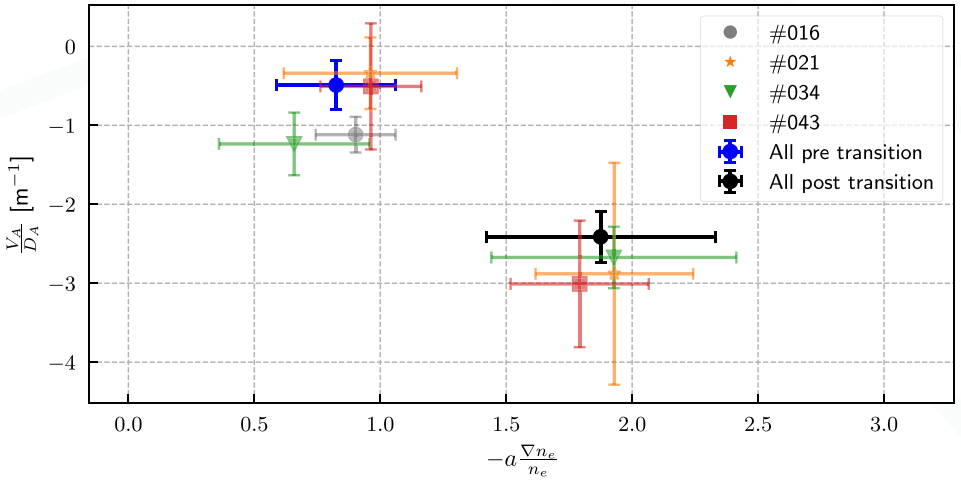
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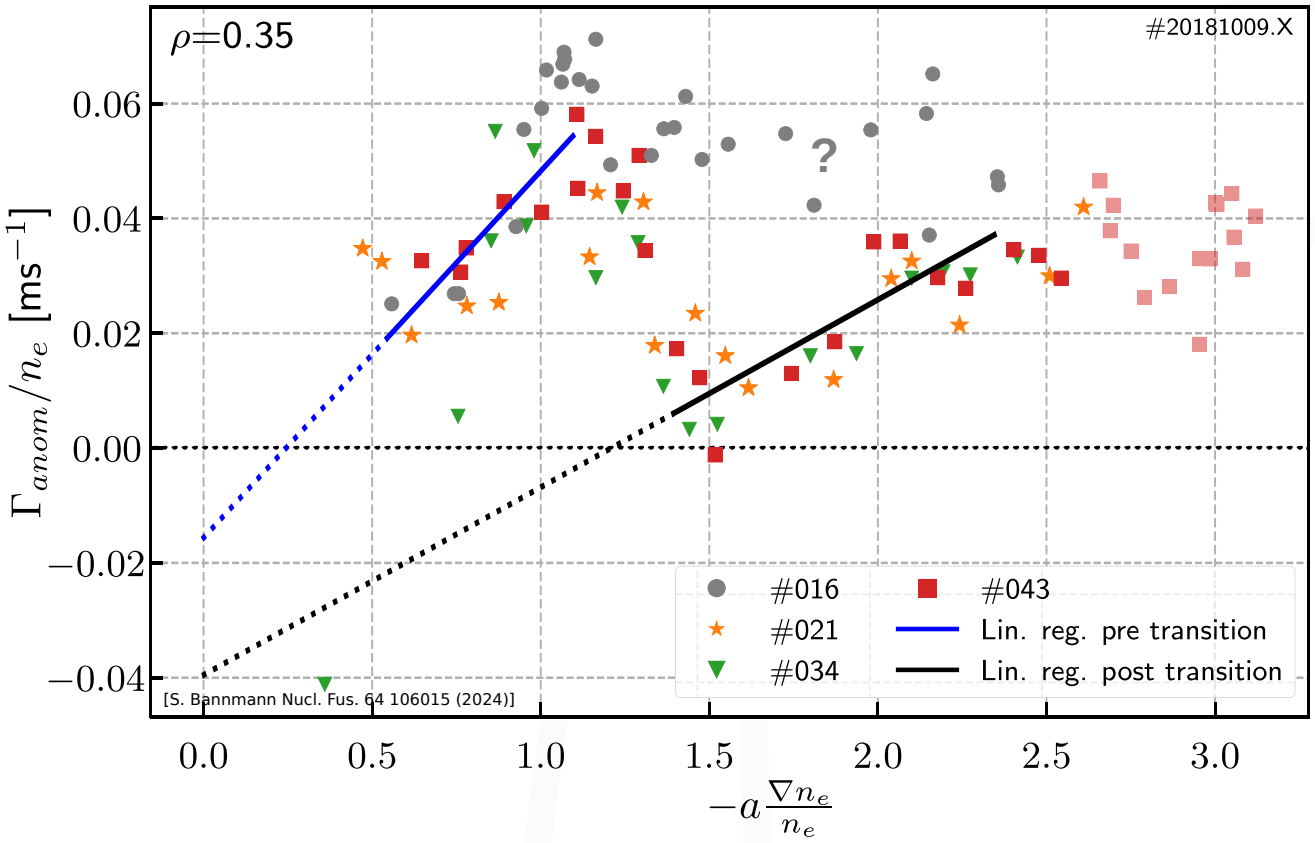

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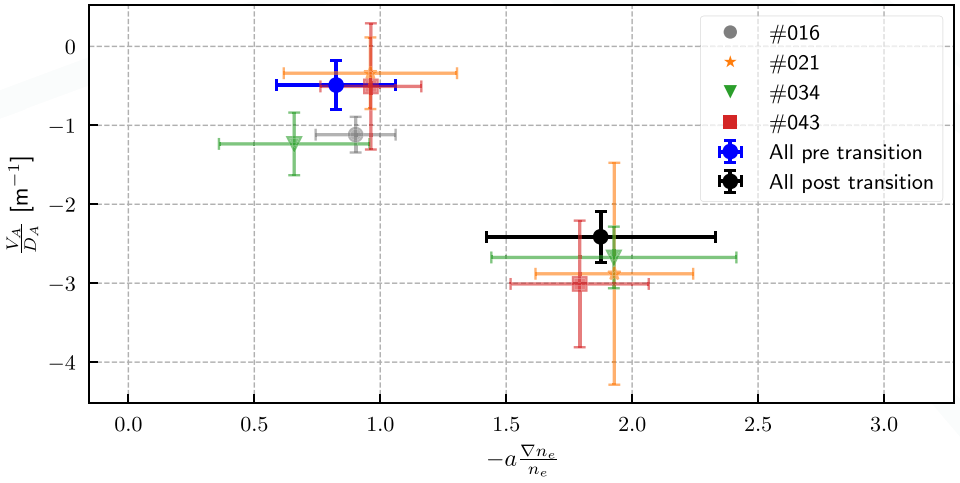
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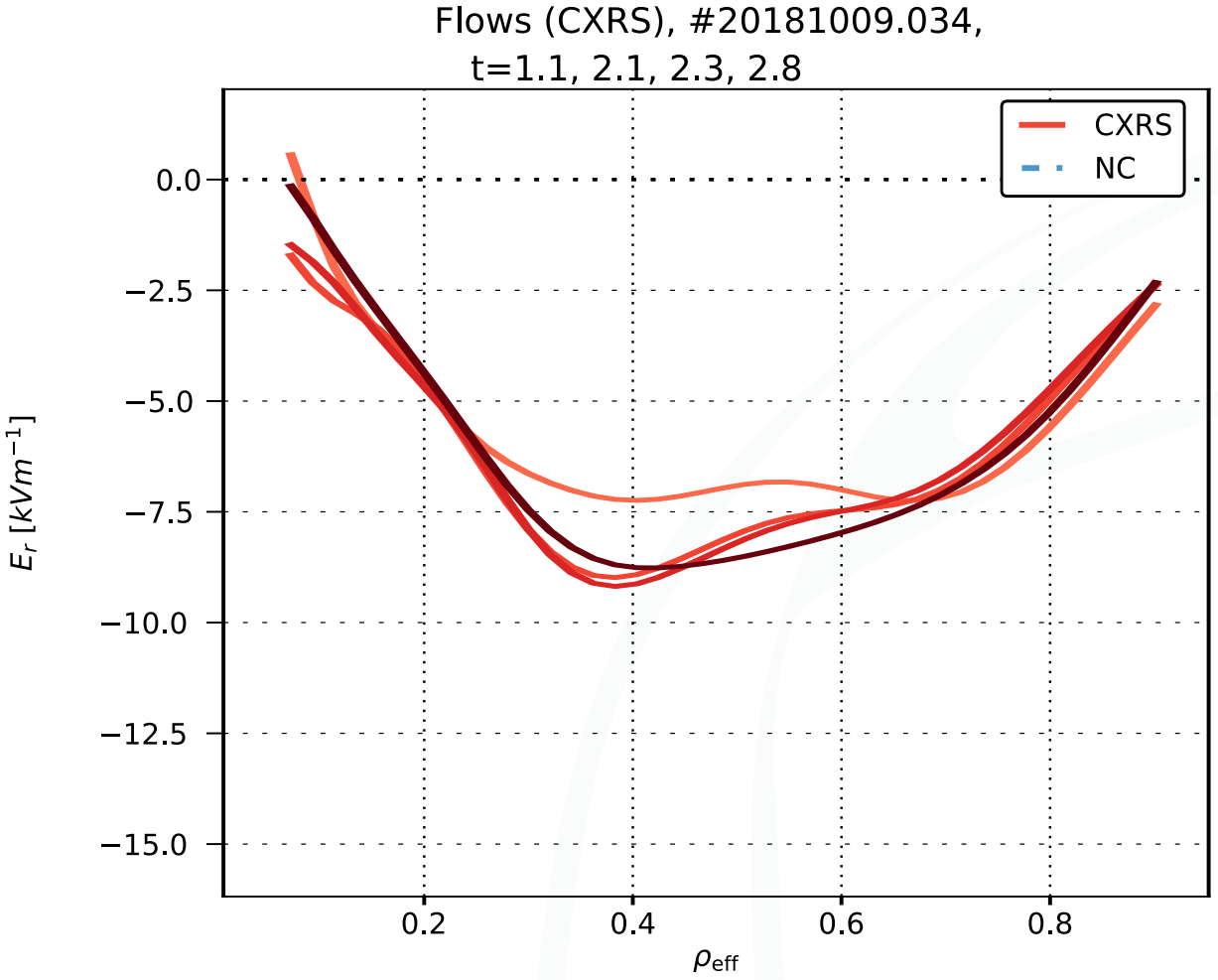

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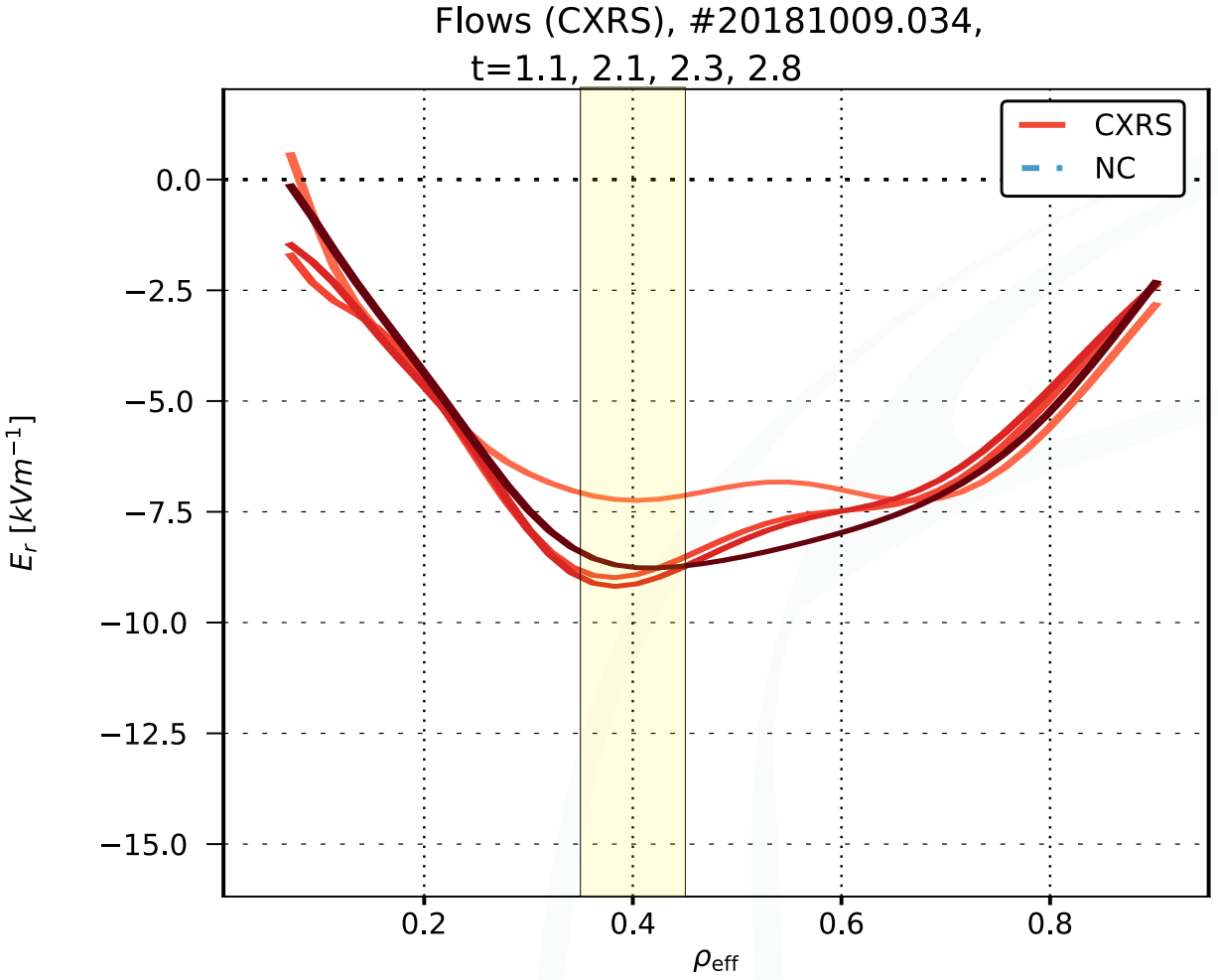
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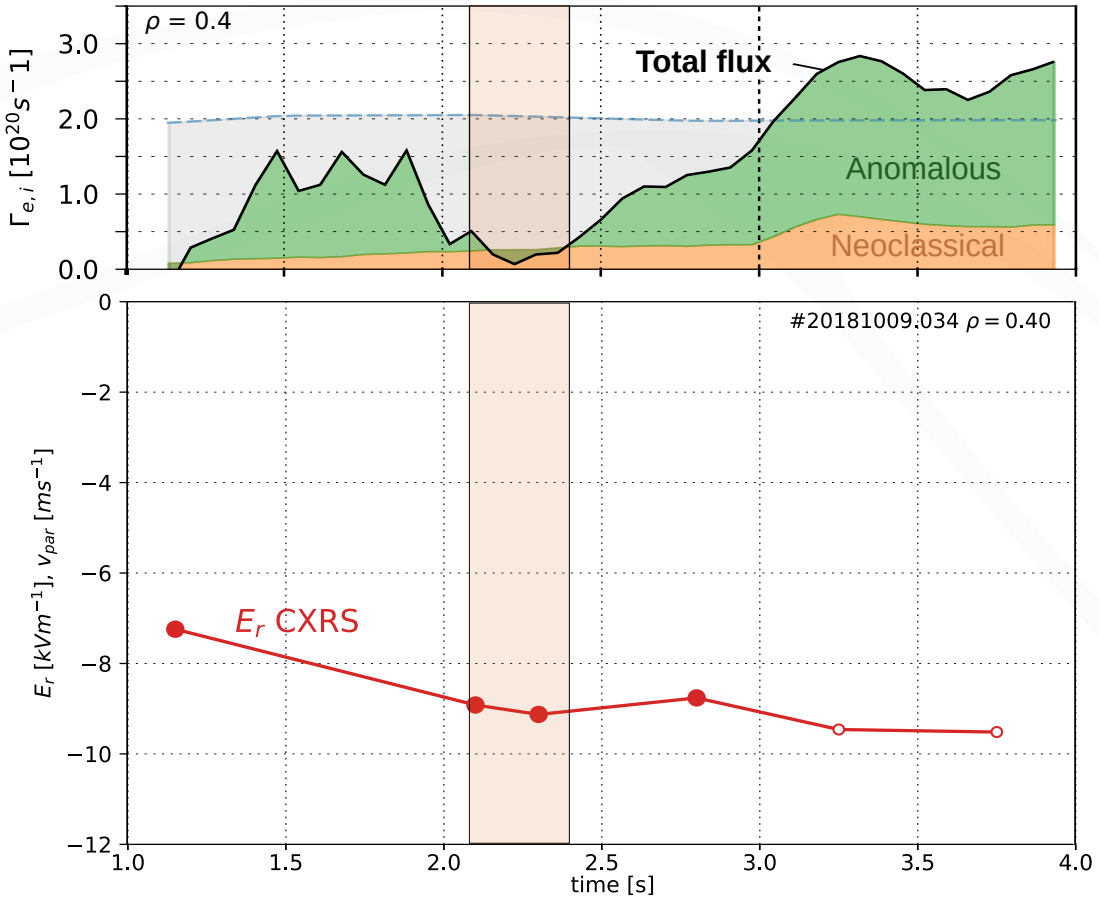
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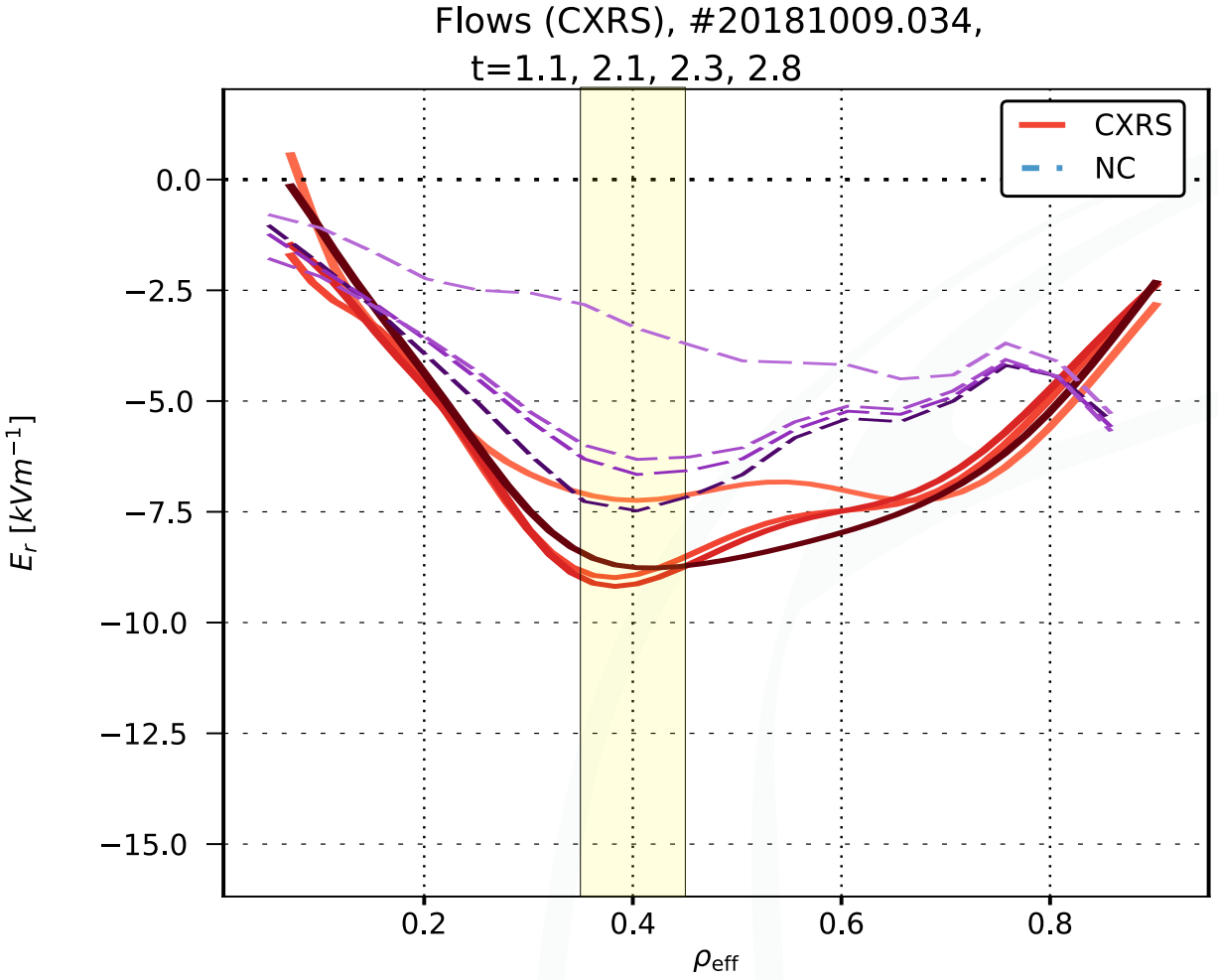
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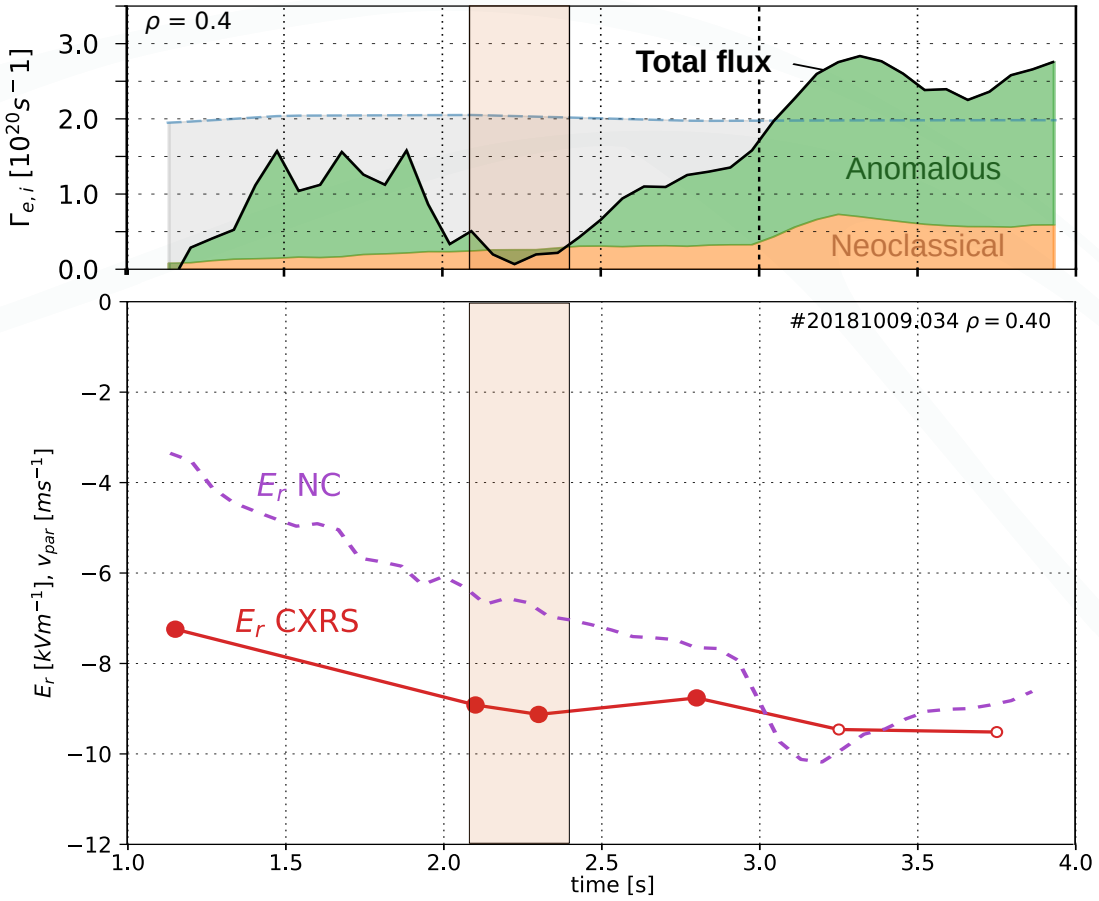


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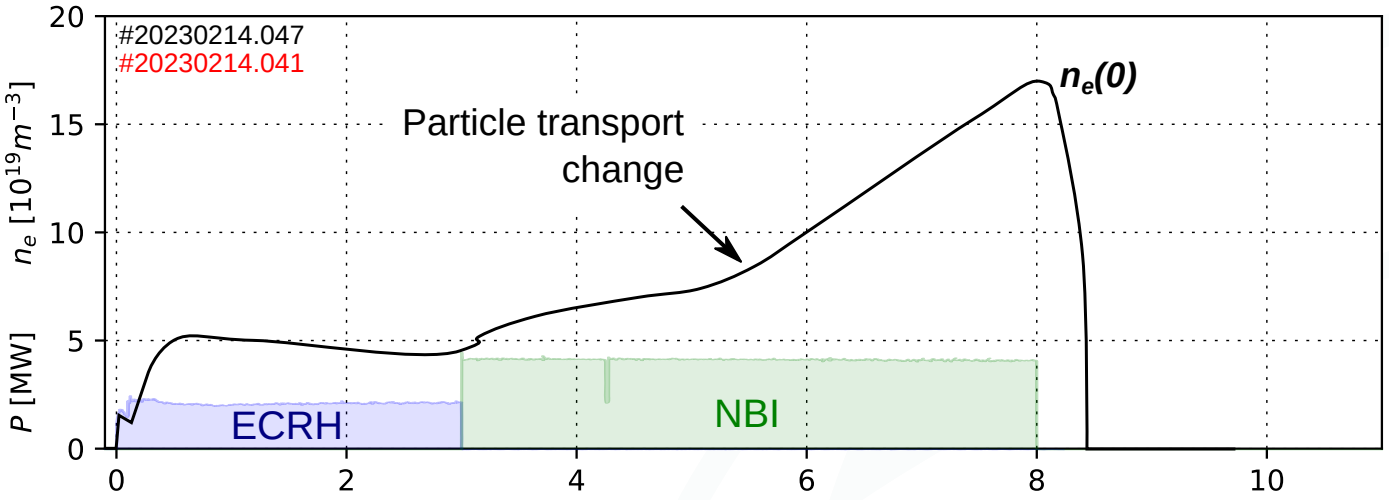


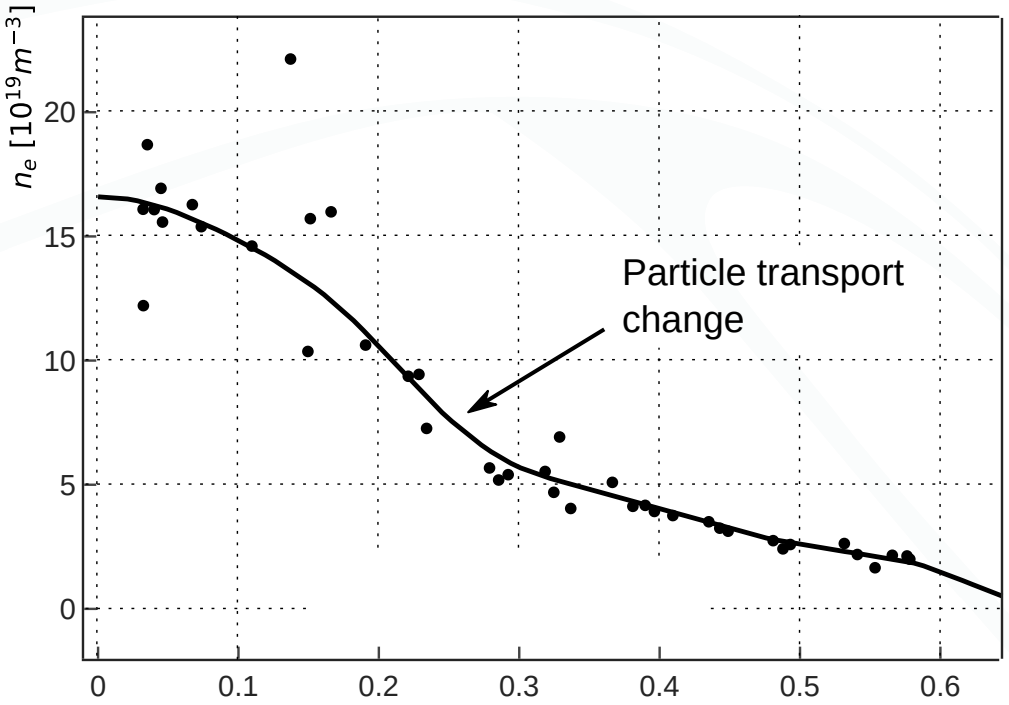



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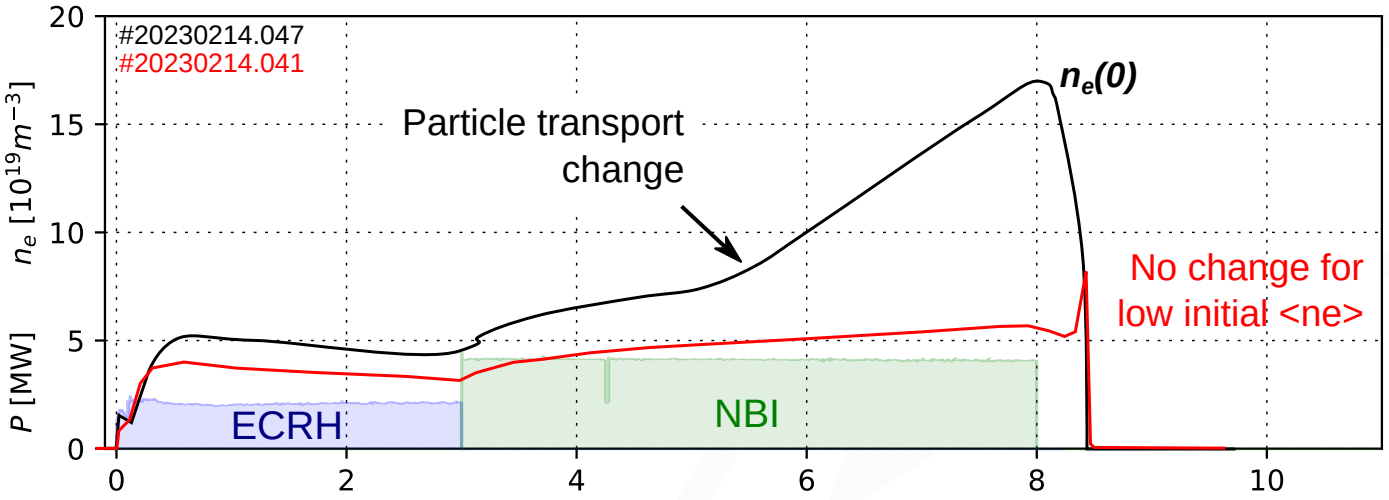


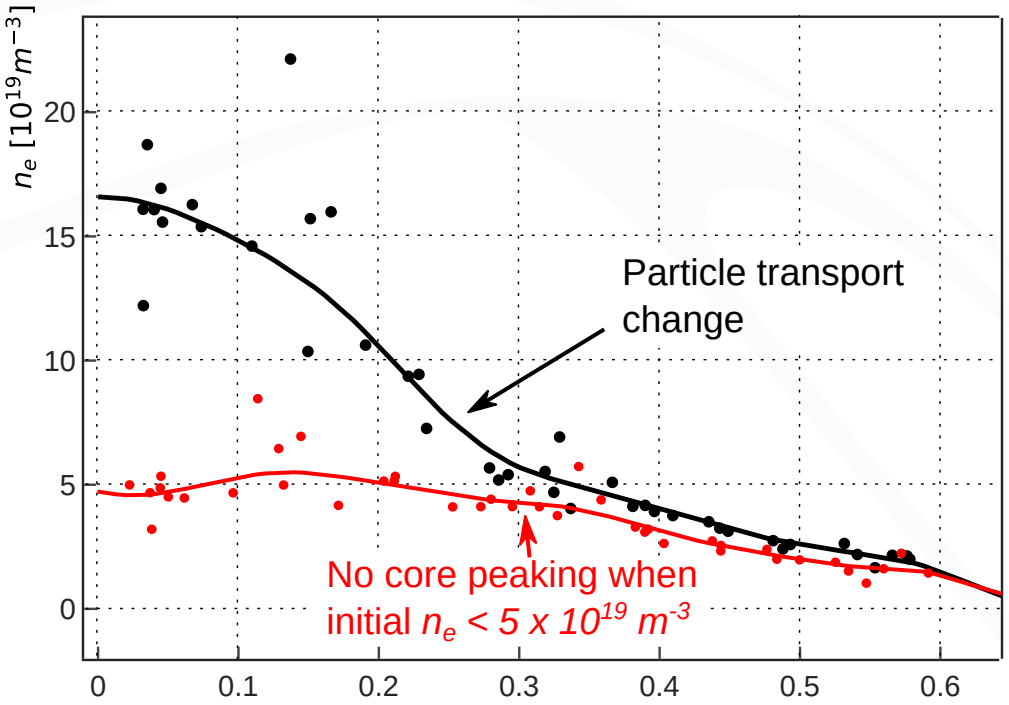



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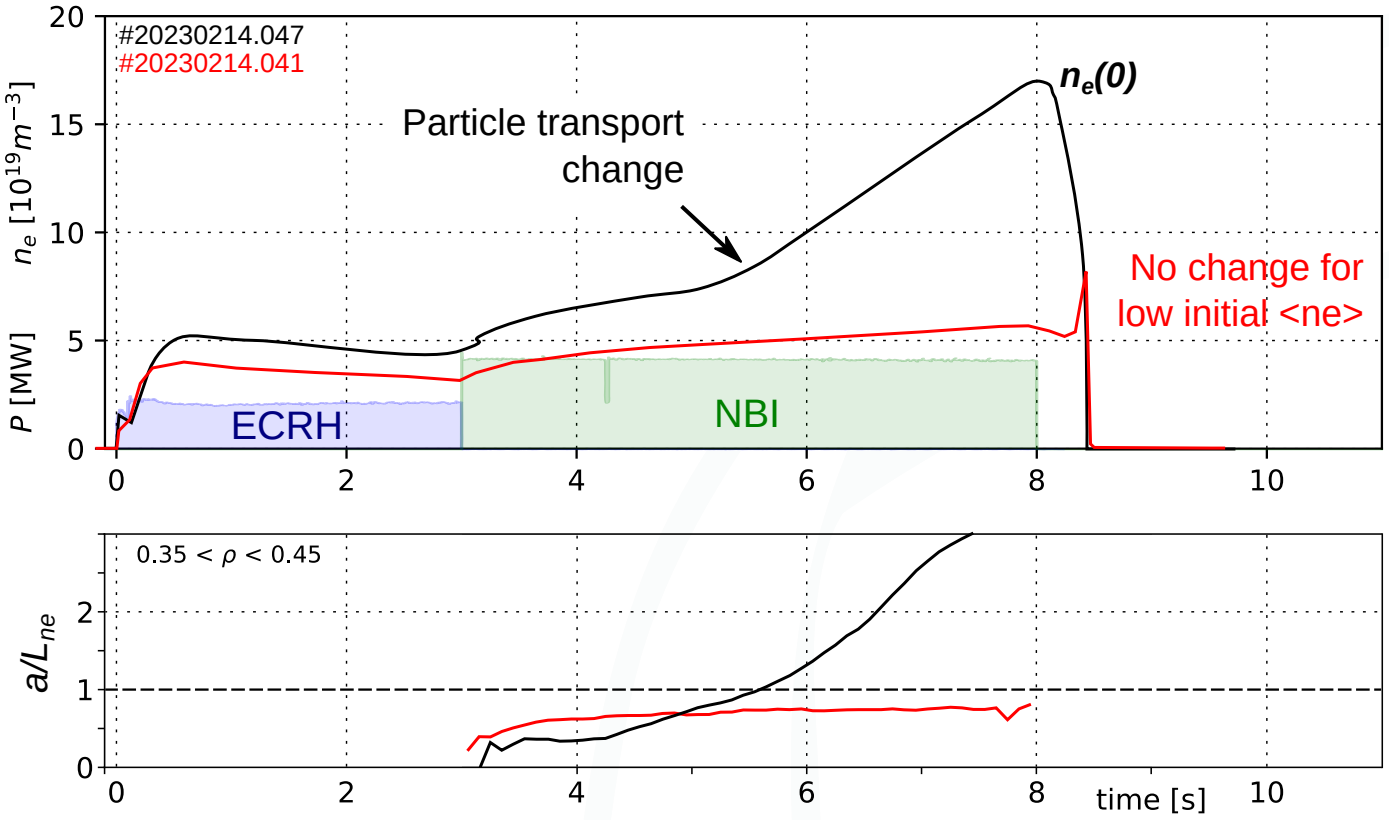


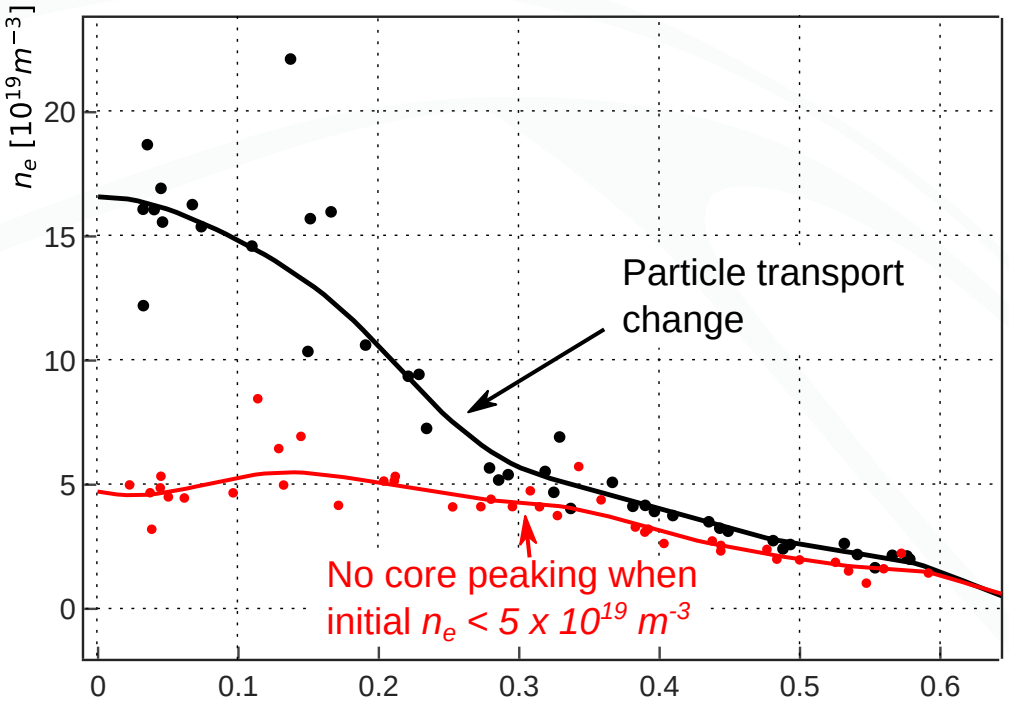



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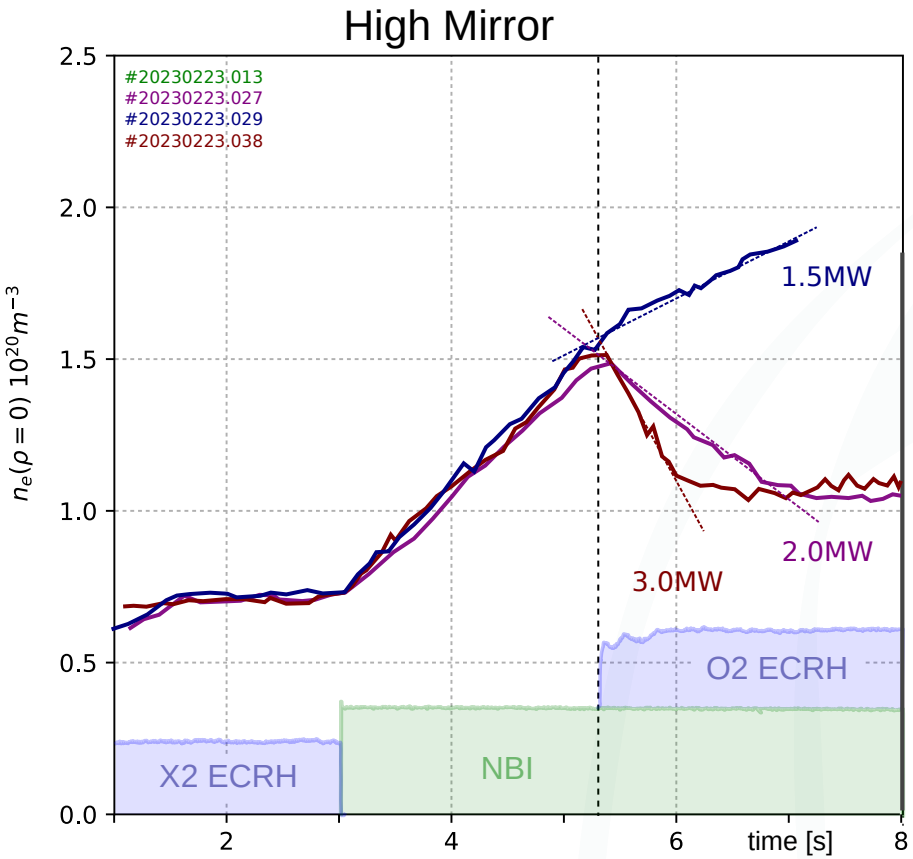


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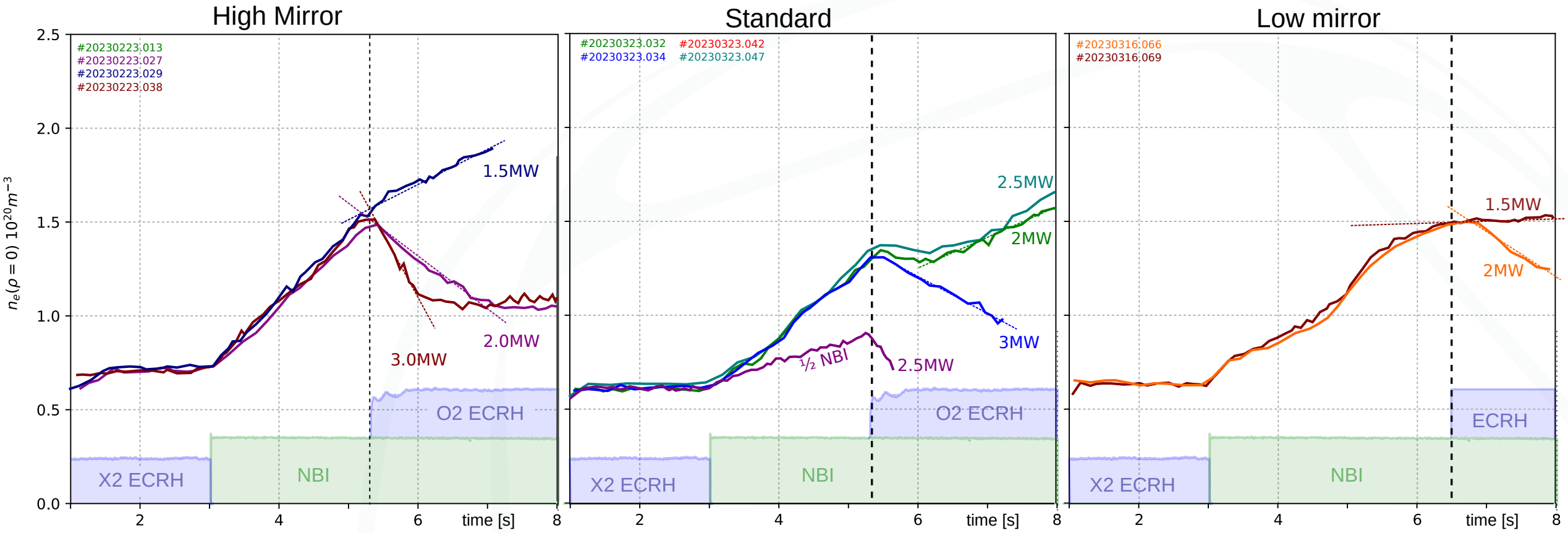


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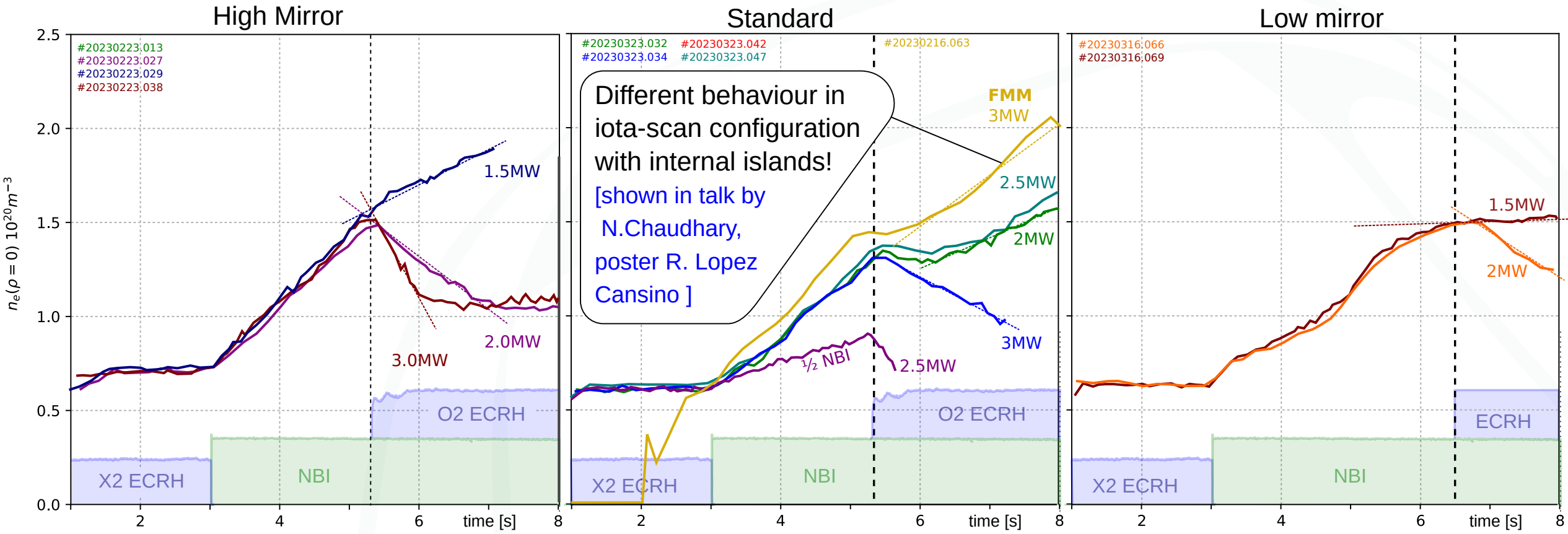


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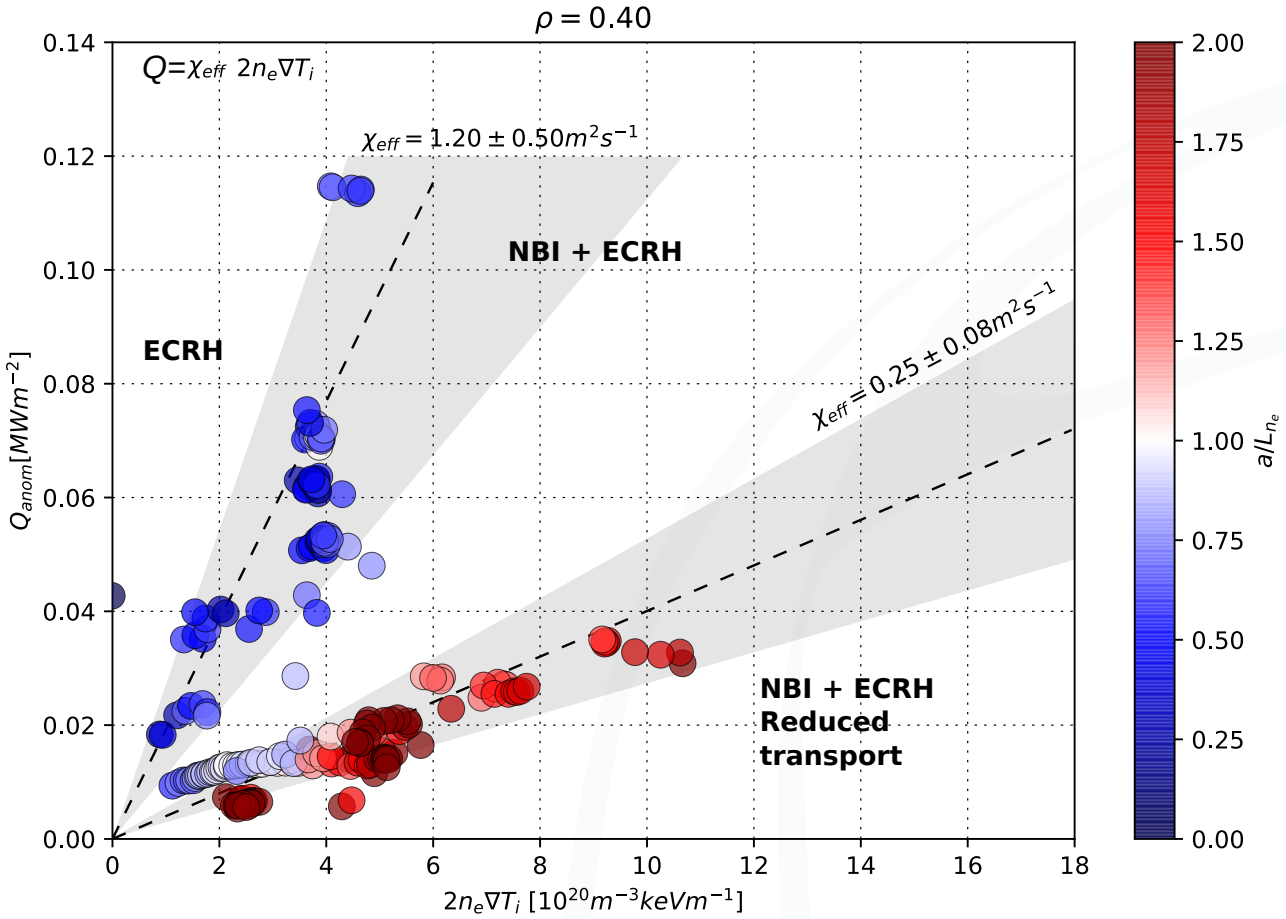
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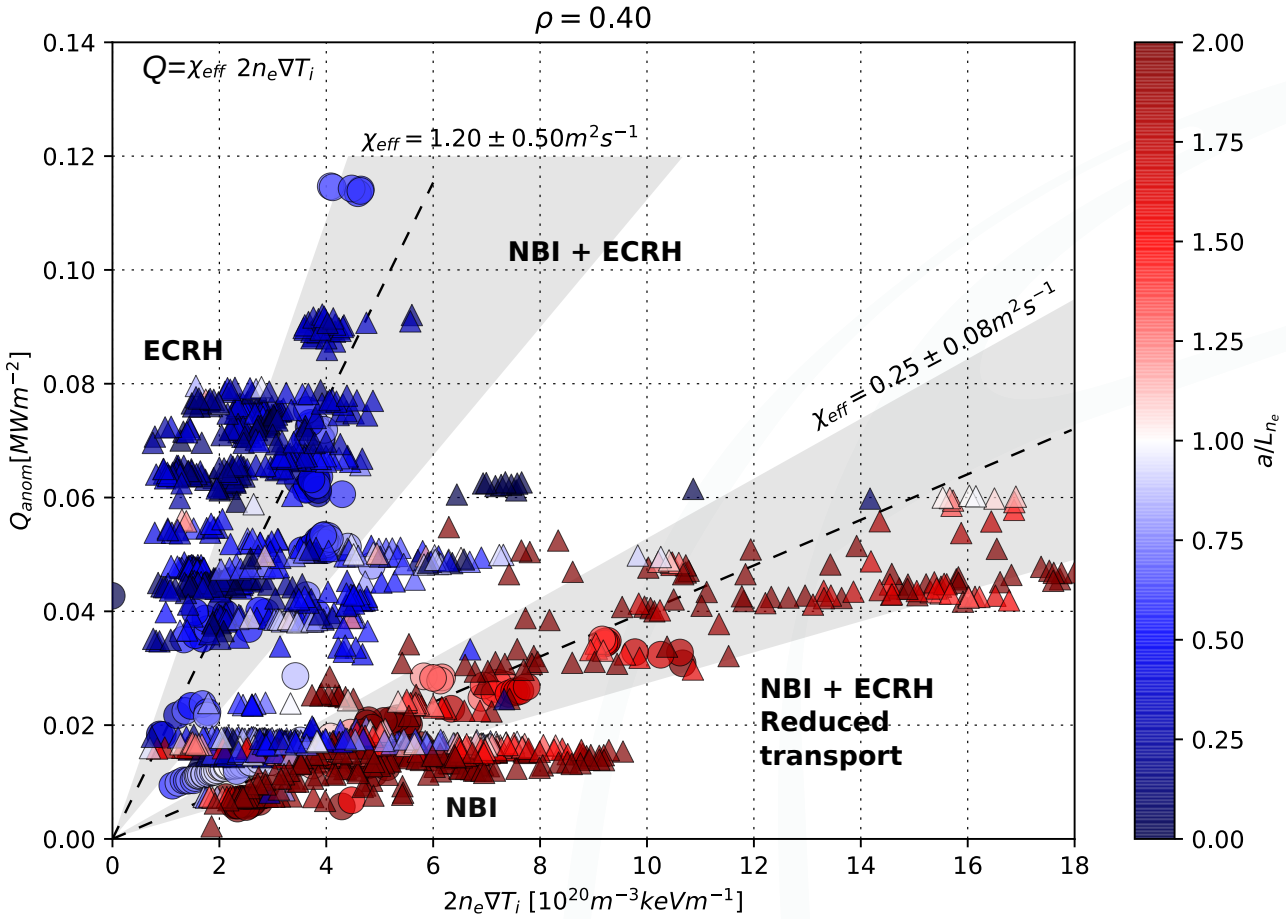
# Balancing ECRH power

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



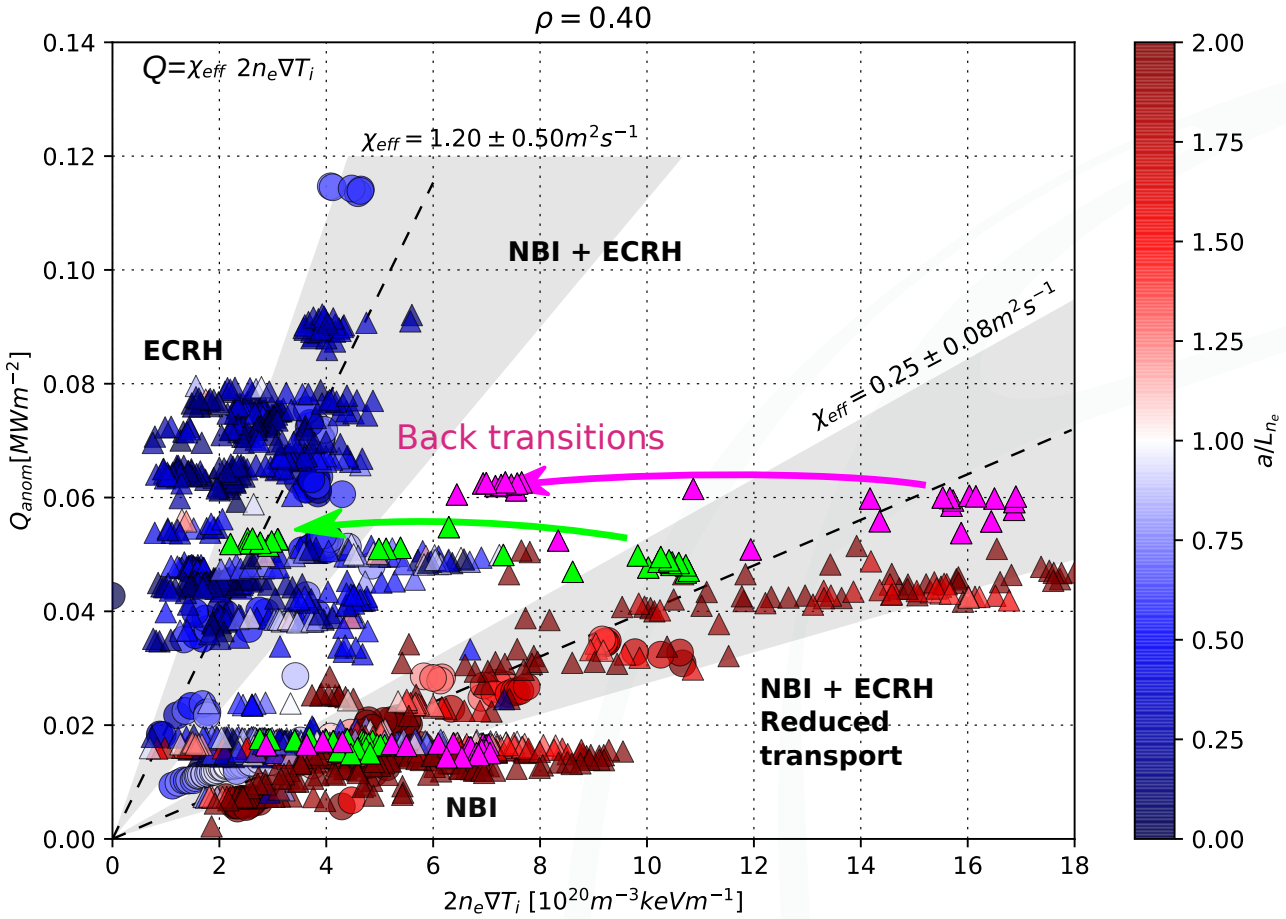
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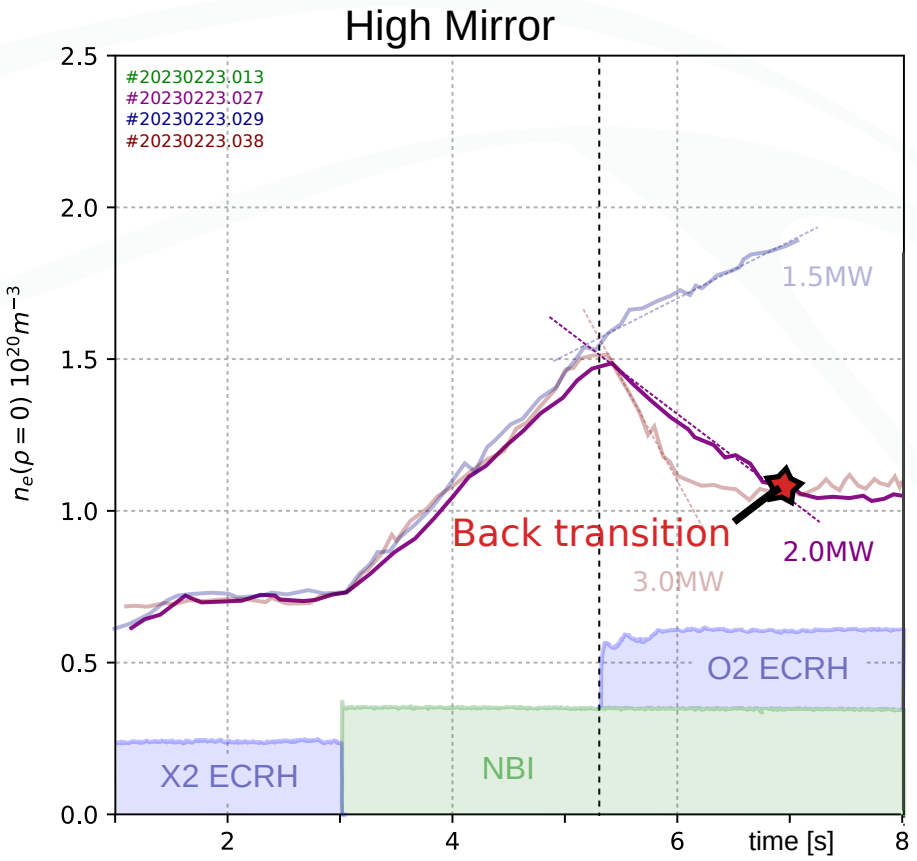
2023 experiments pushed to higher ECRH power to take advantage of reduced heat diffusivity
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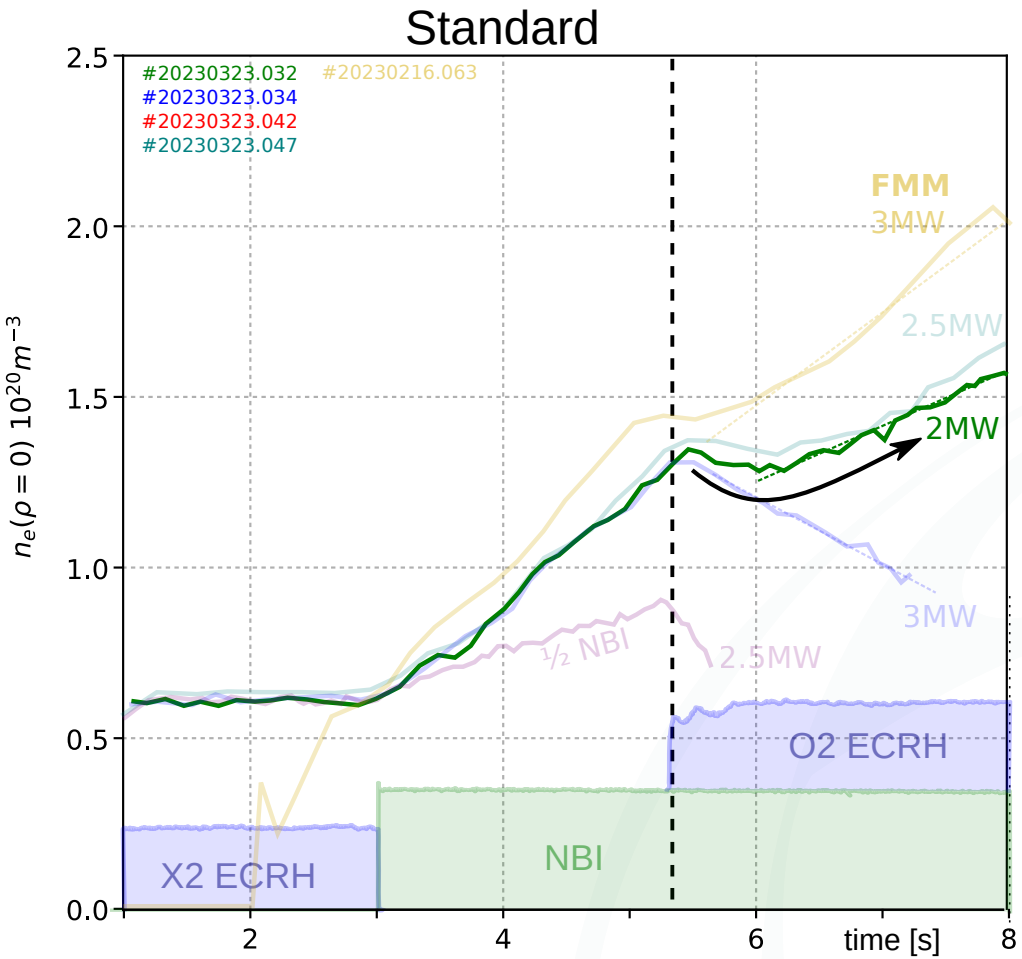
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2023 experiments pushed to higher ECRH power to take advantage of reduced heat diffusivity
- $\chi_{eff}$ ~ 0.25 $m^2s^{-1}$ maintained despite x2 higher $Q_{anom}$. (as high as some turbulent ECRH-only shots)
- Spontaneous back-transition to high transport observed as ECRH reduces density gradient.



# ECRH control




Challenge: Needs to carefully control of ECRH level:

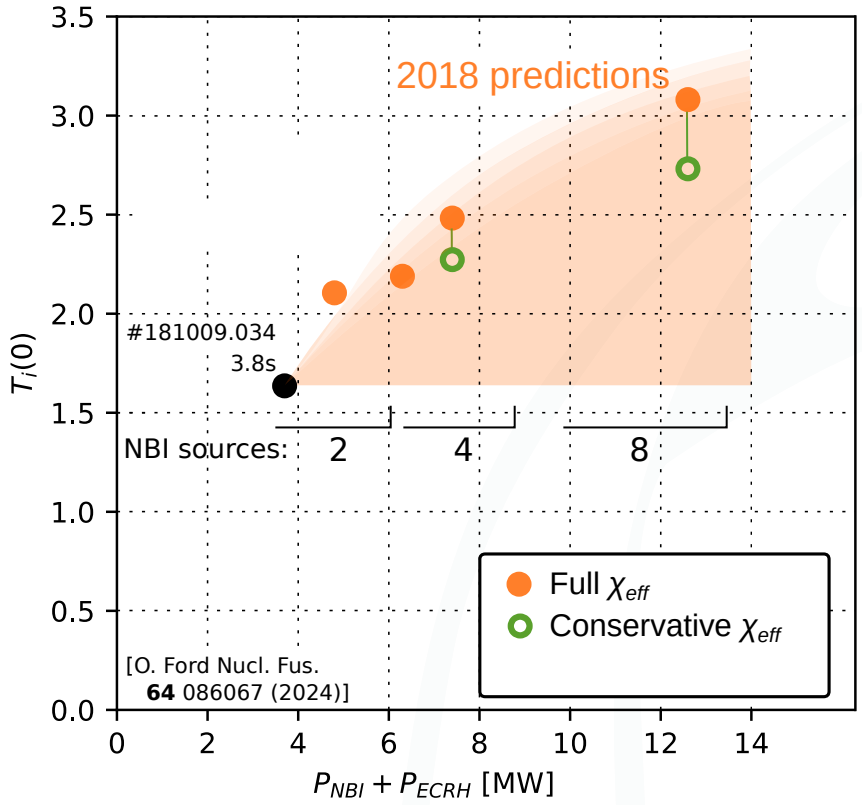
- Too much --> Loss of density gradient
--> back-transition

- Too little --> Too high density, low P/n, impurity accumulation
--> radiation collapse.

For feedback control we would need real-time electron density profile and real-time control of ECRH power.

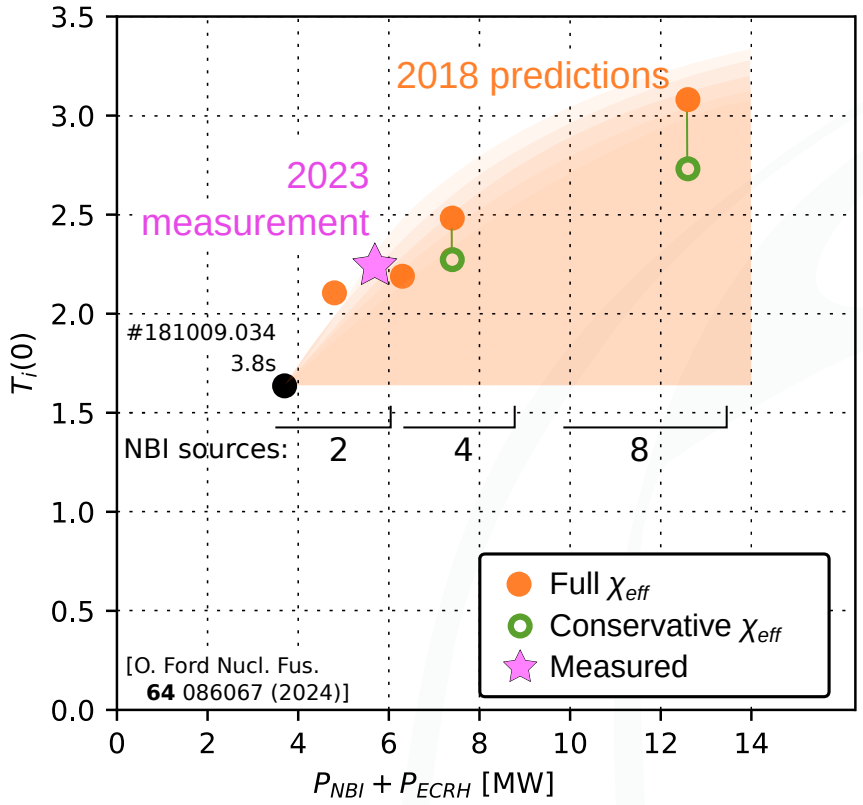
# Achieved performance

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



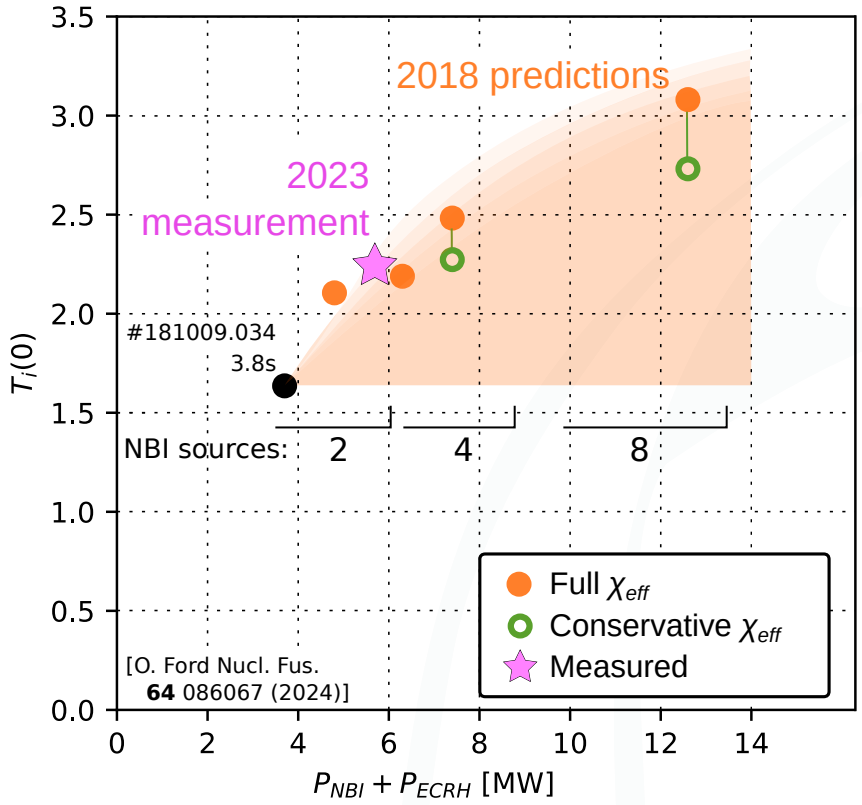
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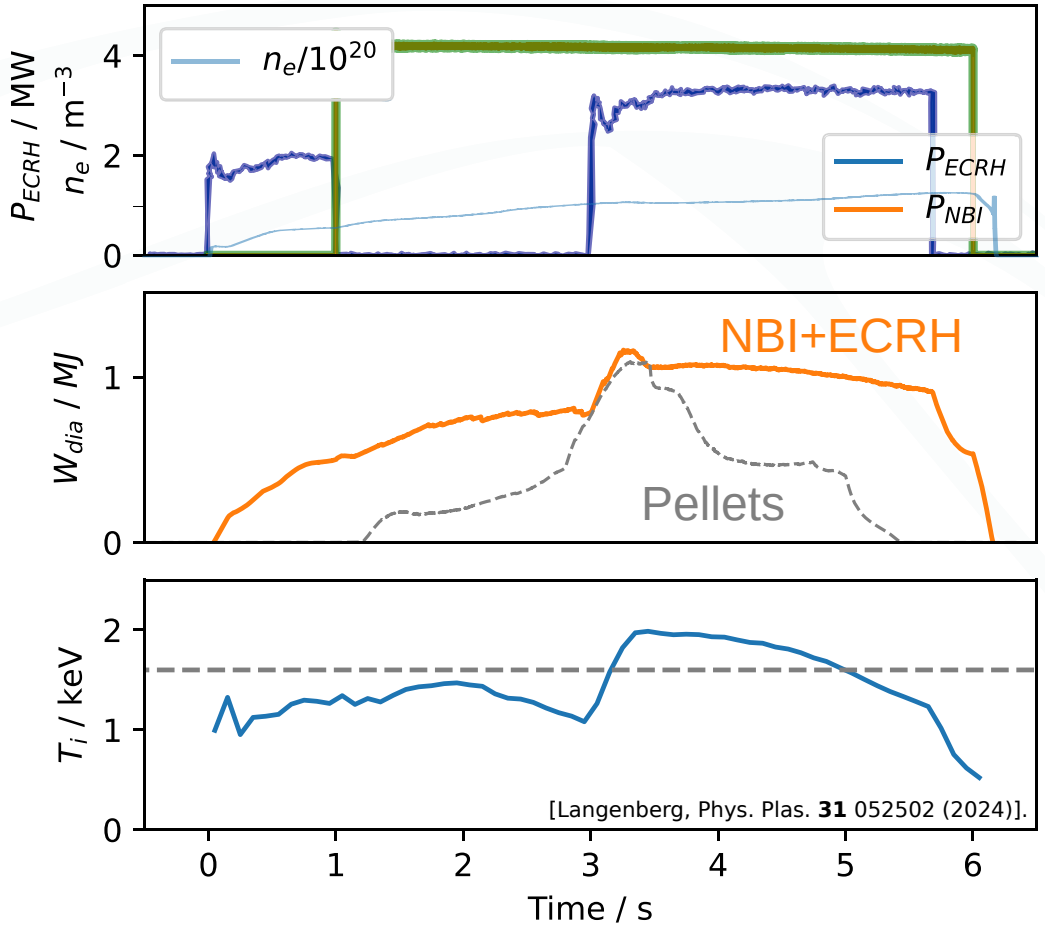
- Predictions made from 2018 data using transport simulation (NTSS) - First point matched in 2023!



# Achieved performance

- Predictions made from 2018 data using transport simulation (NTSS) - First point matched in 2023!
- Highest ECRH power in FMM configuration still does not 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 scenarios 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 when $a/L_{ne} > 1$.

- $D_{anom}$ of main ions drops spontaneously at $a/L_{ne} \sim 1.3$ 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 $a/L_n$.

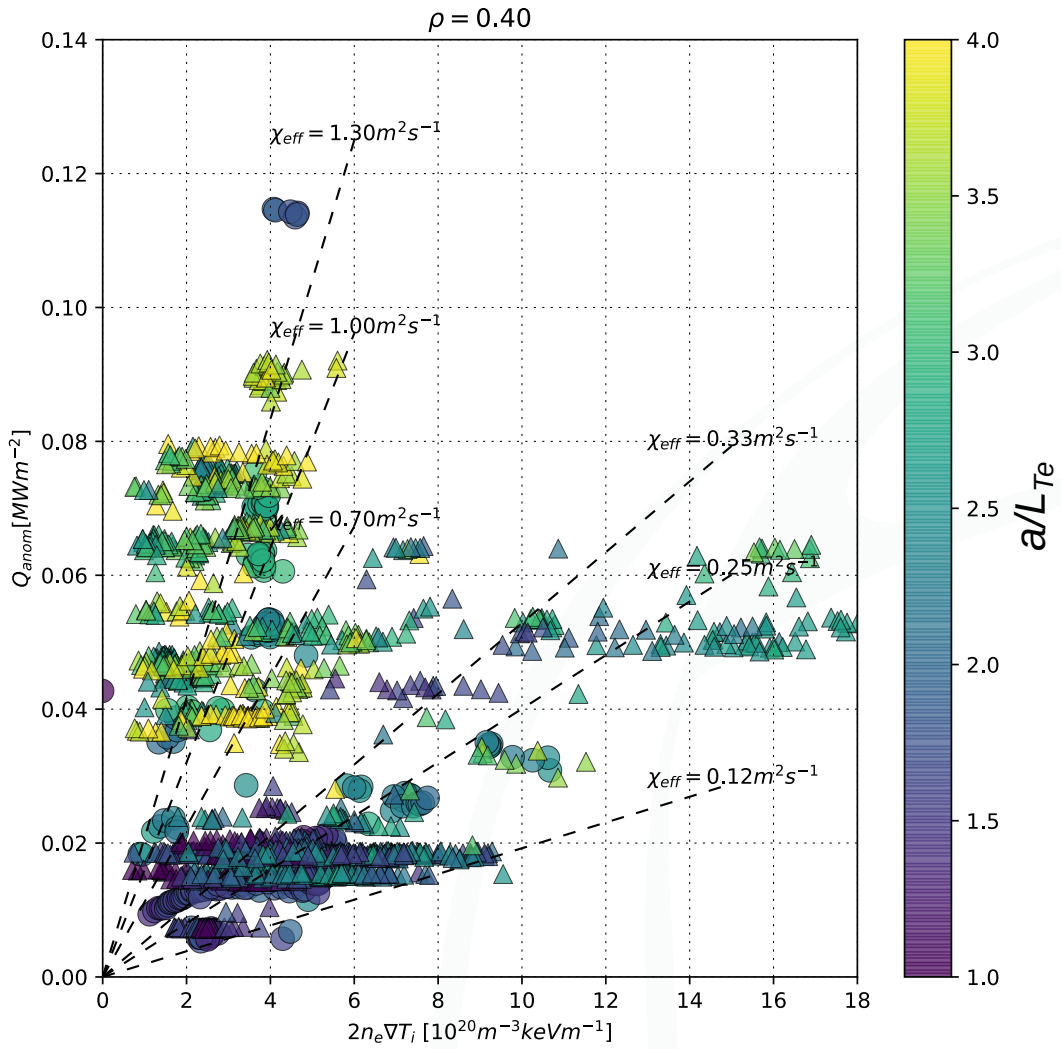
- Reintroduction scenario reproduced and refined in 2023 expeiments.
  - Extend to ECRH power, giving higher $\nabla T_i$ and core $T_i$ well above 1.5 keV.
  - Density pump-out by too-high ECRH leads to back-transition to high $\chi_{eff}$.
  - NTSS simulations of predicted doubling of ECRH power well matched by experiment.
  - Record level of stored energy (marginally above pellets experiments) held for > 2s.

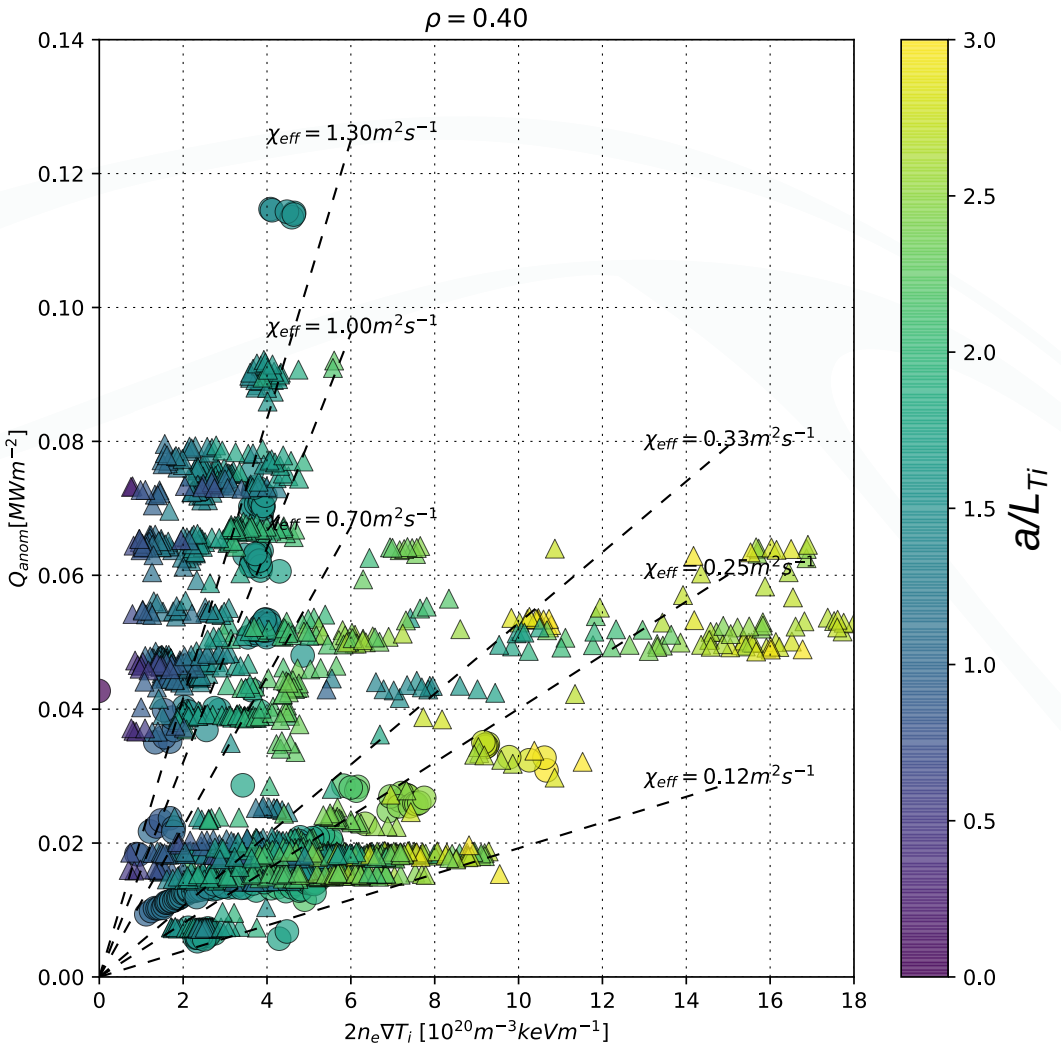
  - Density profile appears to affect transport stronger than magnetic configuration in W7-X

**--> Predicting particle transport critical to performance optimisation.**

# Diffusivity vs temperature gradients

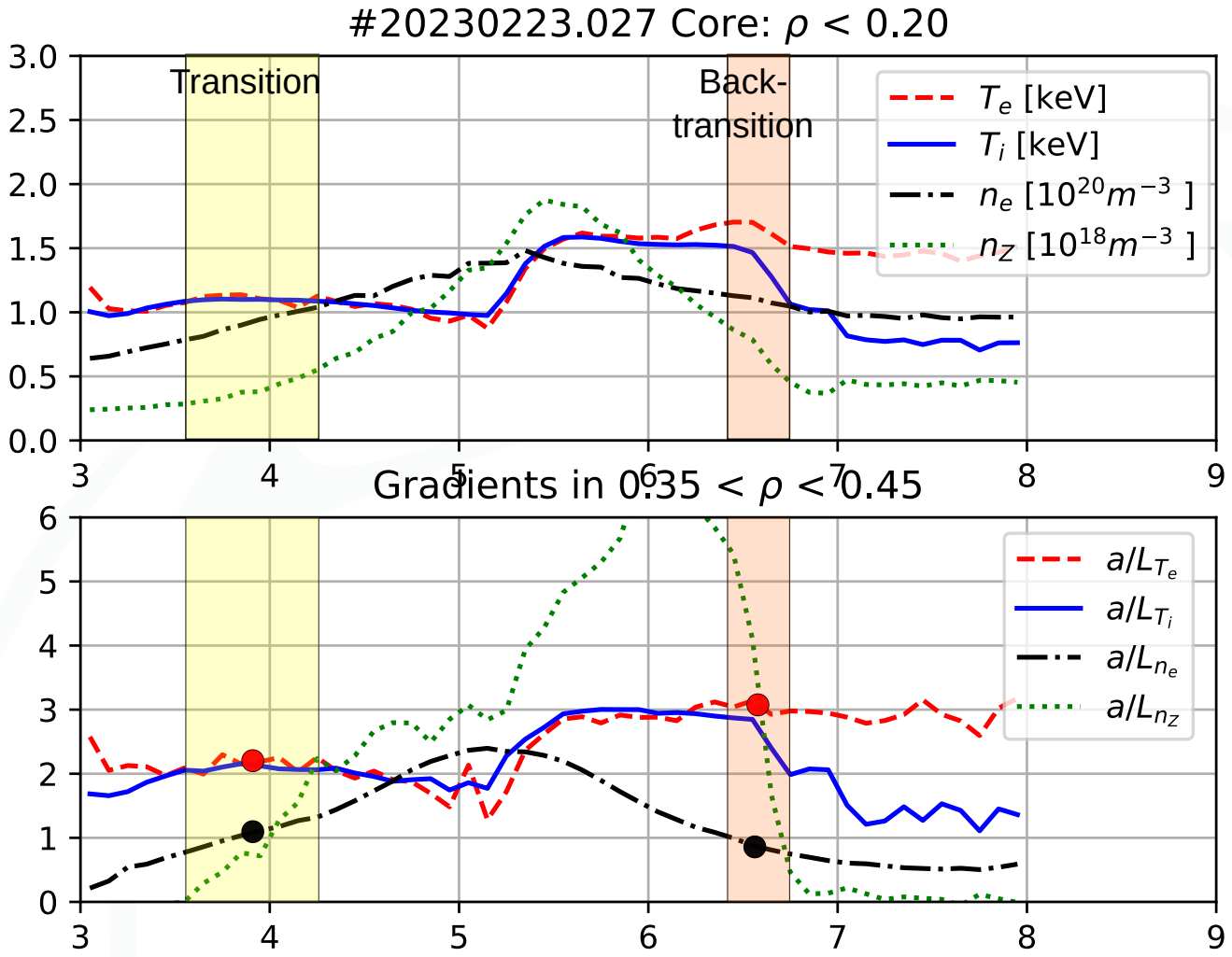
No obvious dependence of $\chi_{eff}$ on $a/L_{Te}$ - at least not clear as $a/L_n$. ($a/L_{T_i}$ is the dependant variable)



# Back transition at different $a/L_T$?

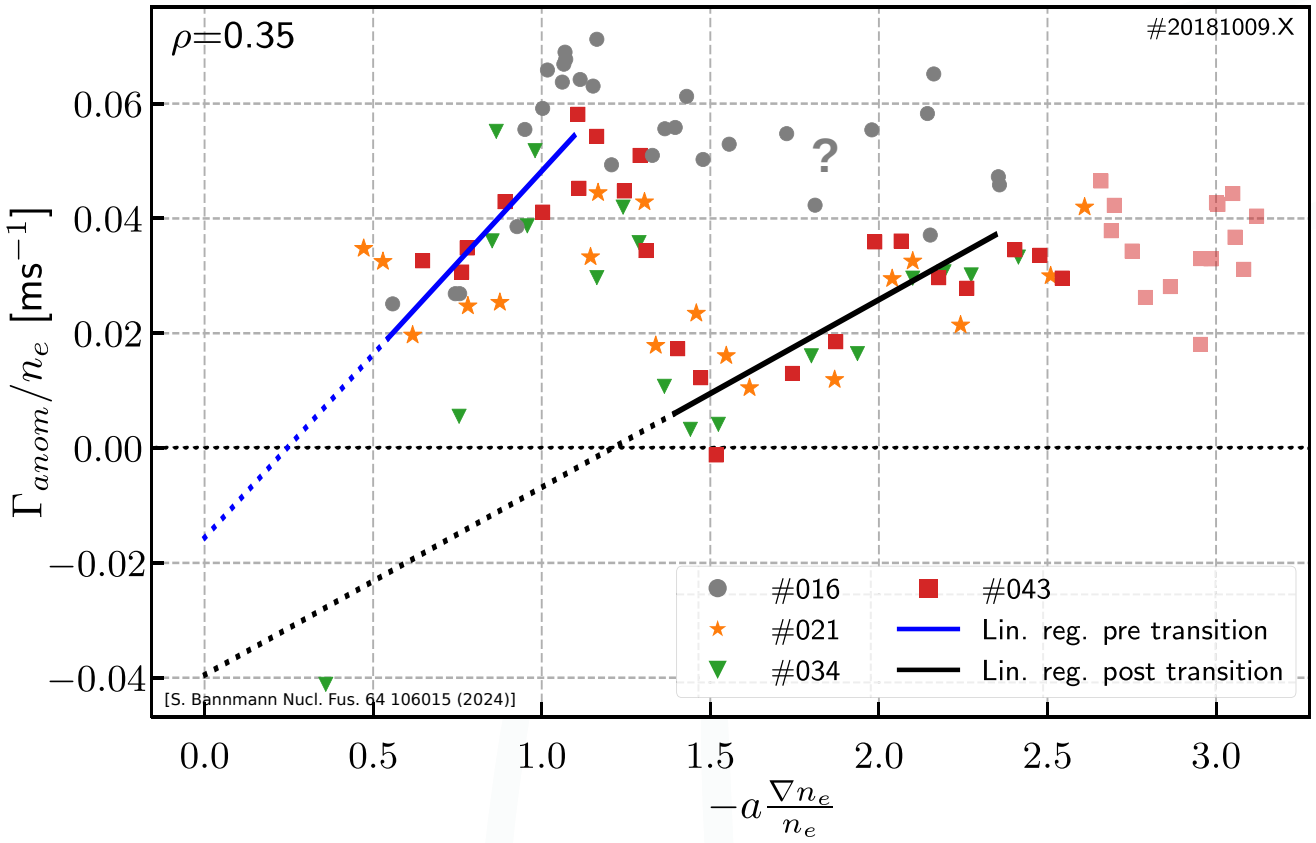
OP2.3 back-transitions allow examination of threshold location in a/LT vs a/LN space:



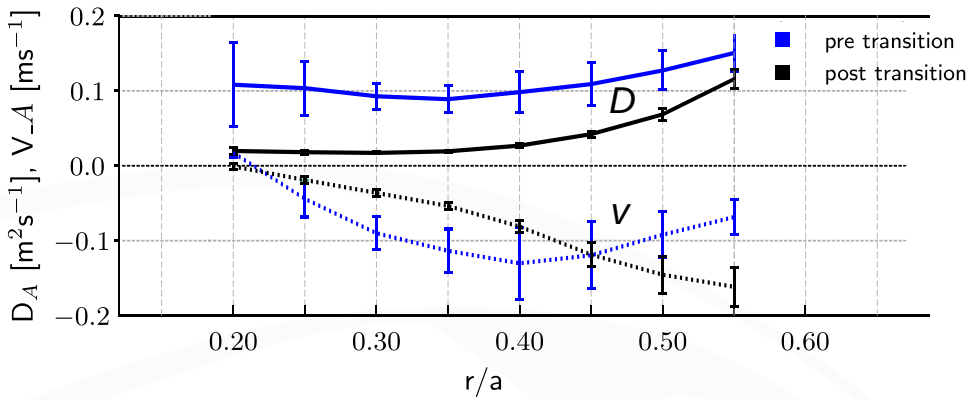
# Pure NBI - Particle transport

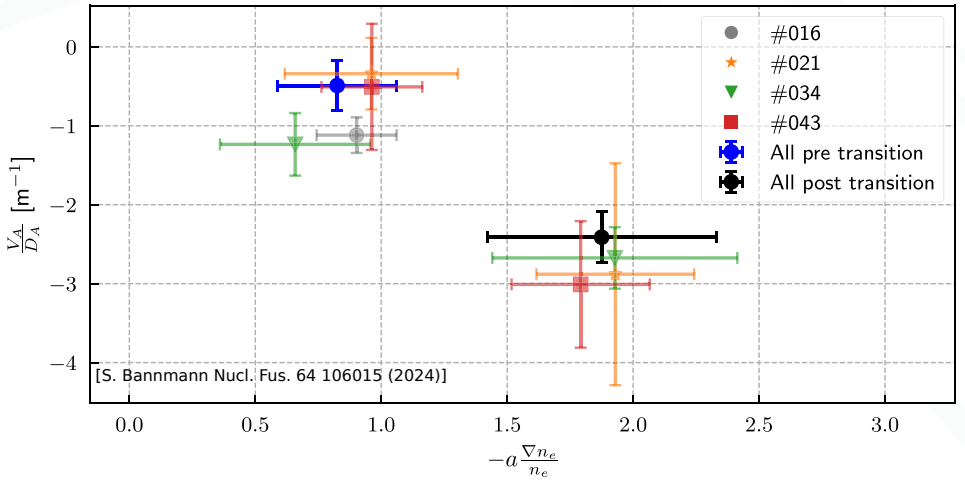
$\nabla n_e$ is changing. What is just an 'expected' reponse to this?
--> Decompose into diffusive $D$ and convective $v$.
- Indicates two phases of ~consistent $v$, $D$, with significant drop of $D$ at $a/L_n$ ~ 1.3.

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




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

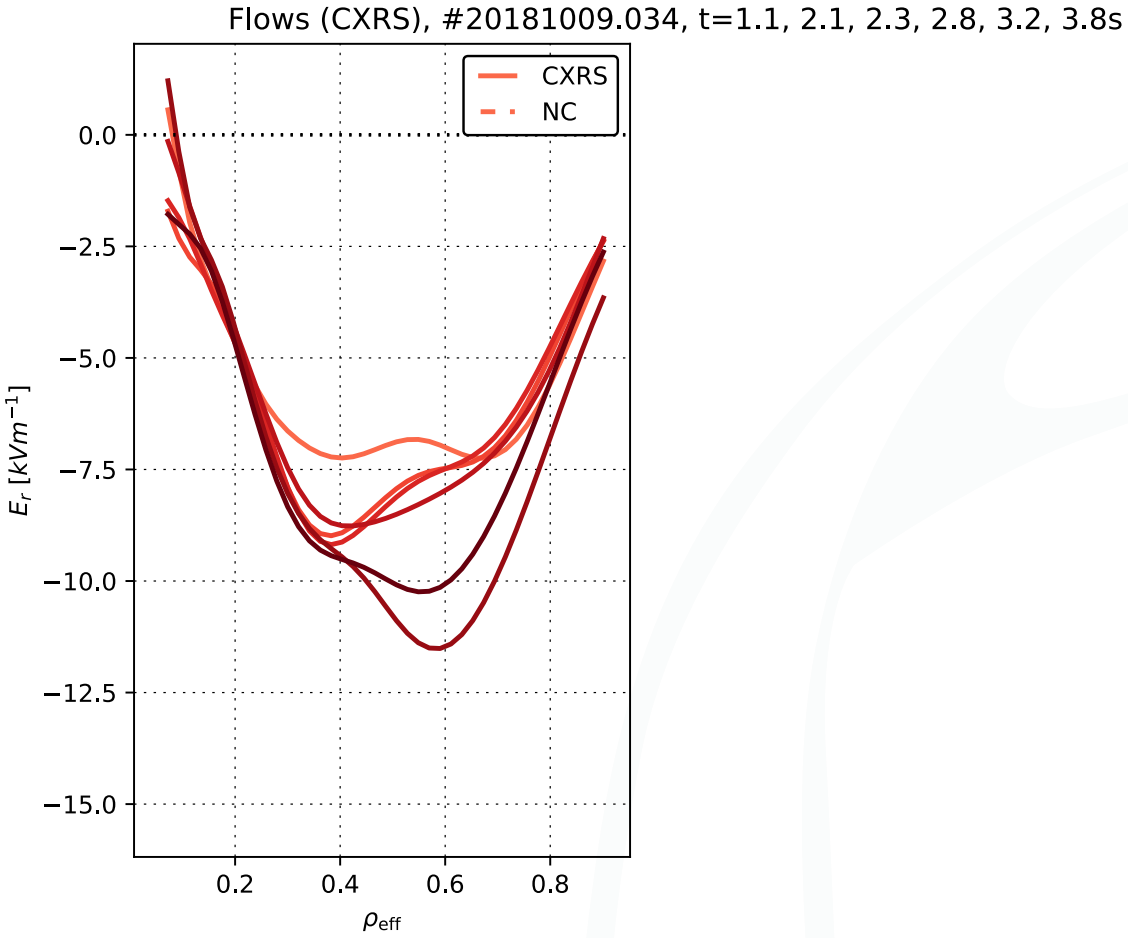



- Threshold not yet reproduced in modelling.
(Range not covered by original STELLA study
[H. Thienpondt, Phys. Rev. Res. 5, L022053 (2023)])

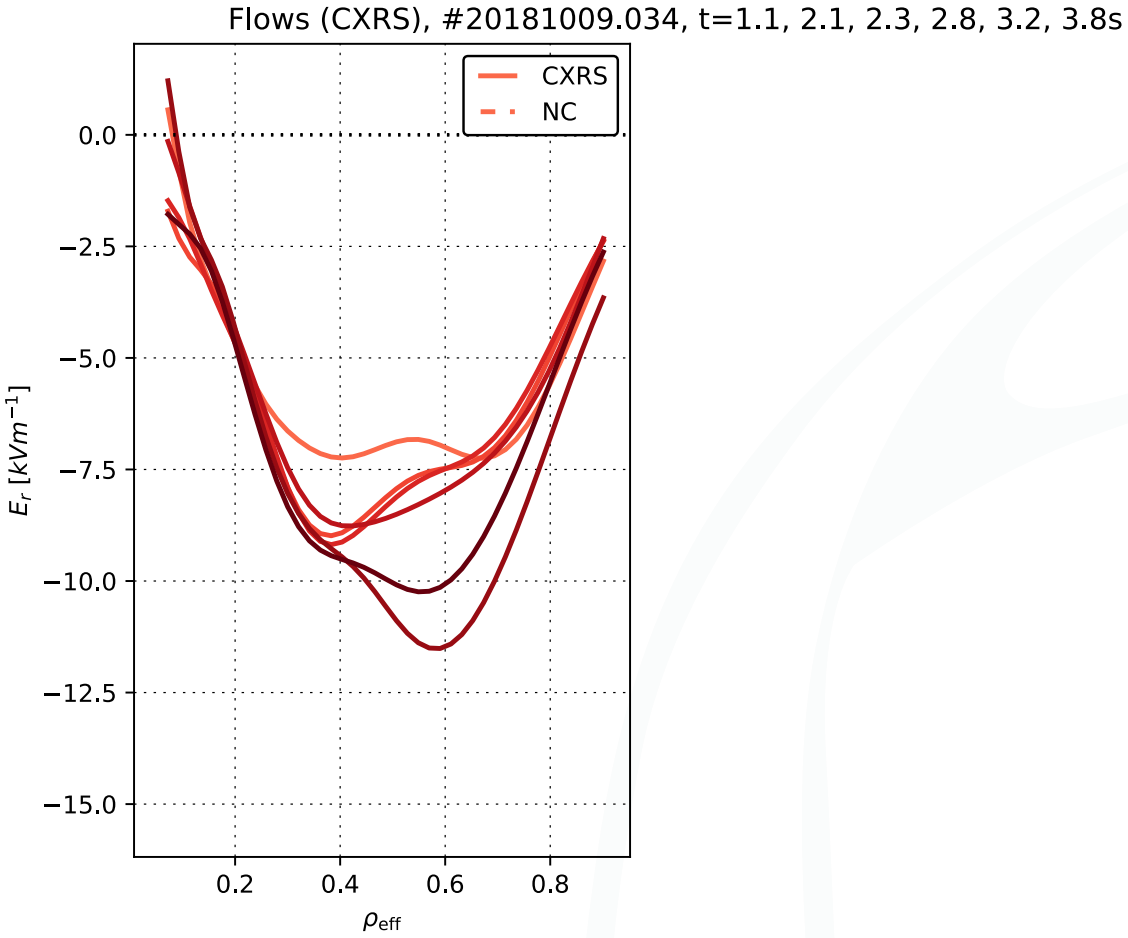
# Pure NBI - Radial Electric Field

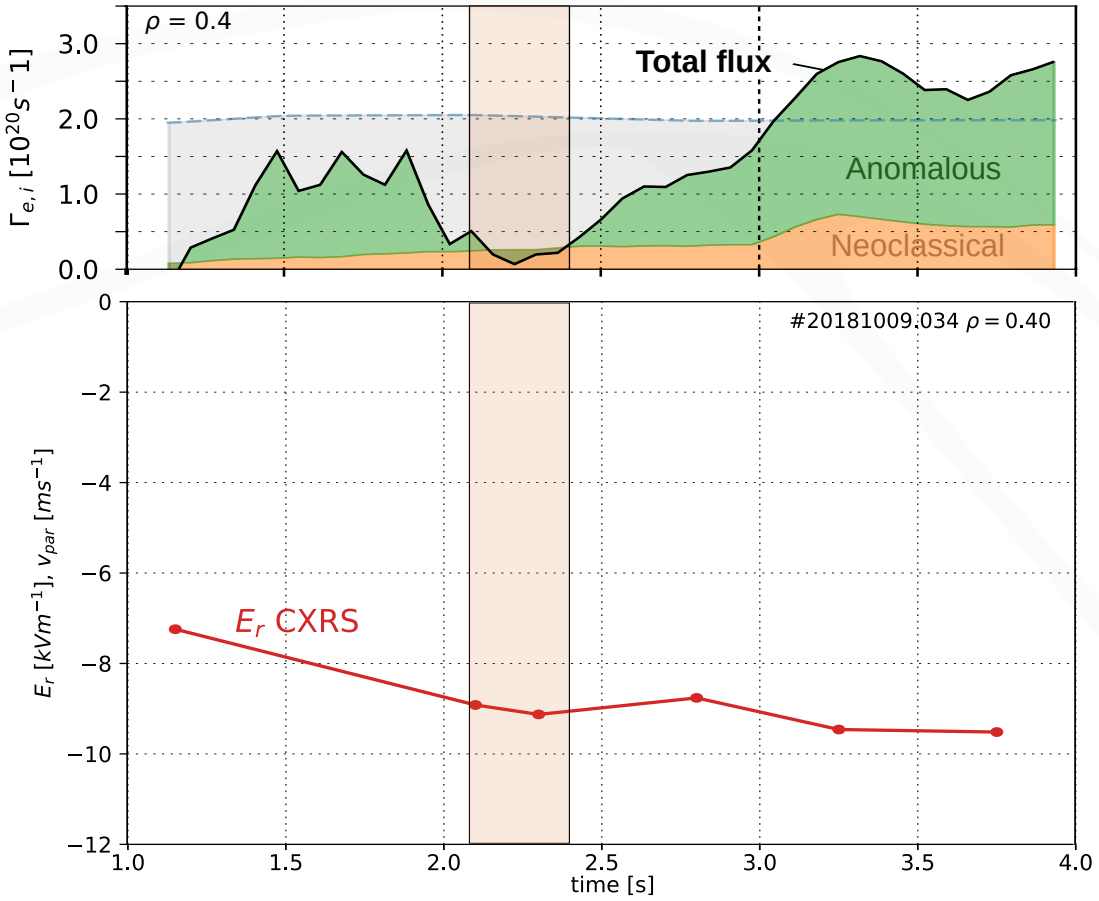
- $E_r$ or Er can affect anomalous transport and often changes strongly in W7-X. e.g. Ion vs Electorn root.
- NBI discharges all ion root with no significant $E_r$ changes at onset time (measured or NC)



# portPure NBI - Radial Electric Field

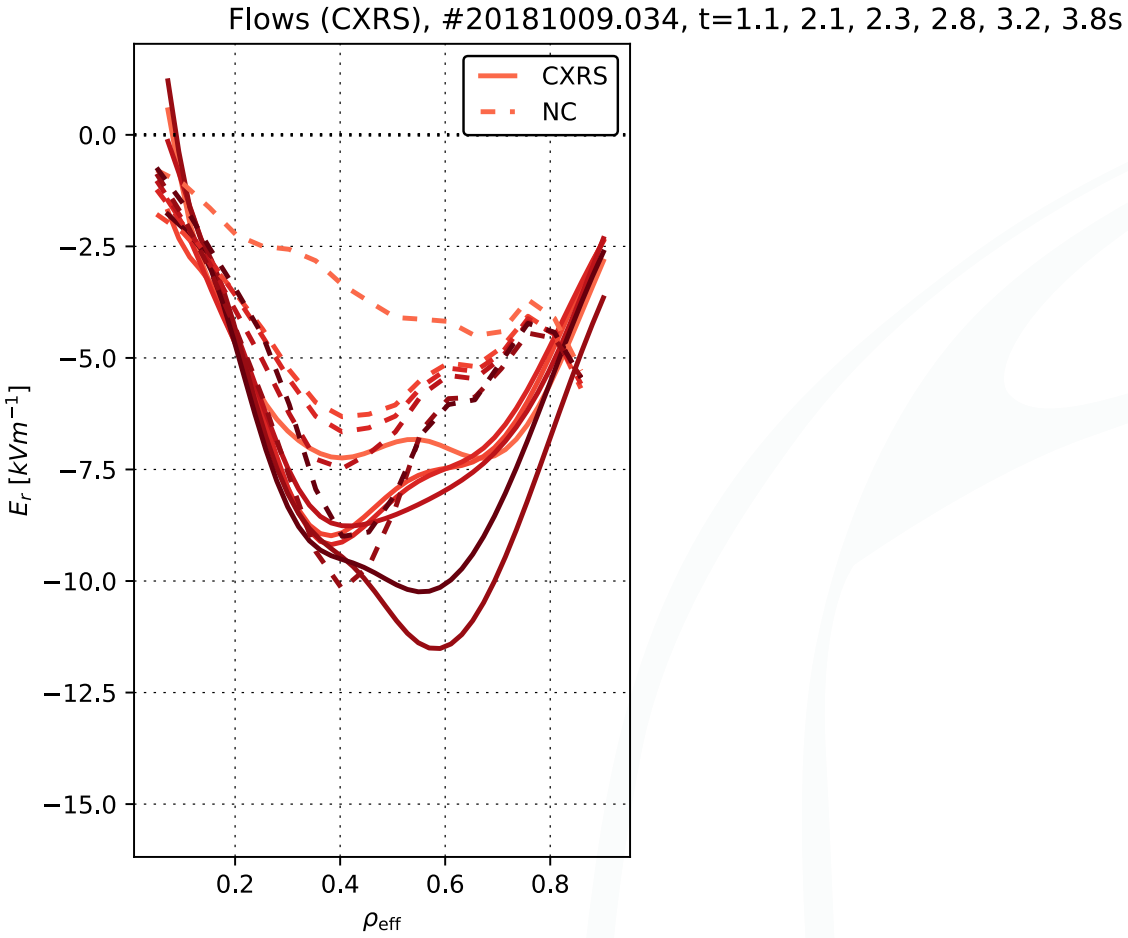
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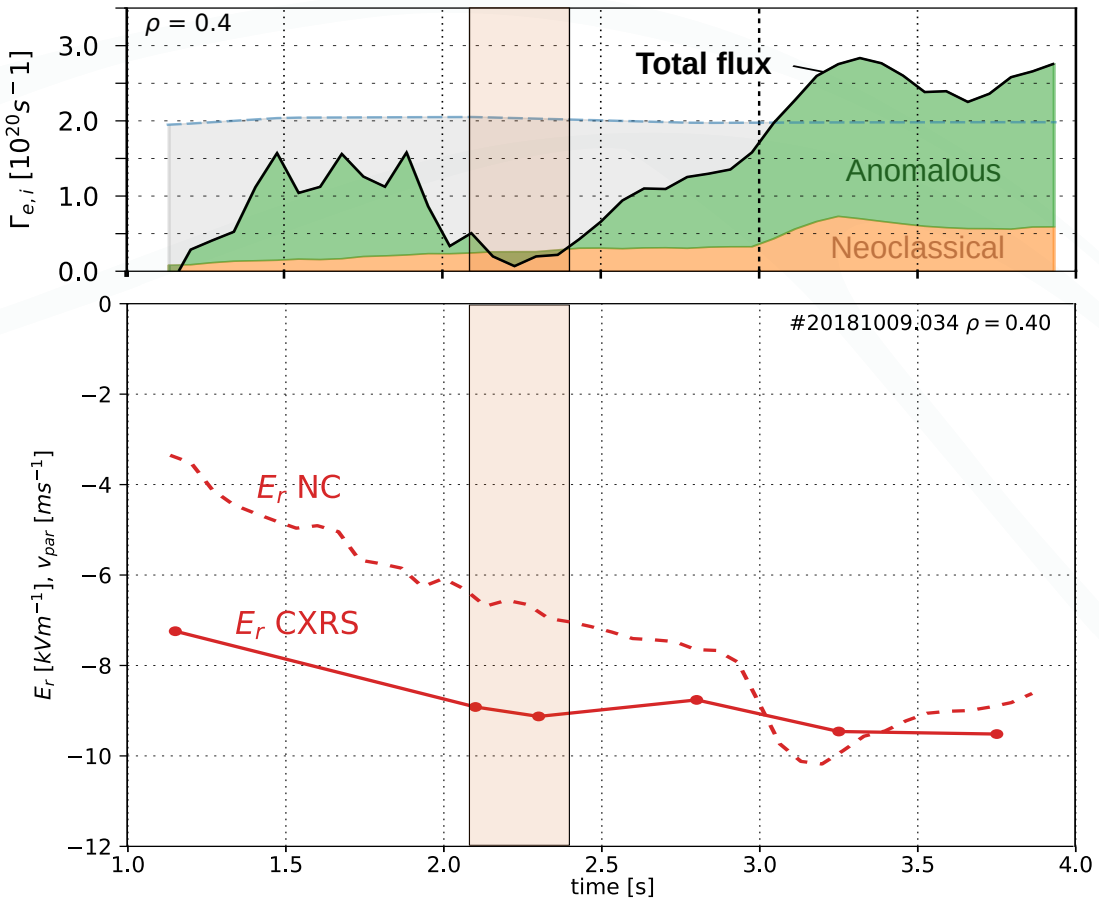


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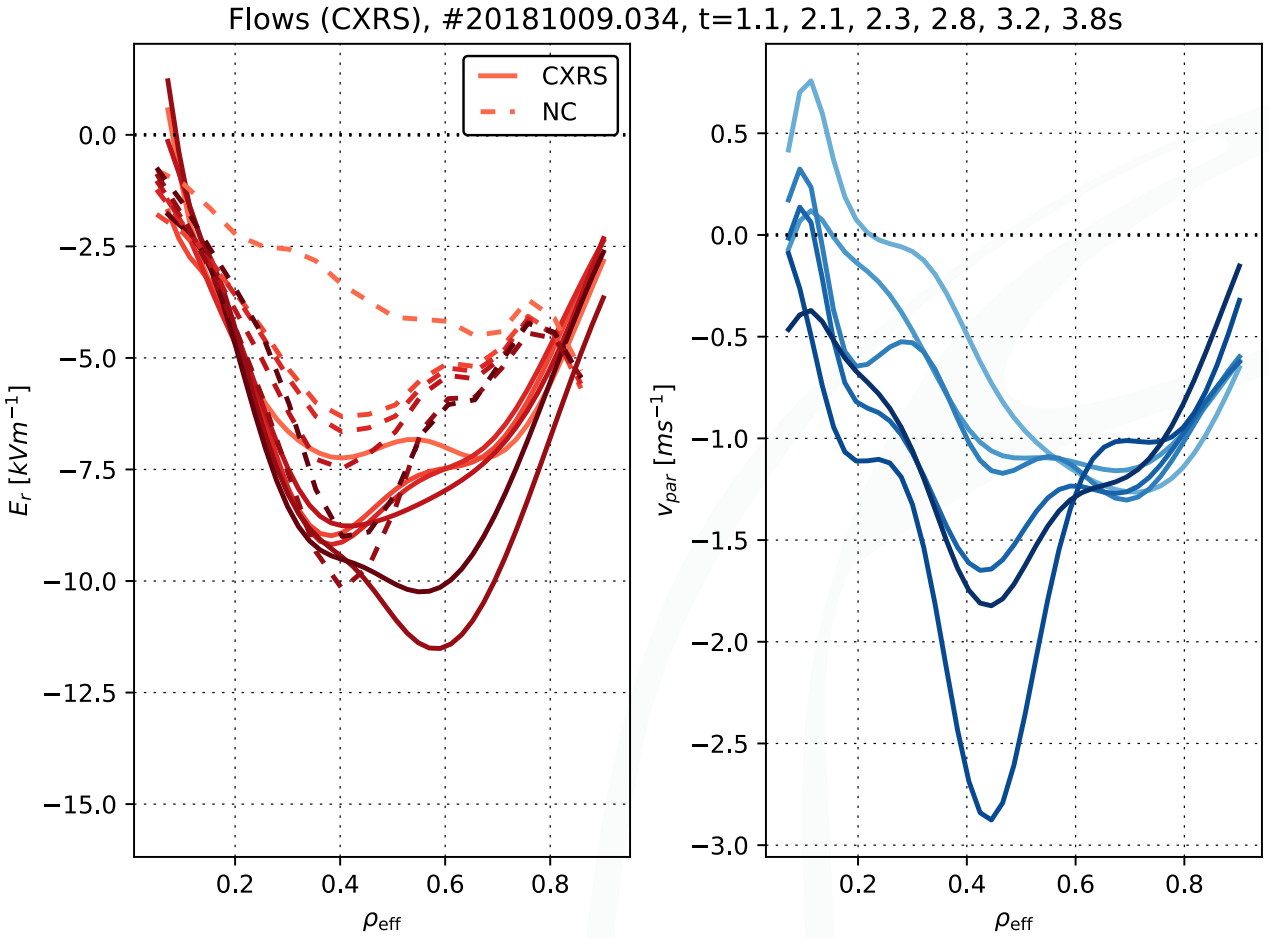
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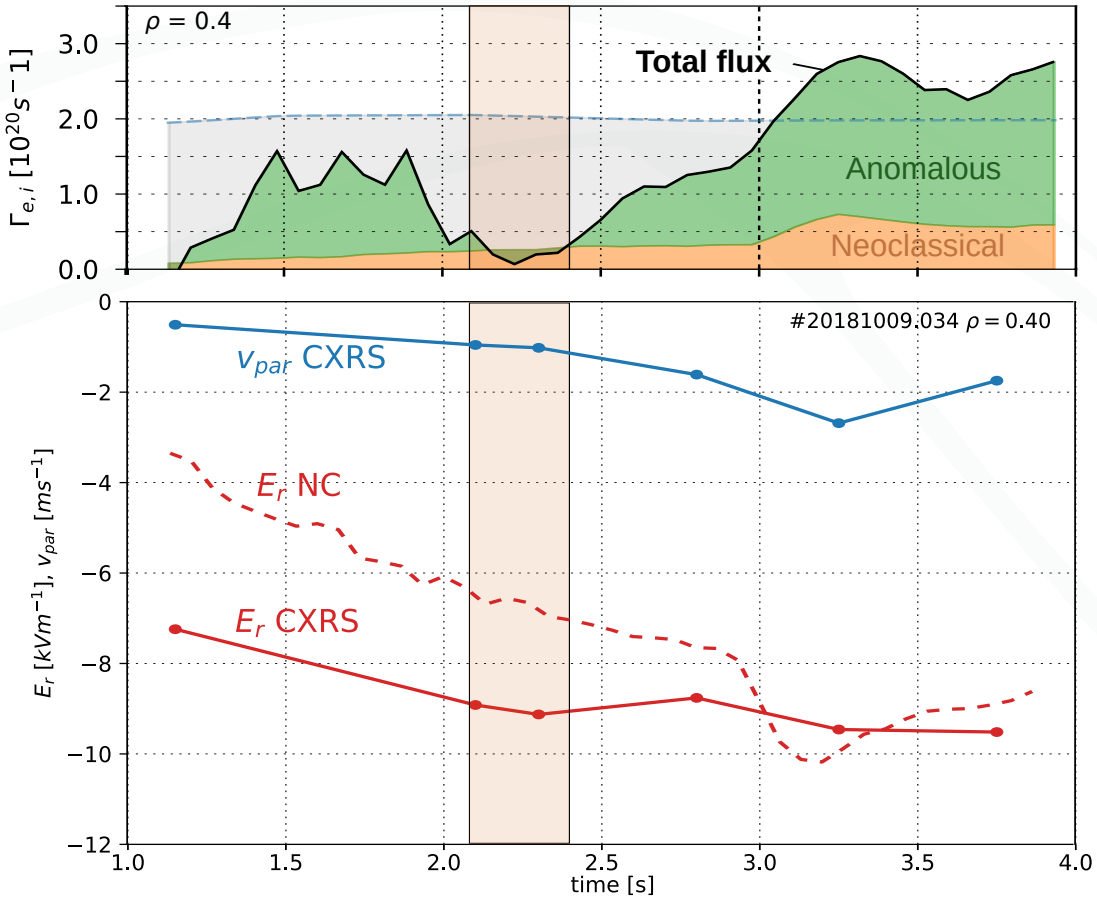


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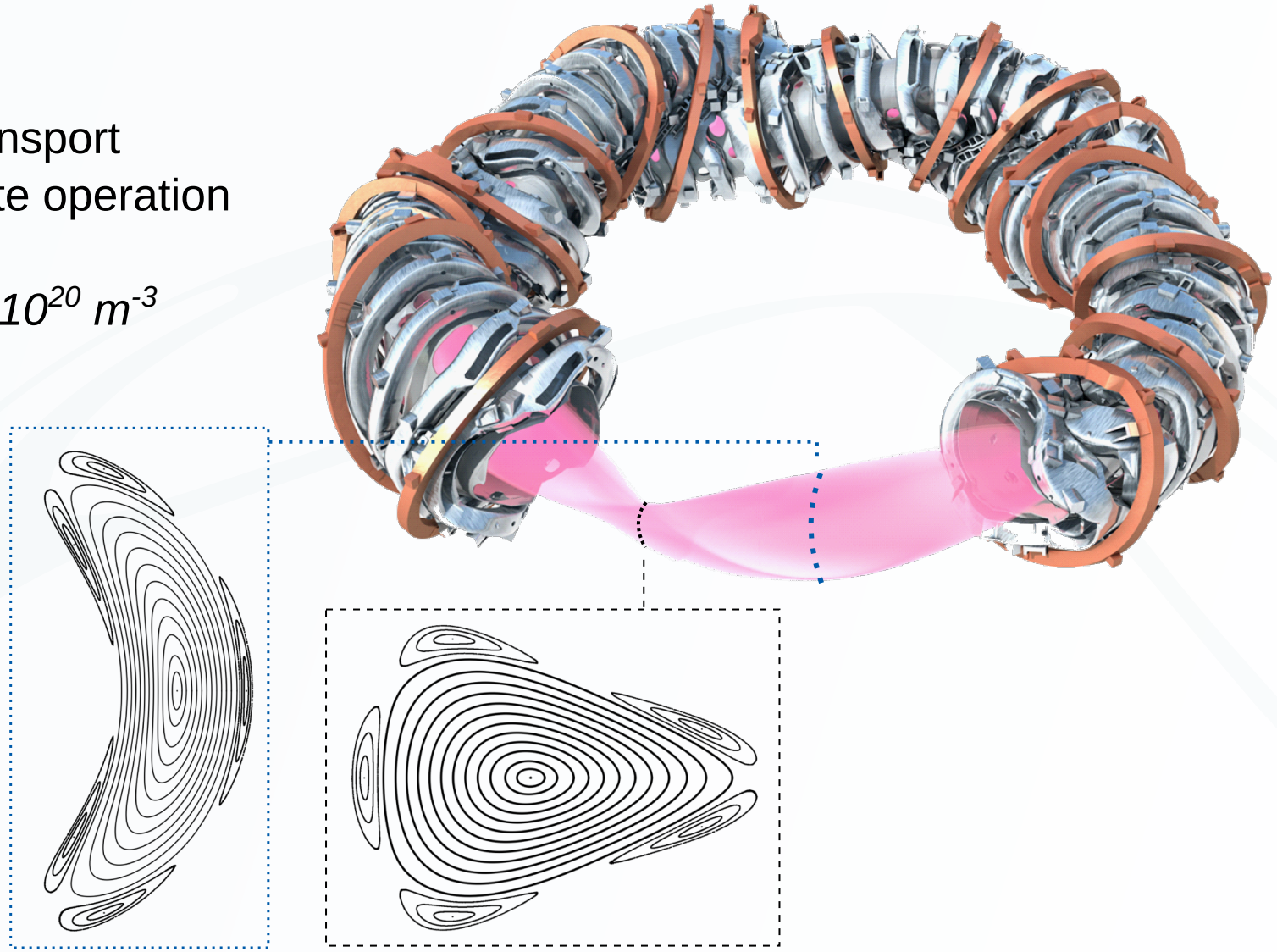



# The Wendelstein 7-X Stellarator

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: $n_e \sim 1.8 \times 10^{20}\ m^{-3}$

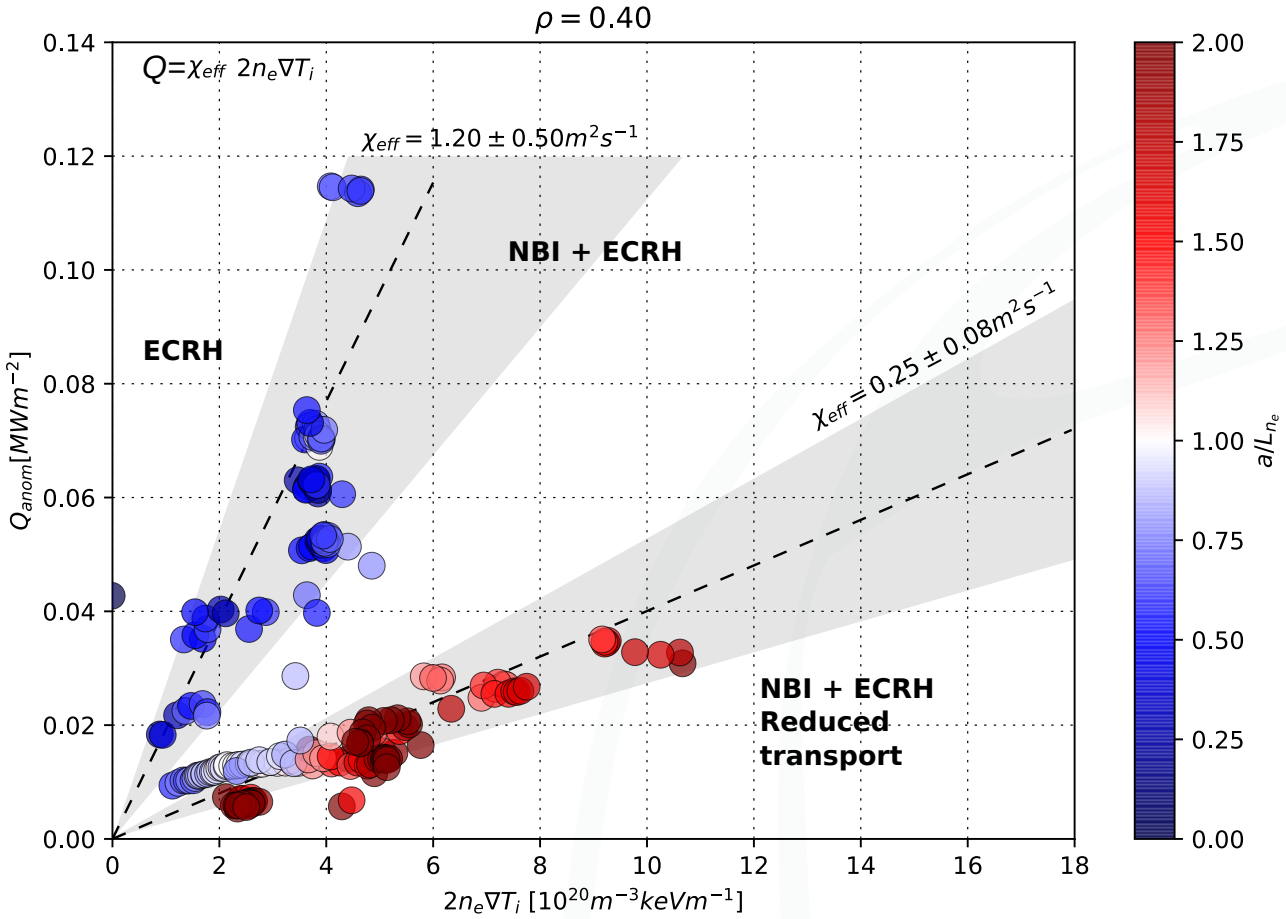
| | |
|---|---|
| $R_0$ | 5.5 m |
| $a$ | 0.5 m |
| $V$ | 30 $m^3$ |
| $B_0$ | ⩽ 3 T |
| $\iota_a$ $(\sim q_{95}^{-1})$ | 5/6 ... 5/4 |

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



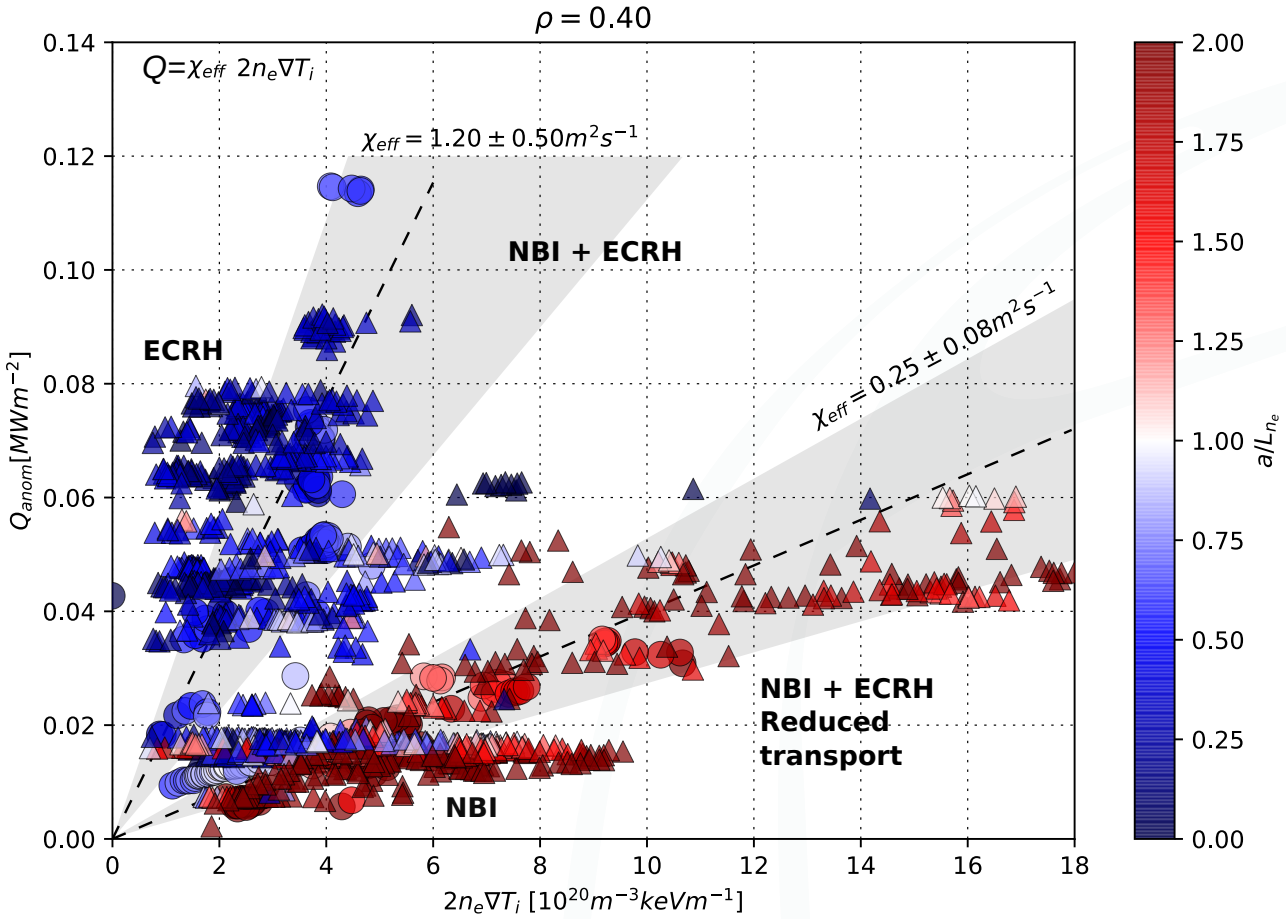
# Balancing ECRH power

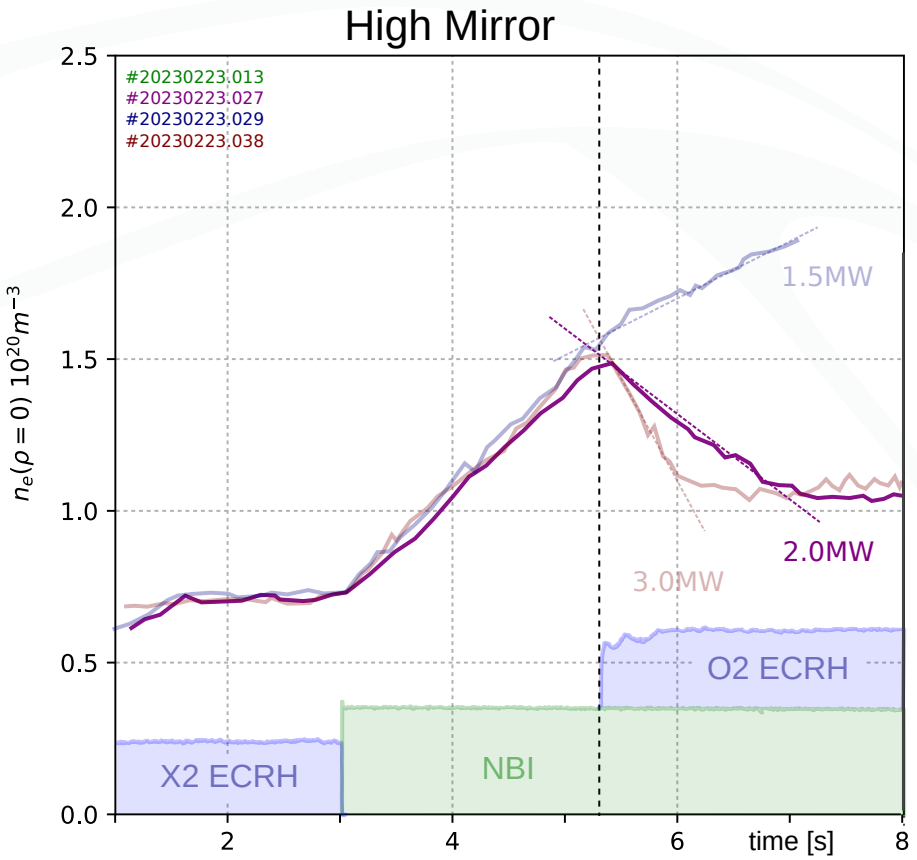
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- $\chi_{eff}$ ~ 0.25 $m^2s^{-1}$ maintained despite x2 higher $Q_{anom}$. (as high as some turbulent ECRH-only shots)



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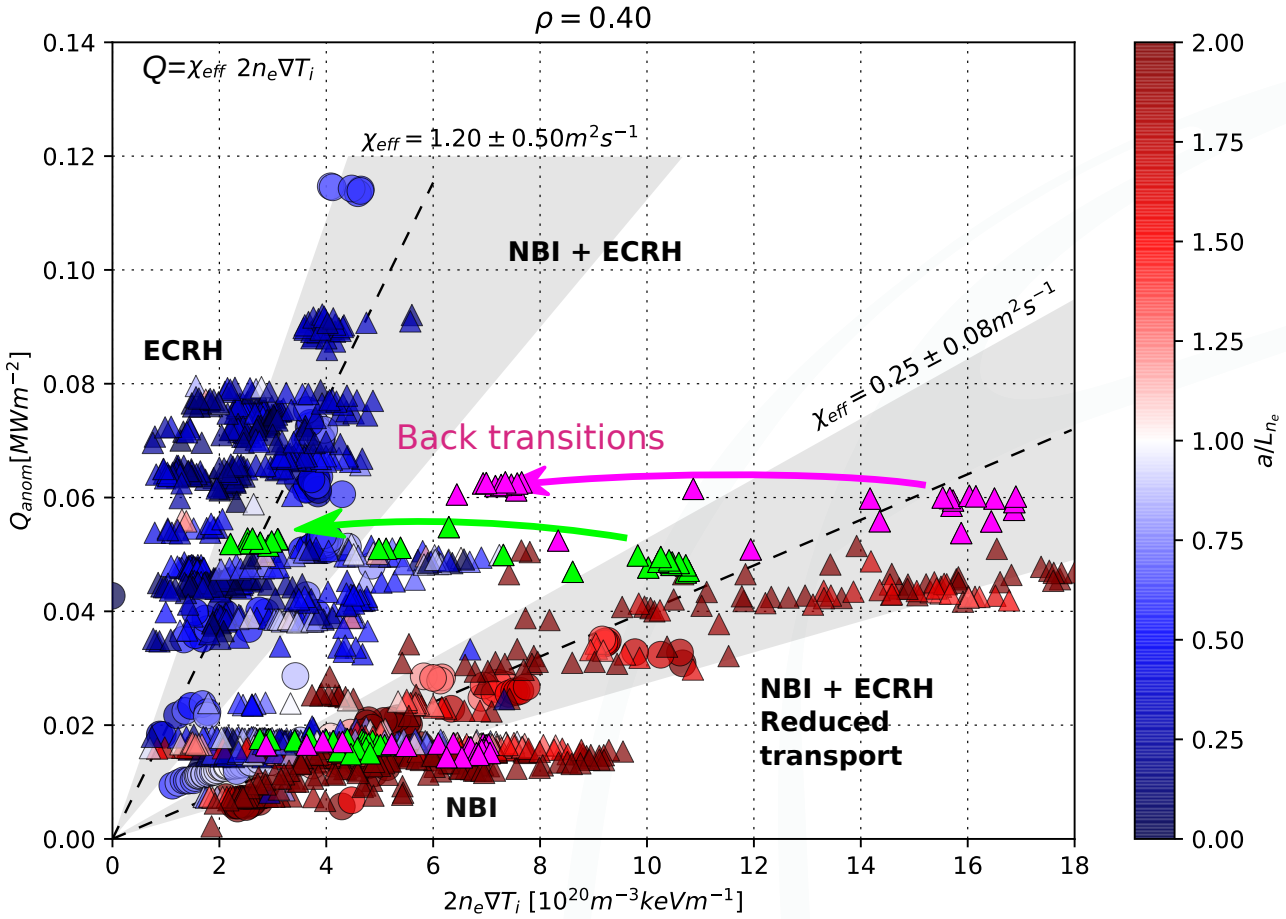
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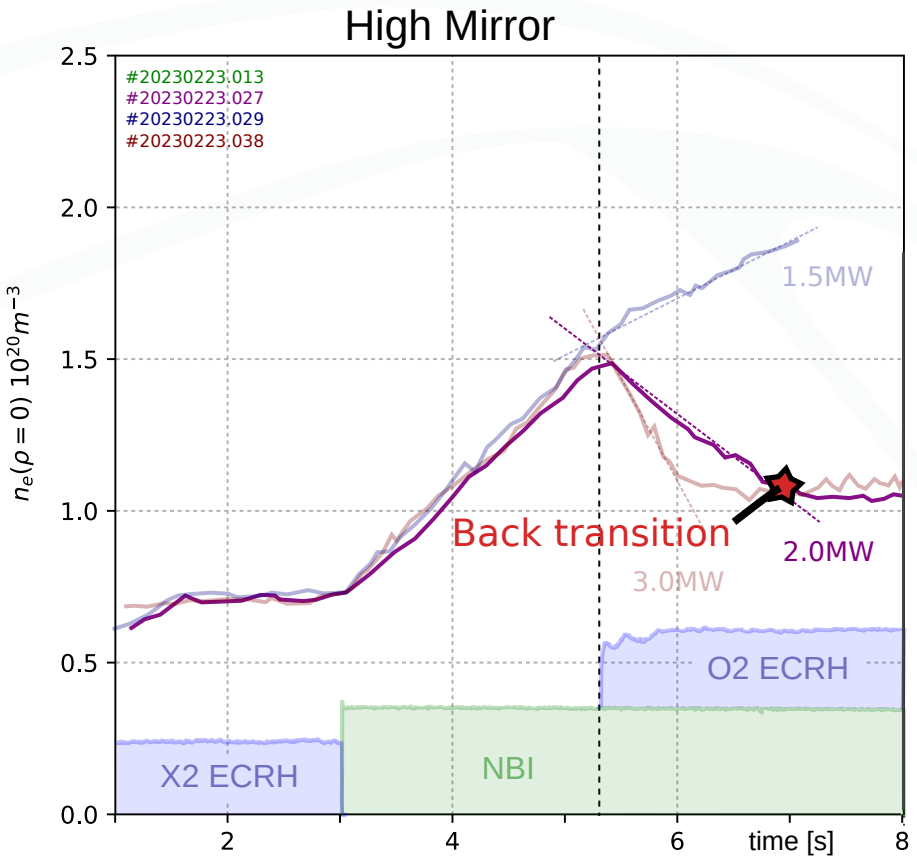


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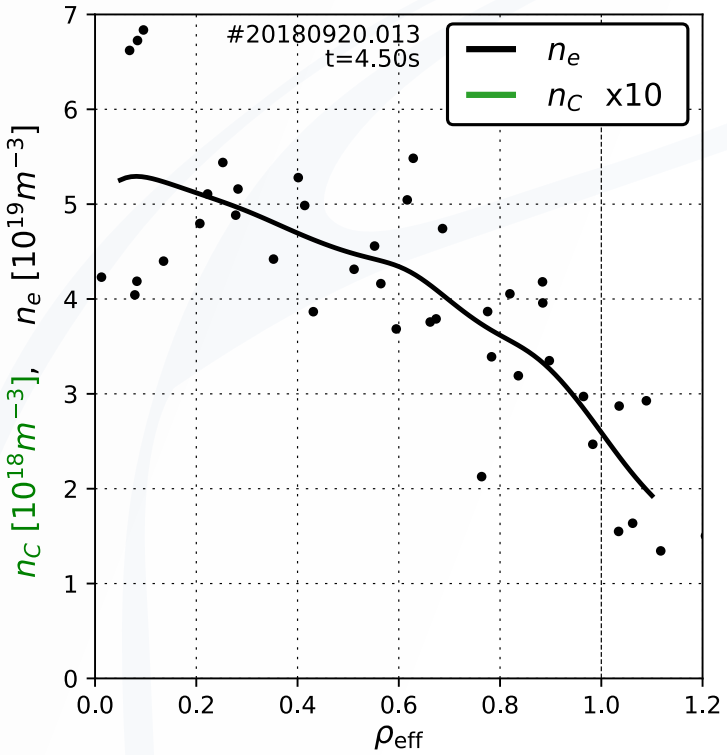
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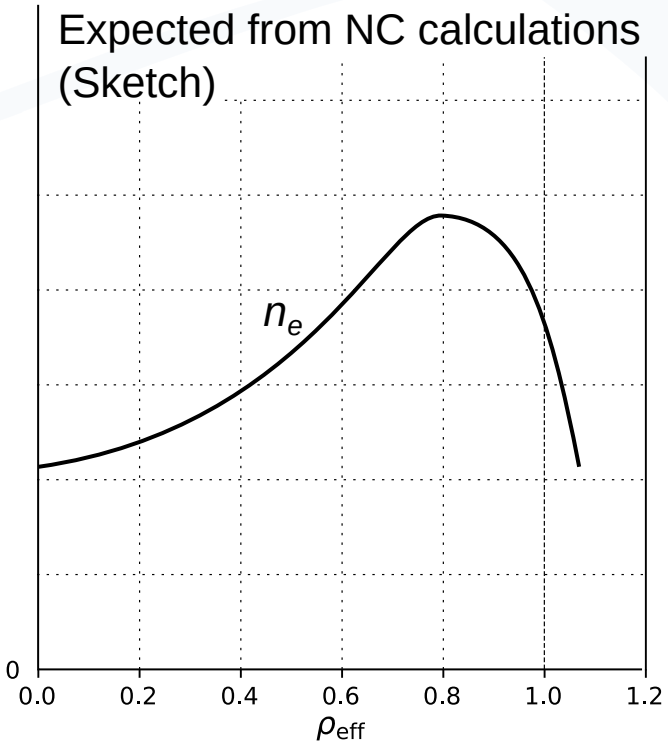
Some text

# Gas-fuelled ECRH discharges

Typical discharges from last campaign (2018):

- On-axis X2 ECRH heating 2 - 6MW; $\langle n_e \rangle \sim 1$ to 10 x $10^{19}$. Gas/recycling fuelled.
- Flat or slightly peaked density profiles despite outward neoclassical thermo-diffusion:
  An anomalous pinch required to counteract *[C D Beidler et al 2018 PPCF 60 105008]*

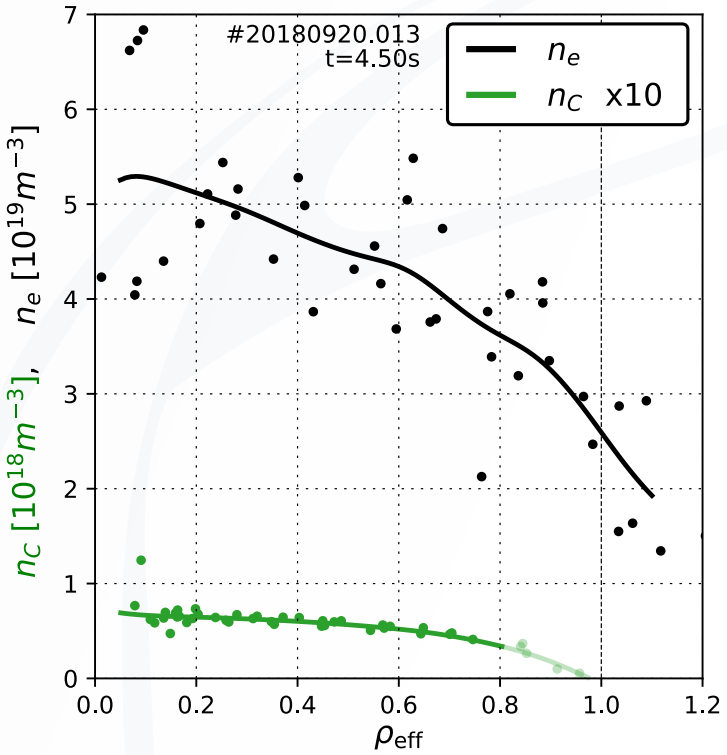


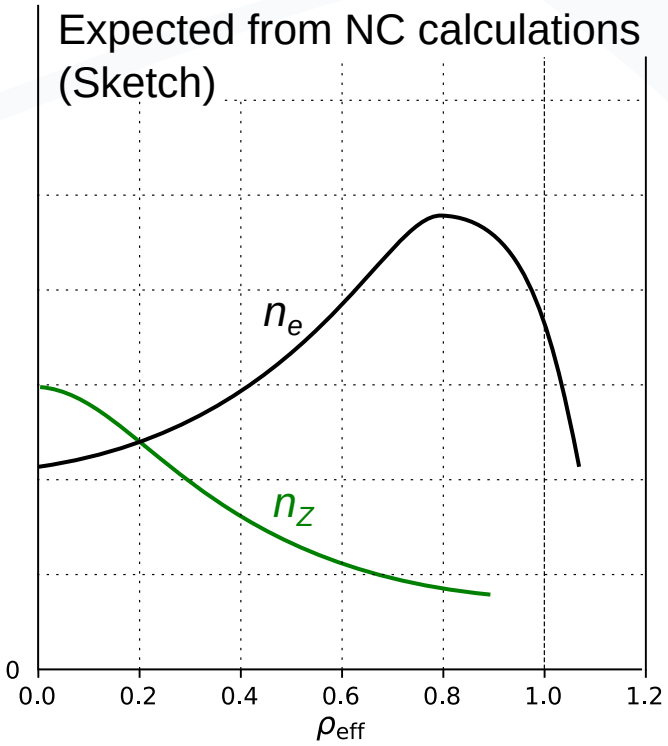



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- Flat impurity profiles despite neoclassical pinch:
  High turbulent impurity diffusion shown by LBO injection experiments *[B. Geiger et al 2019 Nucl. Fus. 59 046009]*

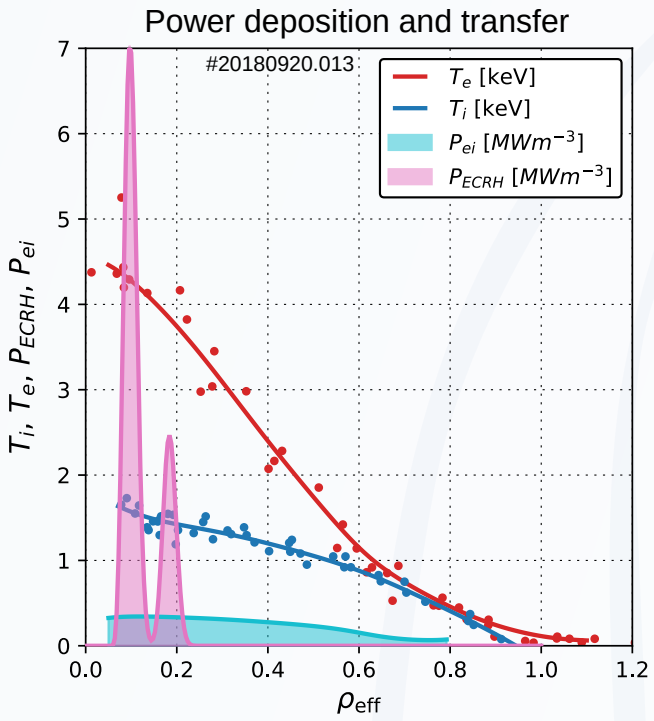


# Ion temperature clamping

Ion temperature clamping explained by combination of effects: [Beurskens et al. Nucl Fus 2021 (submitted), IAEA 2021]

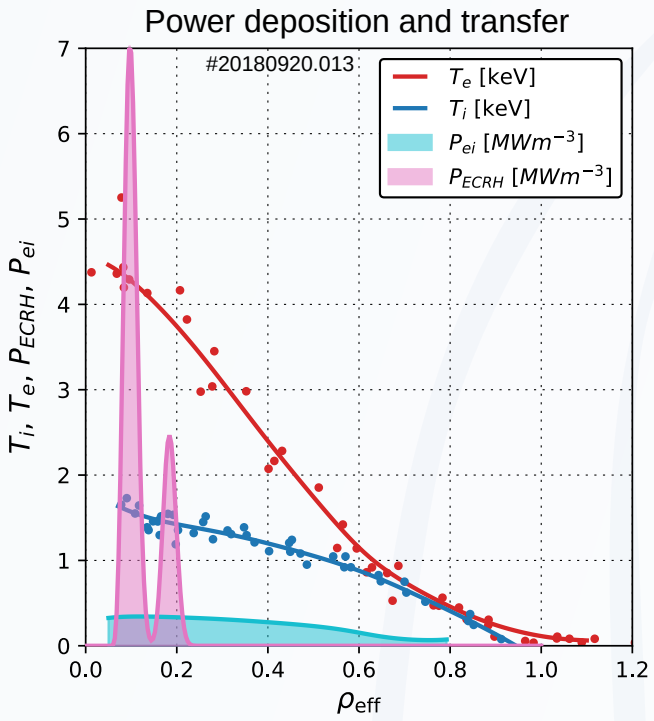
- Collisional coupling gives broad ion heating profile

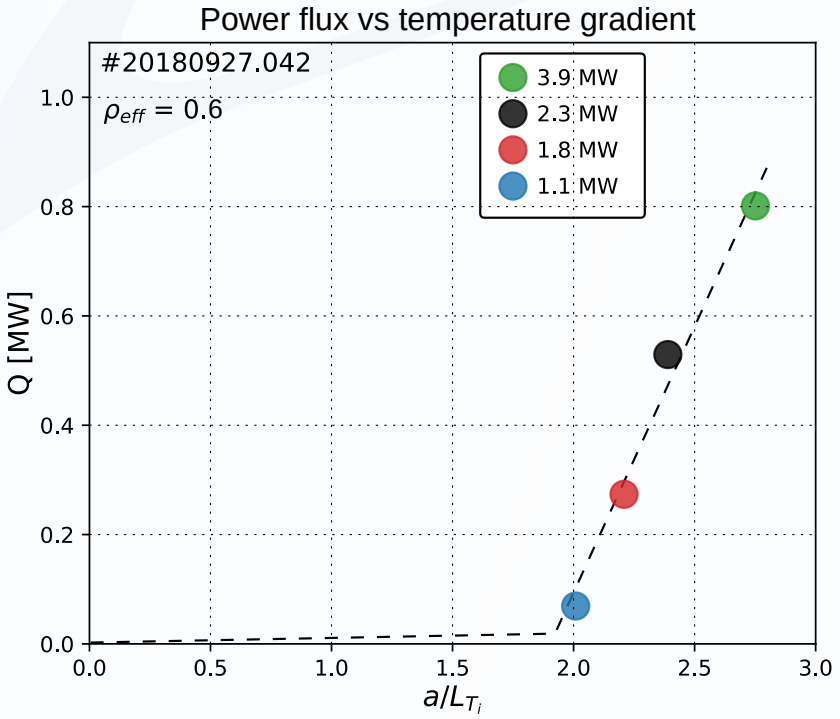


# Ion temperature clamping

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- Collisional coupling gives broad ion heating profile
- Strong profiles stiffness observed in turbulence

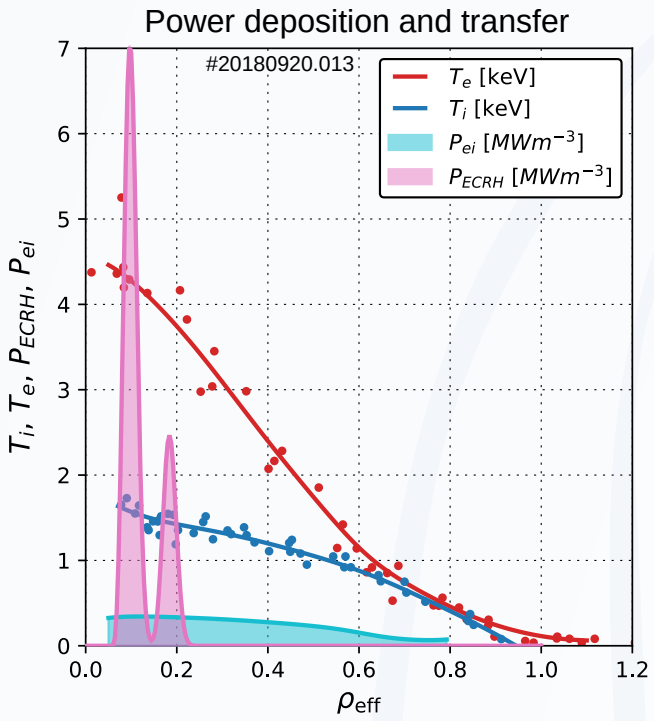


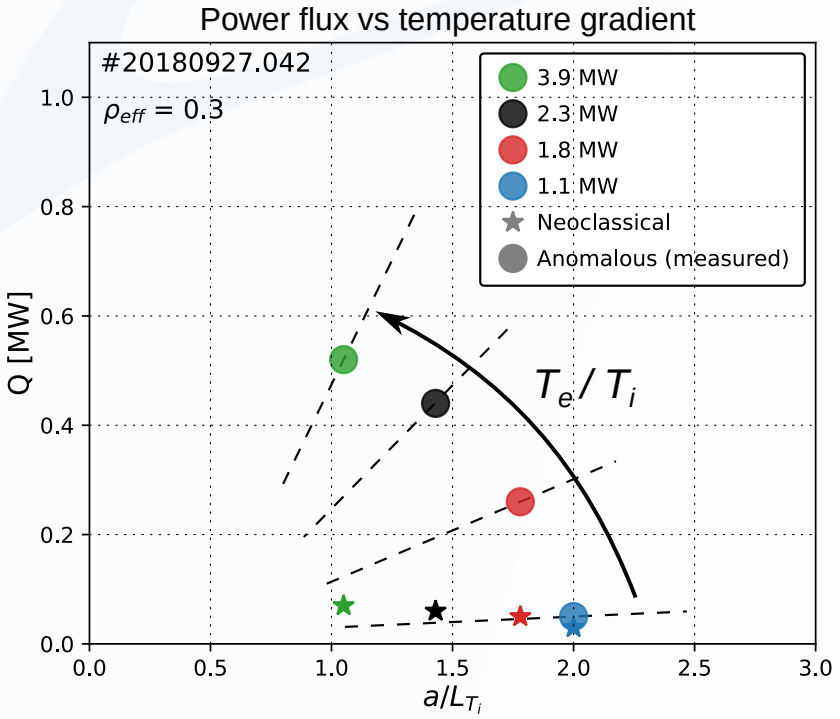



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- Collisional coupling gives broad ion heating profile
- Strong profiles stiffness observed in turbulence
- Increasing ITG turbulence with $T_e / T_i$ exacerbates stiffness with increasing $P_{ECRH}$.



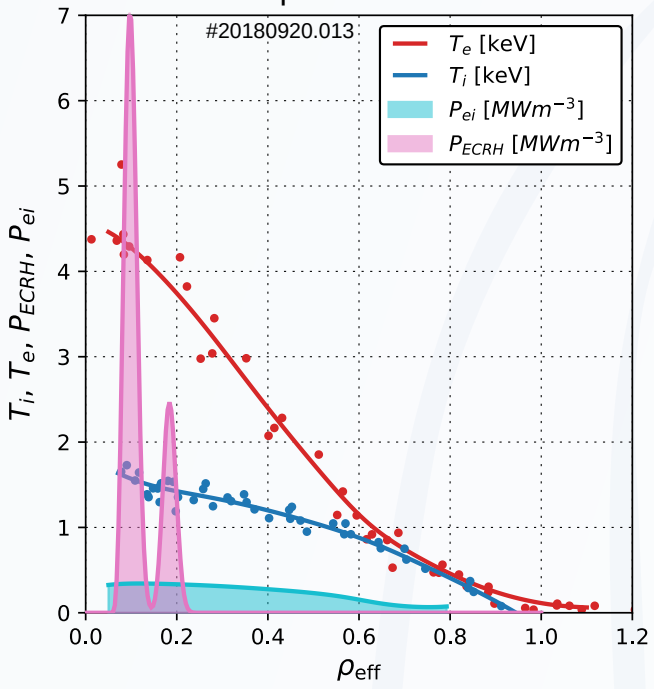
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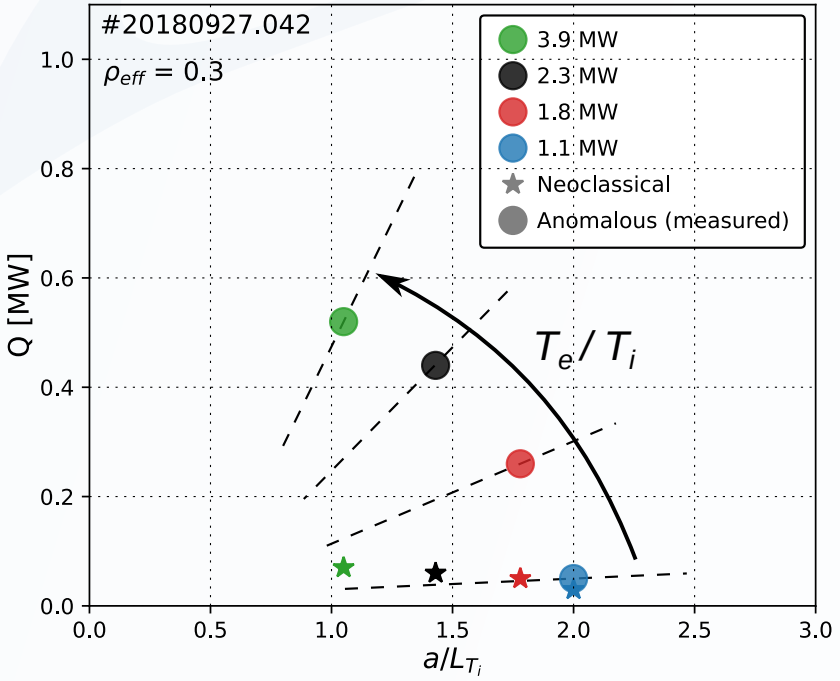
- Collisional coupling gives broad ion heating profile
- Strong profiles stiffness observed in turbulence
- Increasing ITG turbulence with $T_e / T_i$ exacerbates stiffness with increasing $P_{ECRH}$.
  supported by linear growth rate from ITG simulations *[A. Zocco, J. Plasma Phys 2017]*

**---> Typical gas fuelled ECRH W7-X plasmas ITG turbulence dominated**

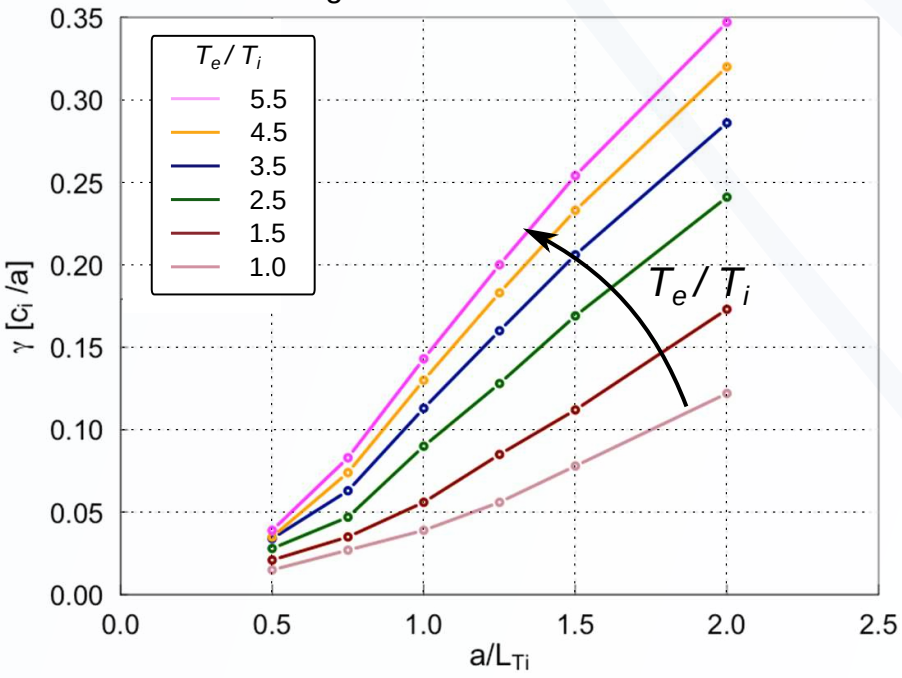
Power deposition and transfer




Power flux vs temperature gradient

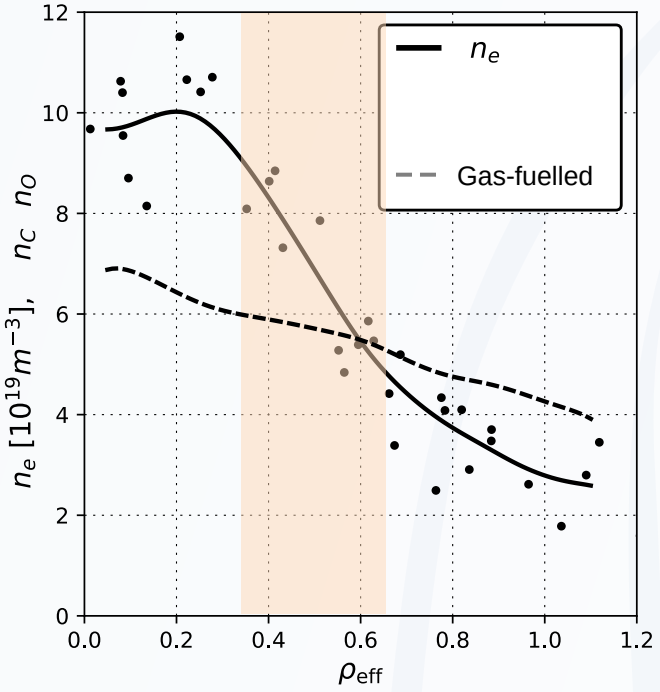


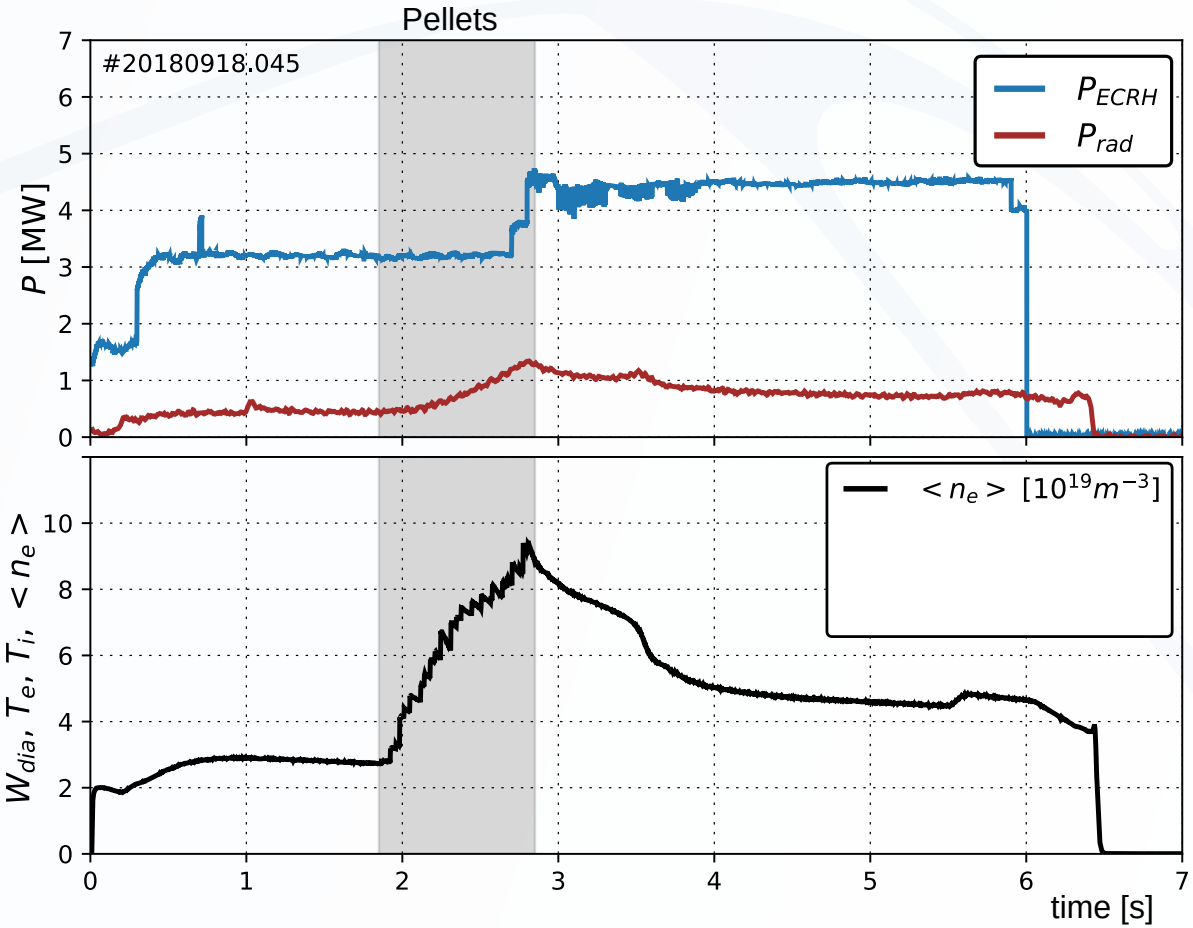

Linear growth rates. ITG simulations.



# Post-pellet turbulence suppression

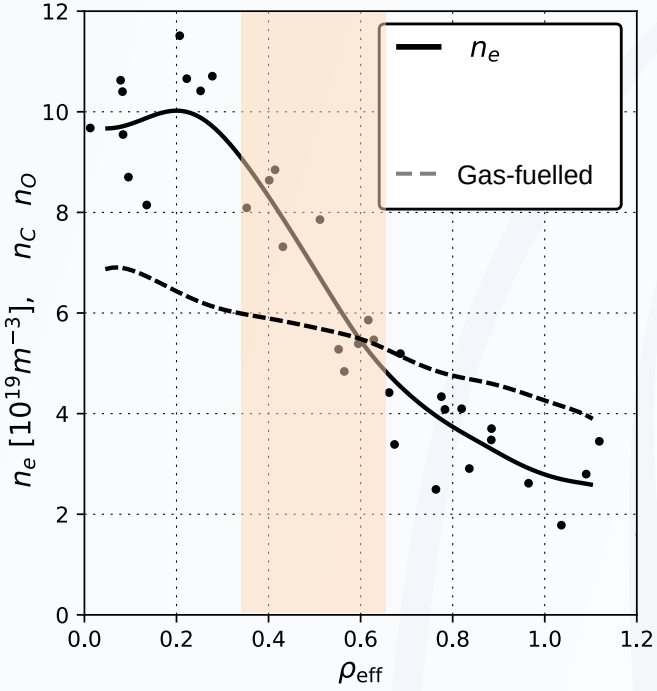
Steep density profiles after rapid series of hydrogen ice pellets.

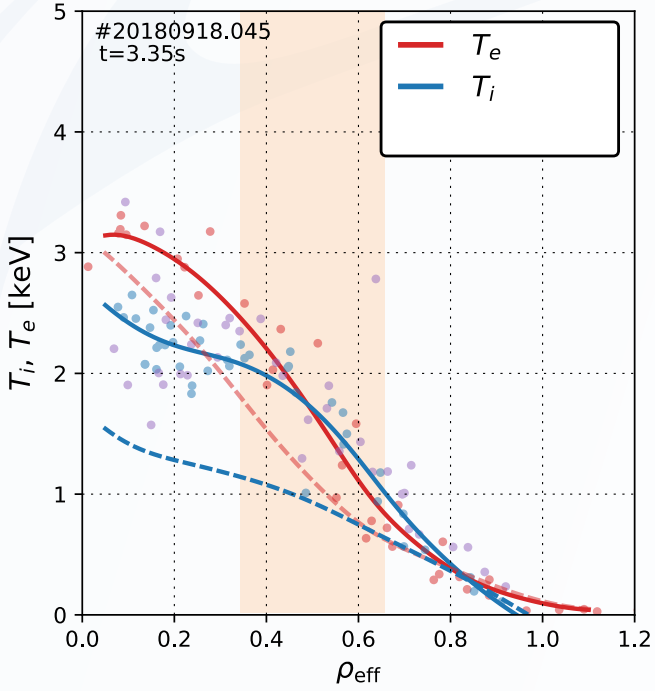


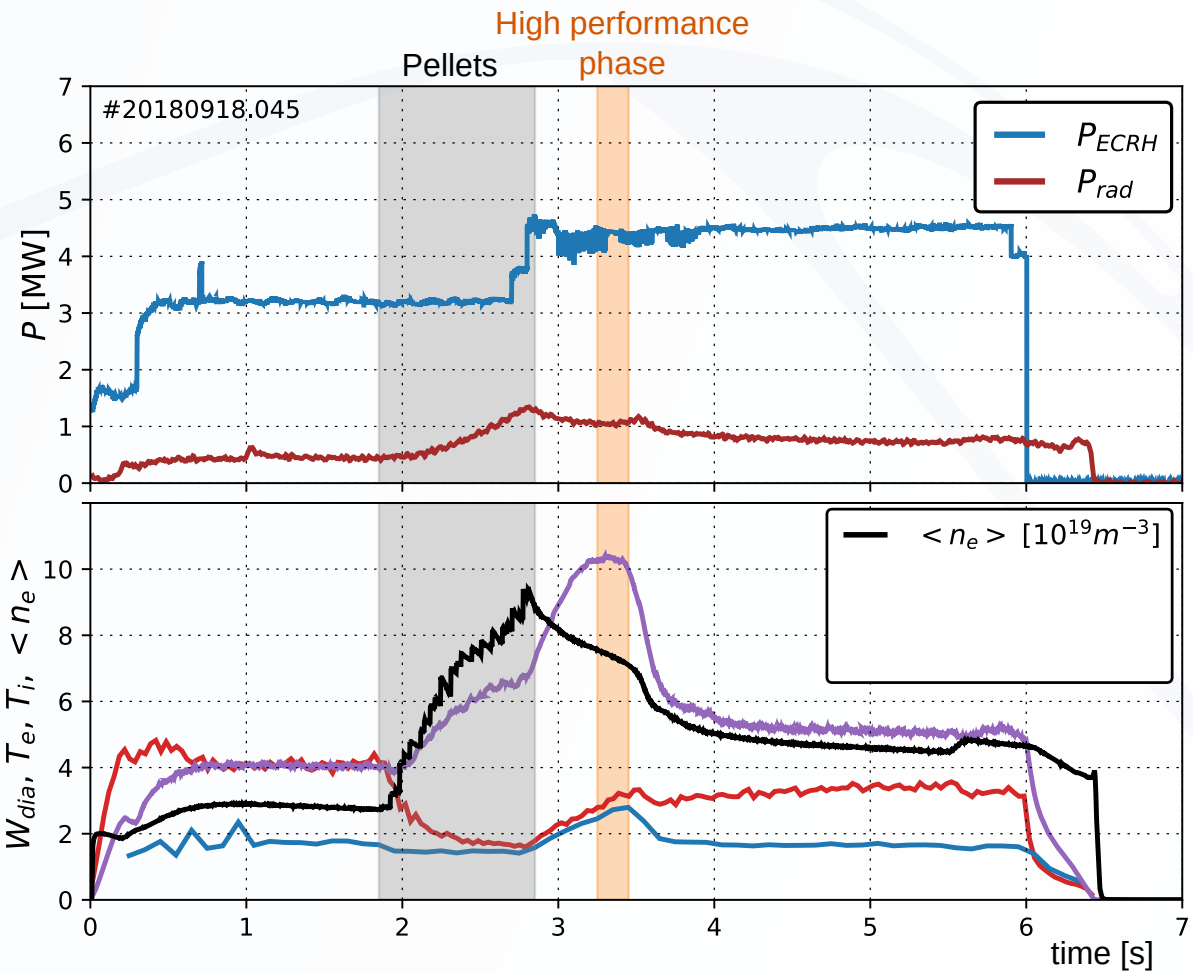



# Post-pellet turbulence suppression

Steep density profiles after rapid series of hydrogen ice pellets.
- High confinement $T_i = T_e$ phase builds slowly ~5 $\tau_E$ after end of pellets.
- Stable for ~1.5$\tau_E$ before density gradient and $T_i$ collapse.

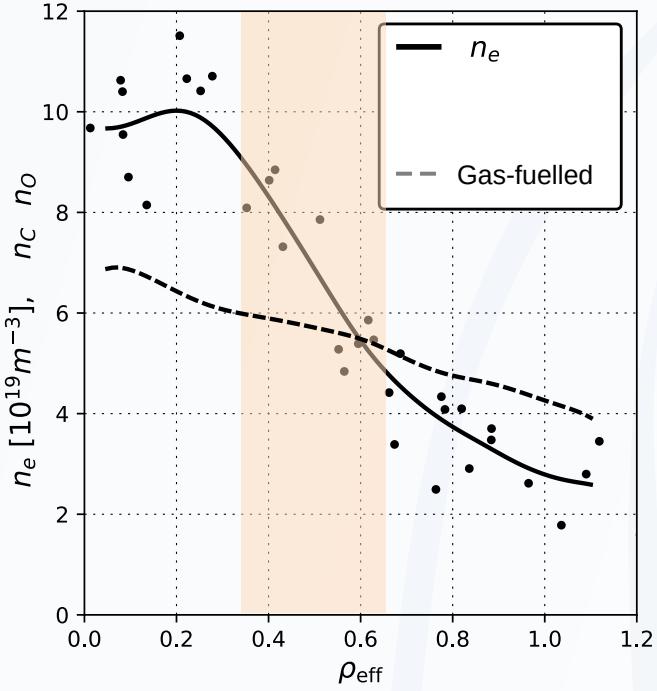


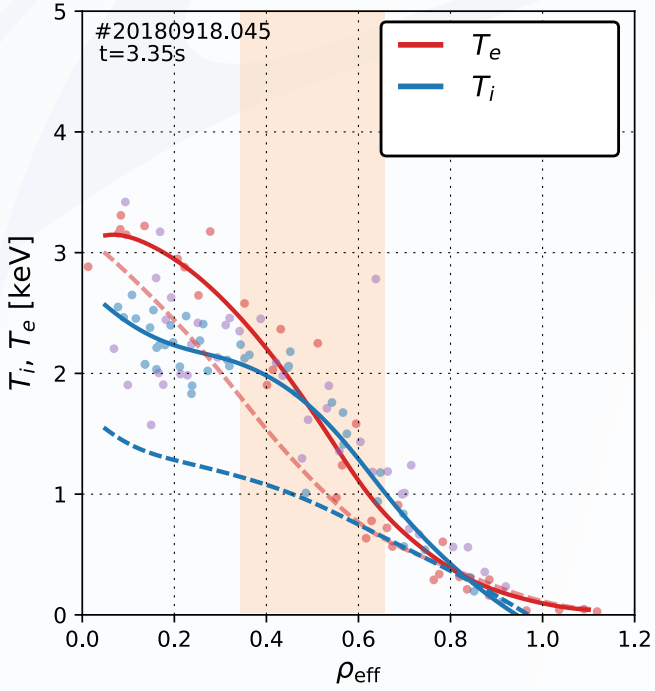



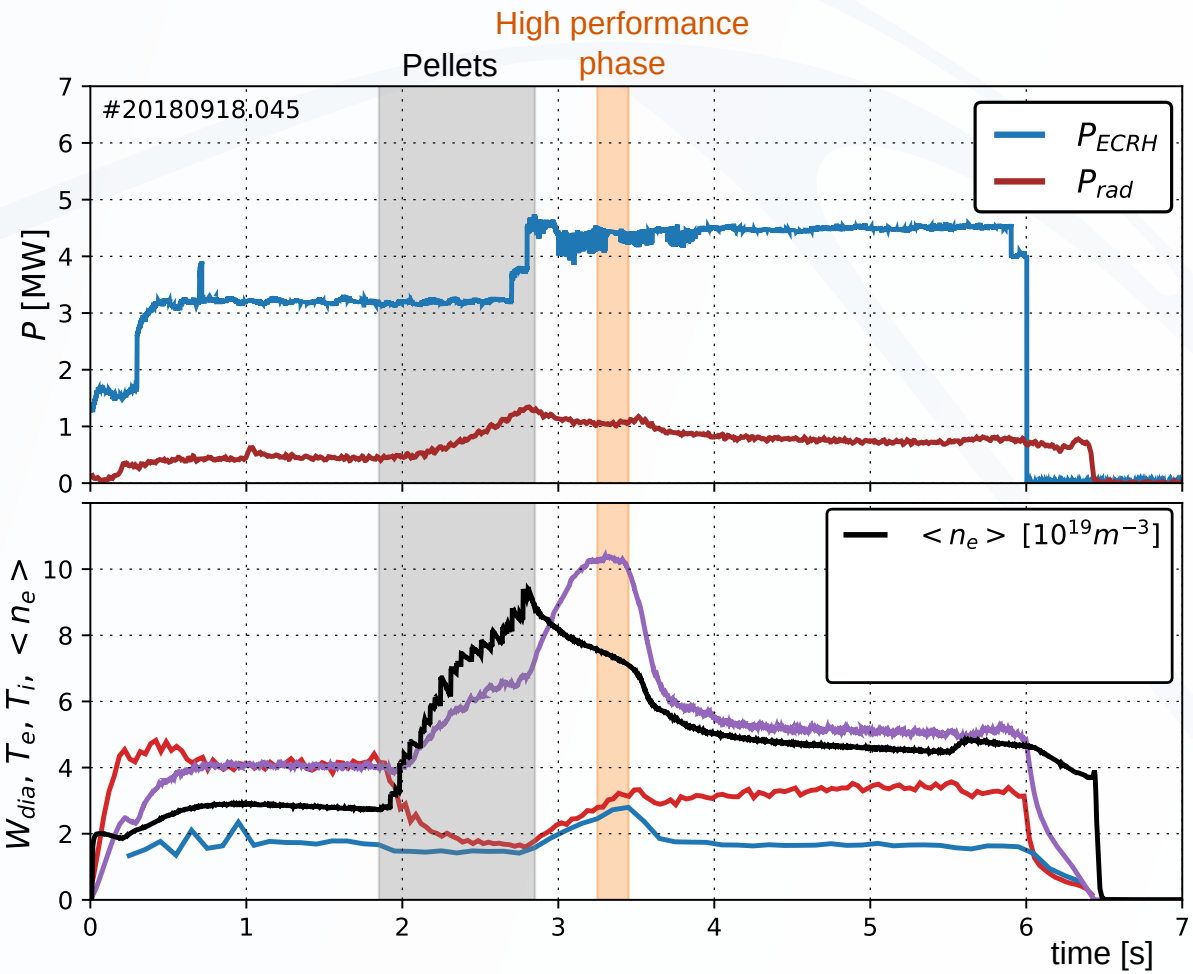



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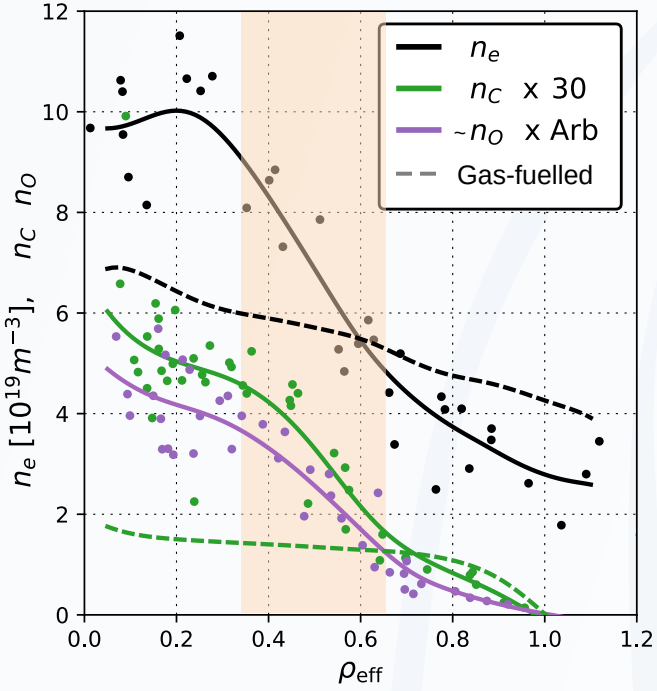


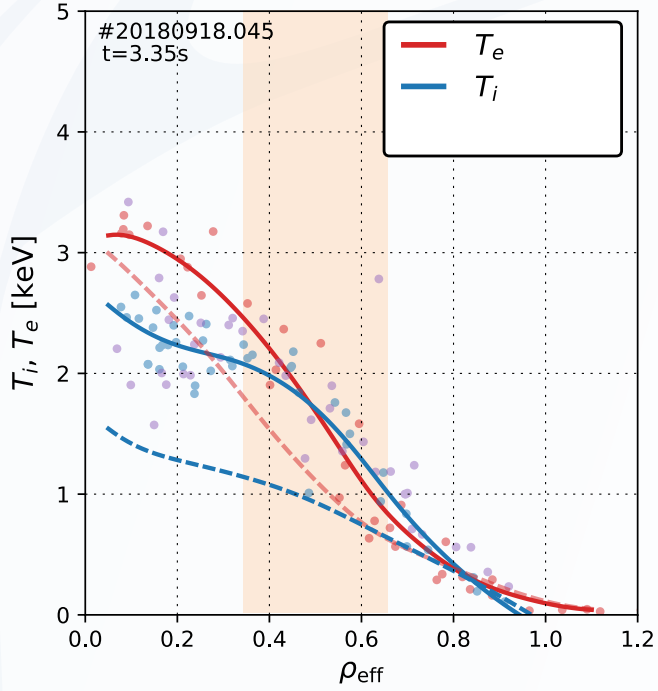



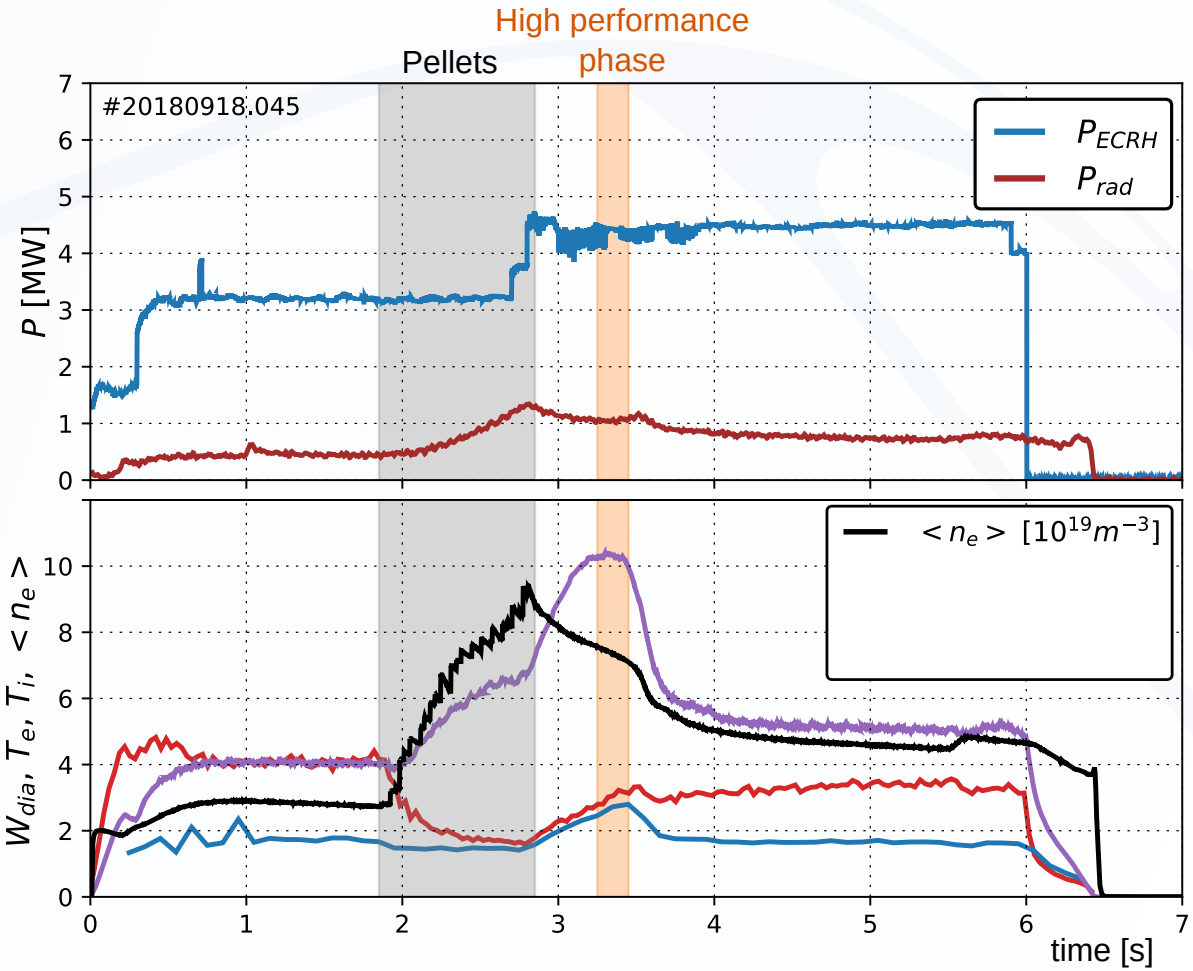



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- High confinement $T_i = T_e$ phase builds slowly ~5 $\tau_E$ after end of pellets.
- Stable for ~1.5$\tau_E$ before density gradient and $T_i$ collapse.
- Peaking of impurities observed consistent with reduced turbulence, but $n_C$ still < 1% ($Z_{Eff}$ < 1.5)



# Post-pellet turbulence suppression

- Ion heat transport reduced to order of neoclassical level.
- Electron heat transport significantly reduced.

Typical gas-fuelled plasma

Post-pellets plasma



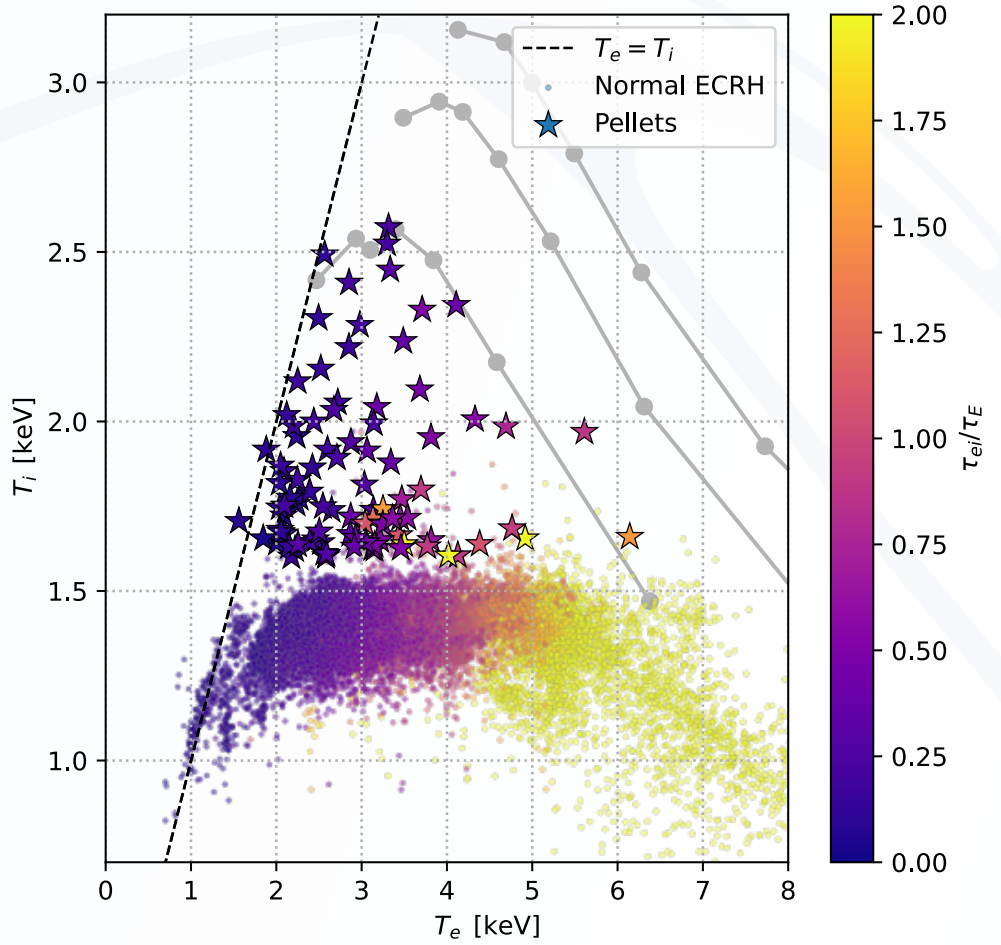
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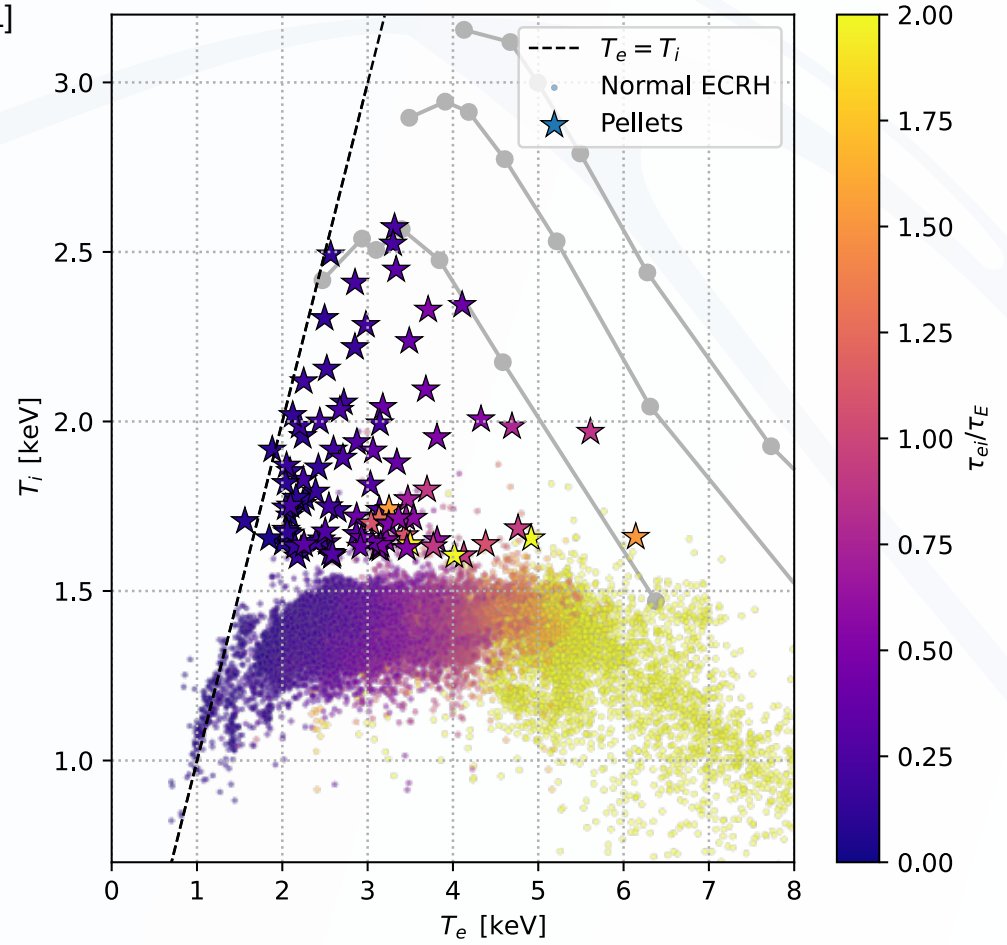
# Post-pellet turbulence suppression

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- Electron heat transport significantly reduced.
- Central $T_i$ raised significantly above clamping limit.
- Sufficient to demonstrate NC optimisation of W7-X [Beidler et al. Nature, 2021]
- Record stellarator $n\,T\,\tau_E$ *[Pedersen et al. PPCF 61 (2019)]*

Typical gas-fuelled plasma

Post-pellets plasma



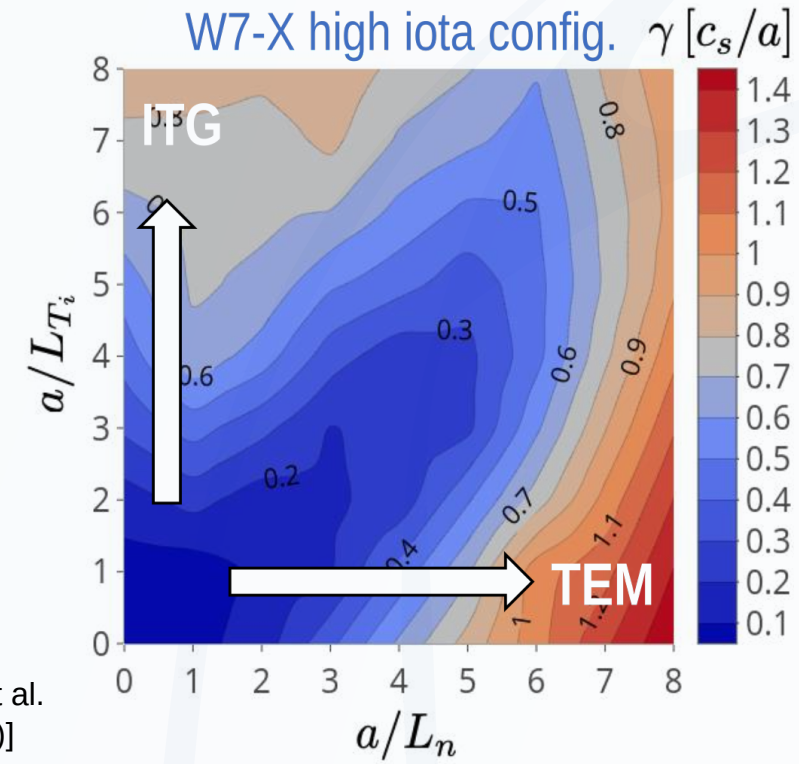



# Post-pellet turbulence suppression

- Theoretical undestanding:
  - Density gradient strongly stabilises ITG. W7-X resilient to TEM due to optimisation [Proll et. al. PRL 2012].

# Post-pellet turbulence suppression

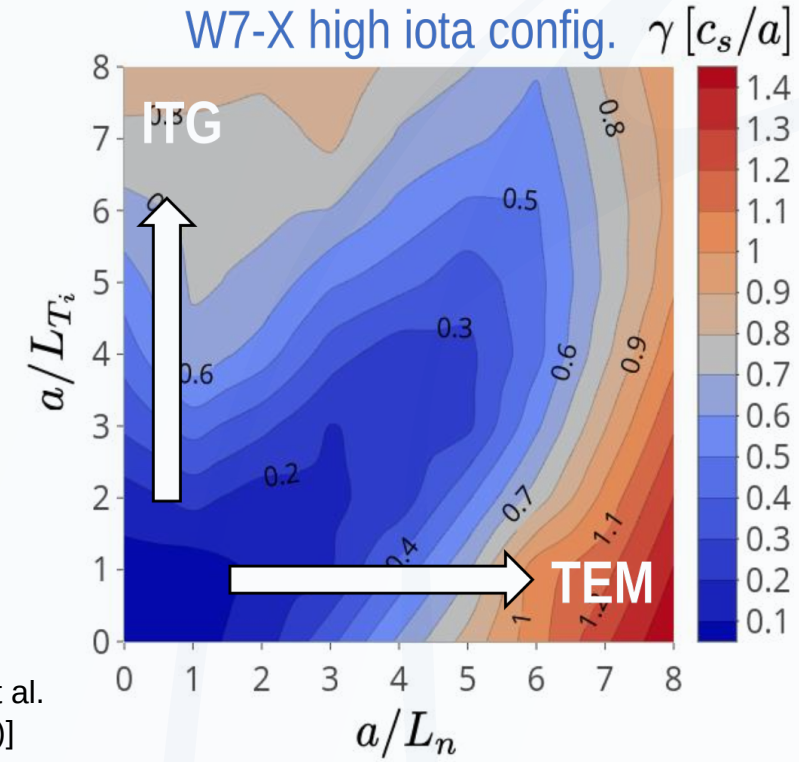
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  - Density gradient strongly stabilises ITG. W7-X resilient to TEM due to optimisation [Proll et. al. PRL 2012].
  - 'Stability valley' around $a/Ln_e \sim a/LT_i$ [J. A. Alcusón et al. PPCF 21 (2020)]
  - Non-linear simulations show transistion of from ITG to iTEM during post-pellet phase. [P. Xanthopoulos et. al. PRL 2021]
  - Reduction in fluctuation levels seen by PCI [Z. Huang, this conference], Doppler reflectometer [T. Estrada et al., Nucl. Fus. 2021] and even in SOL Beam Emission Spectroscopy [L. Édes, this conference]



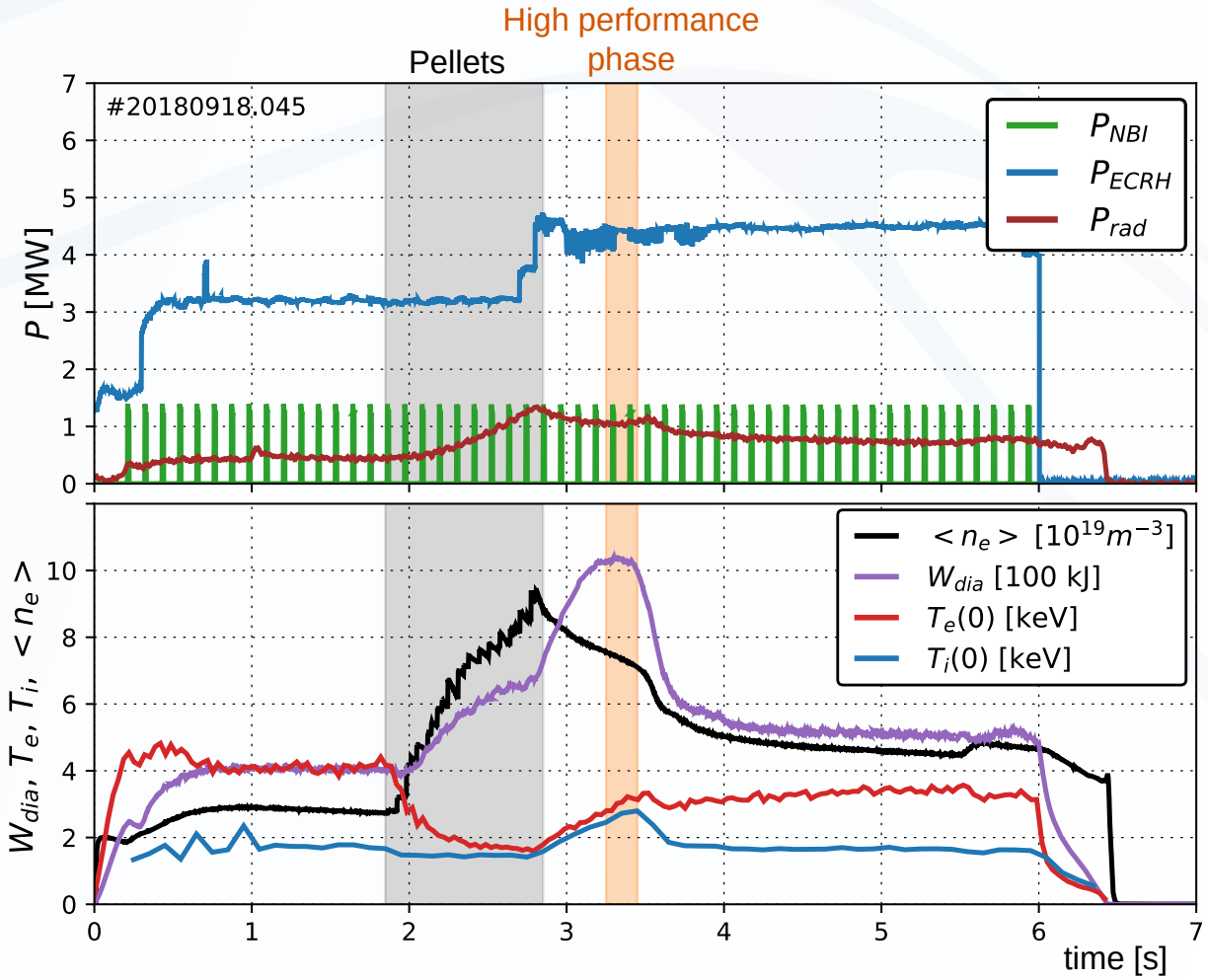

[J. A. Alcusón et al. PPCF 21 (2020)]

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[P. Xanthopoulos et. al. PRL 2021]

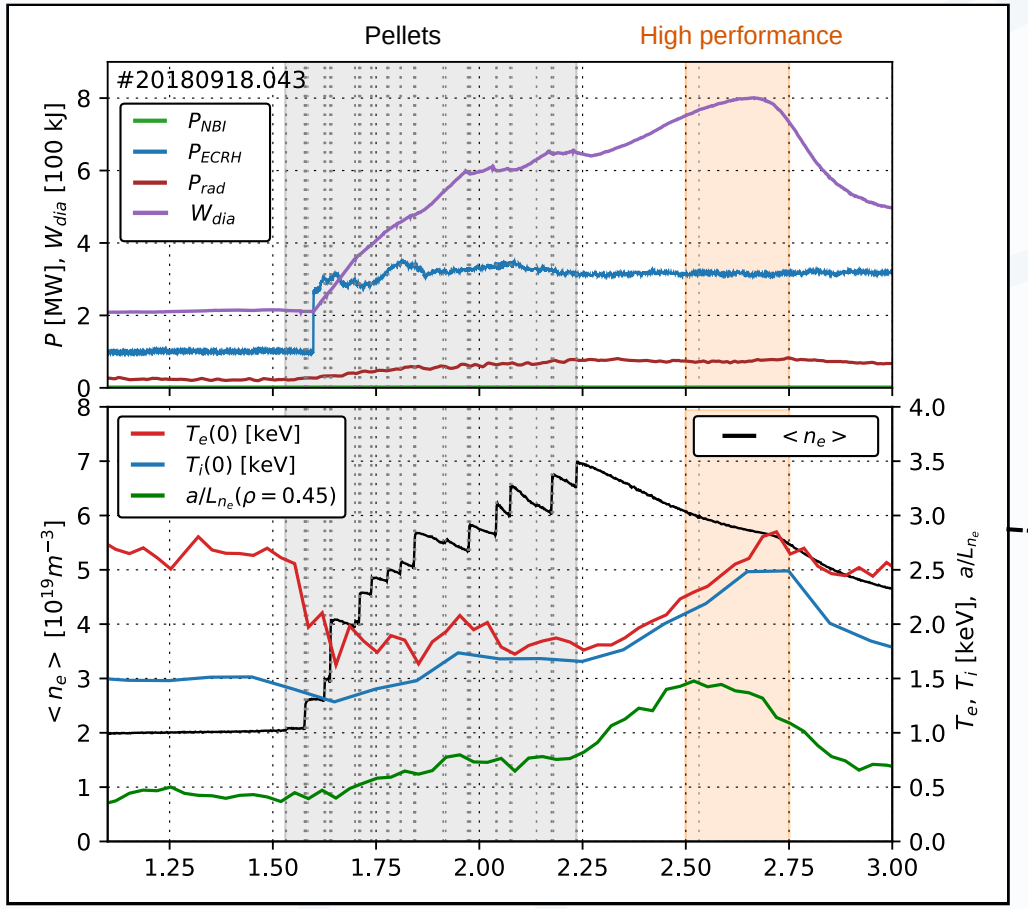
# Post-pellet turbulence suppression

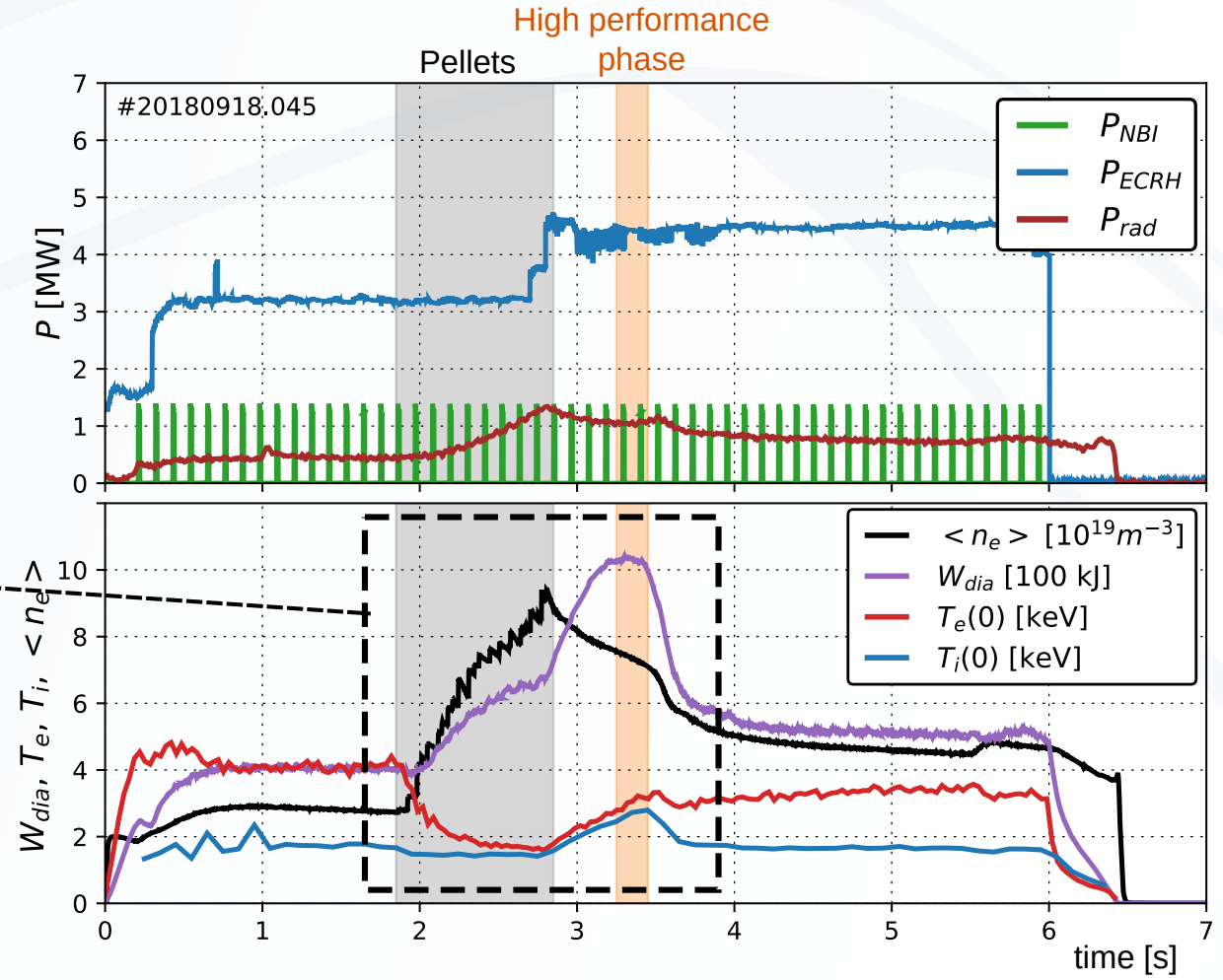
- Steady-state pellet injector next campaign to investigate ability to maintain high performance phase *during* pellets.



# Post-pellet turbulence suppression

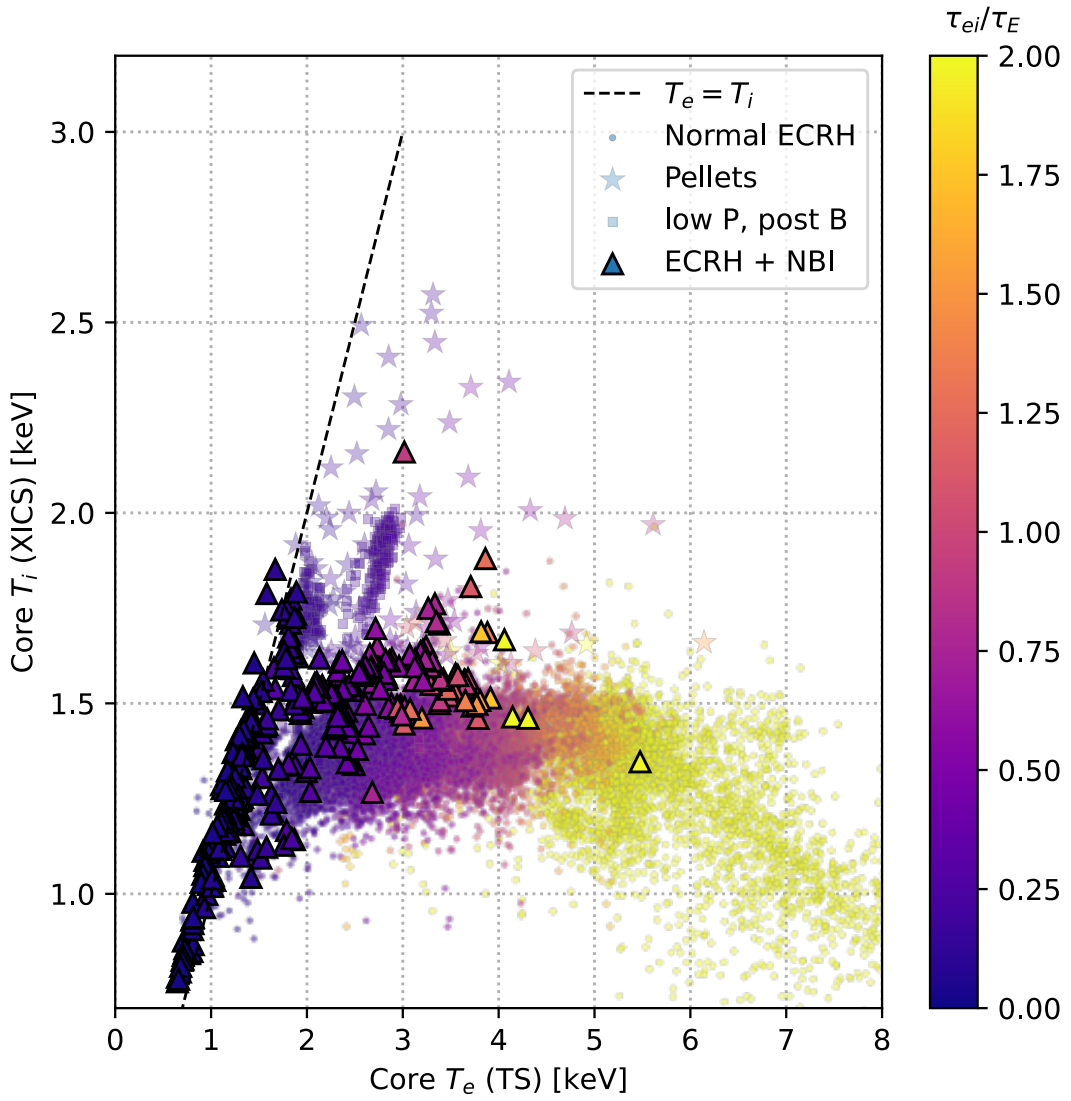
- Steady-state pellet injector next campaign to investigate ability to maintain high performance phase *during* pellets.
- So far, density gradient only observed after injection of last pellet.



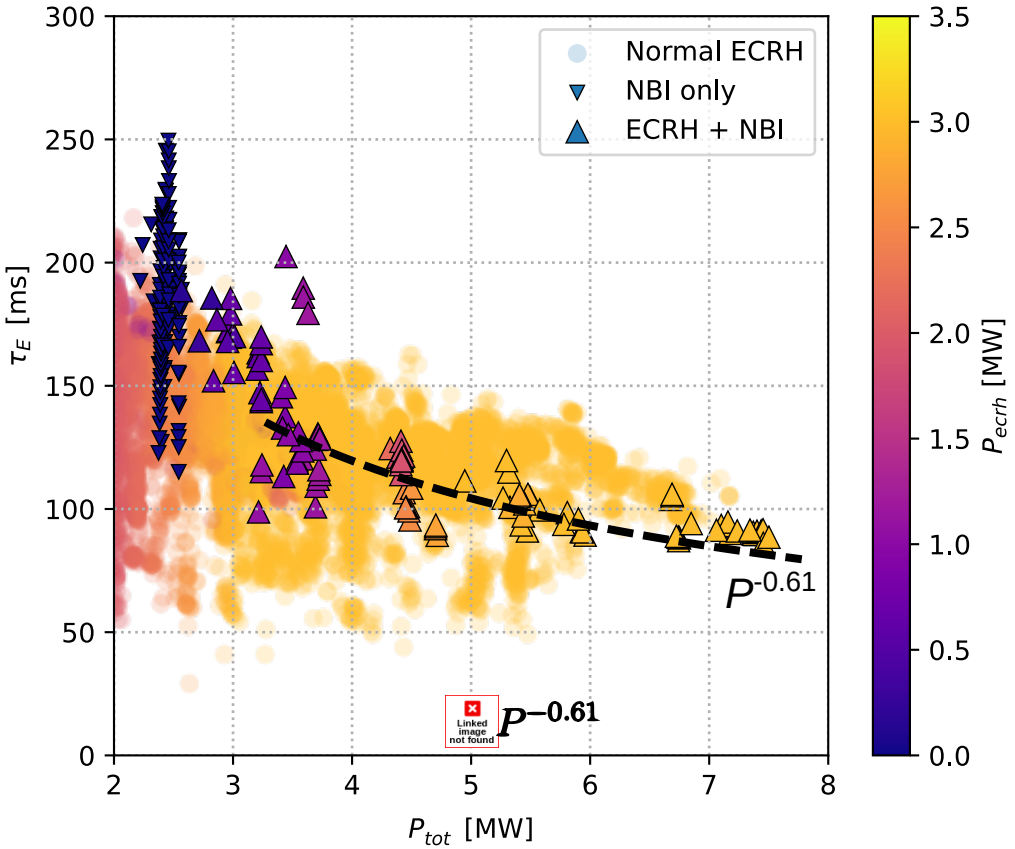
# NBI : ECRH ratio

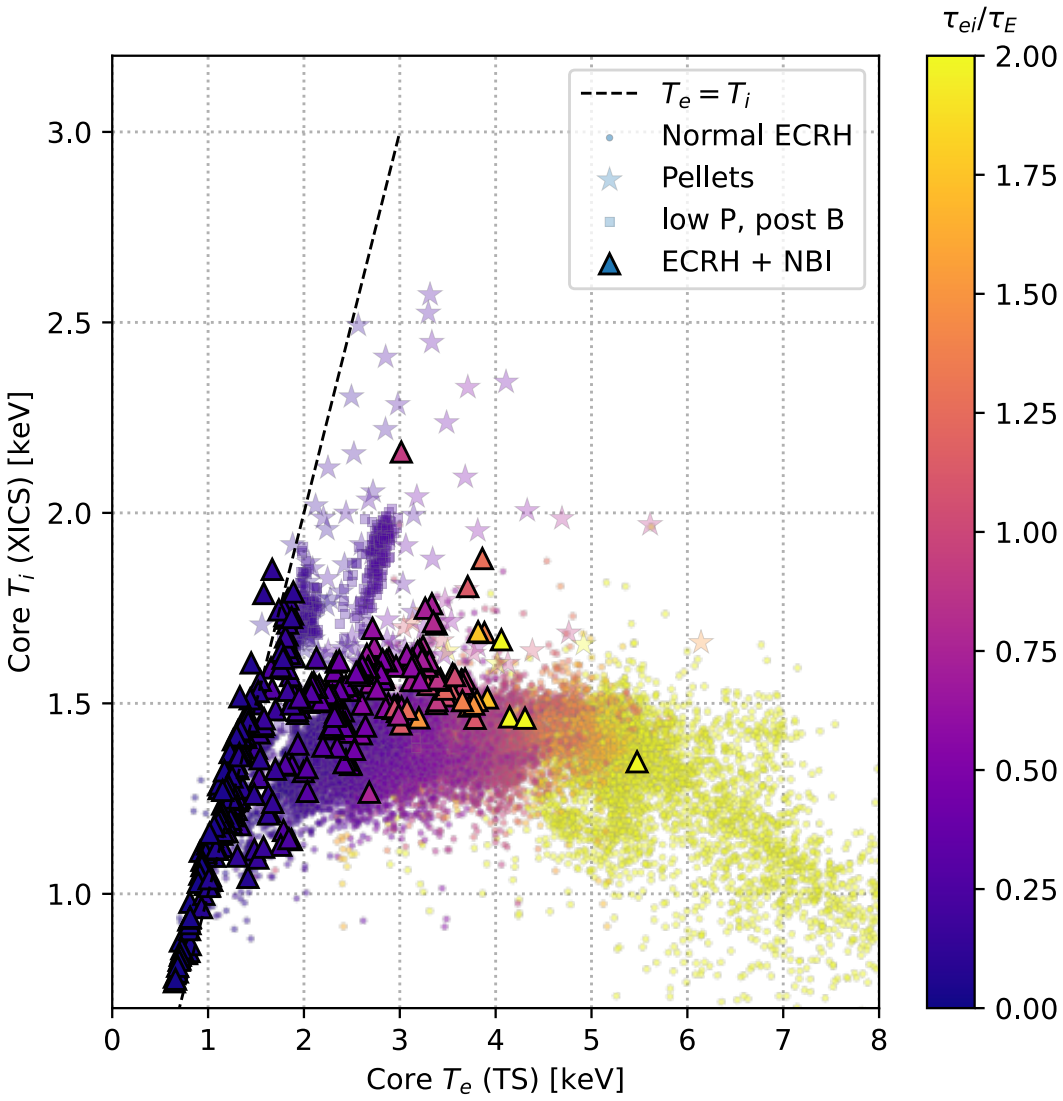
- NBI mostly supplementary to moderate-high ECRH power.



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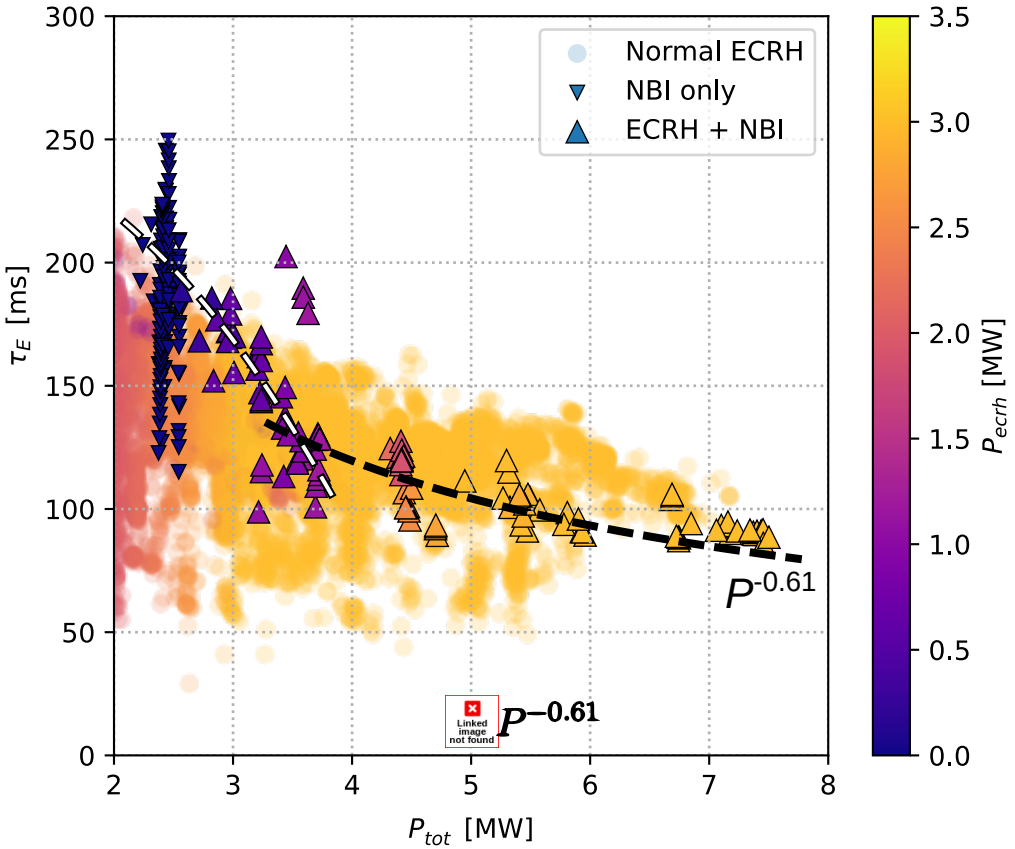
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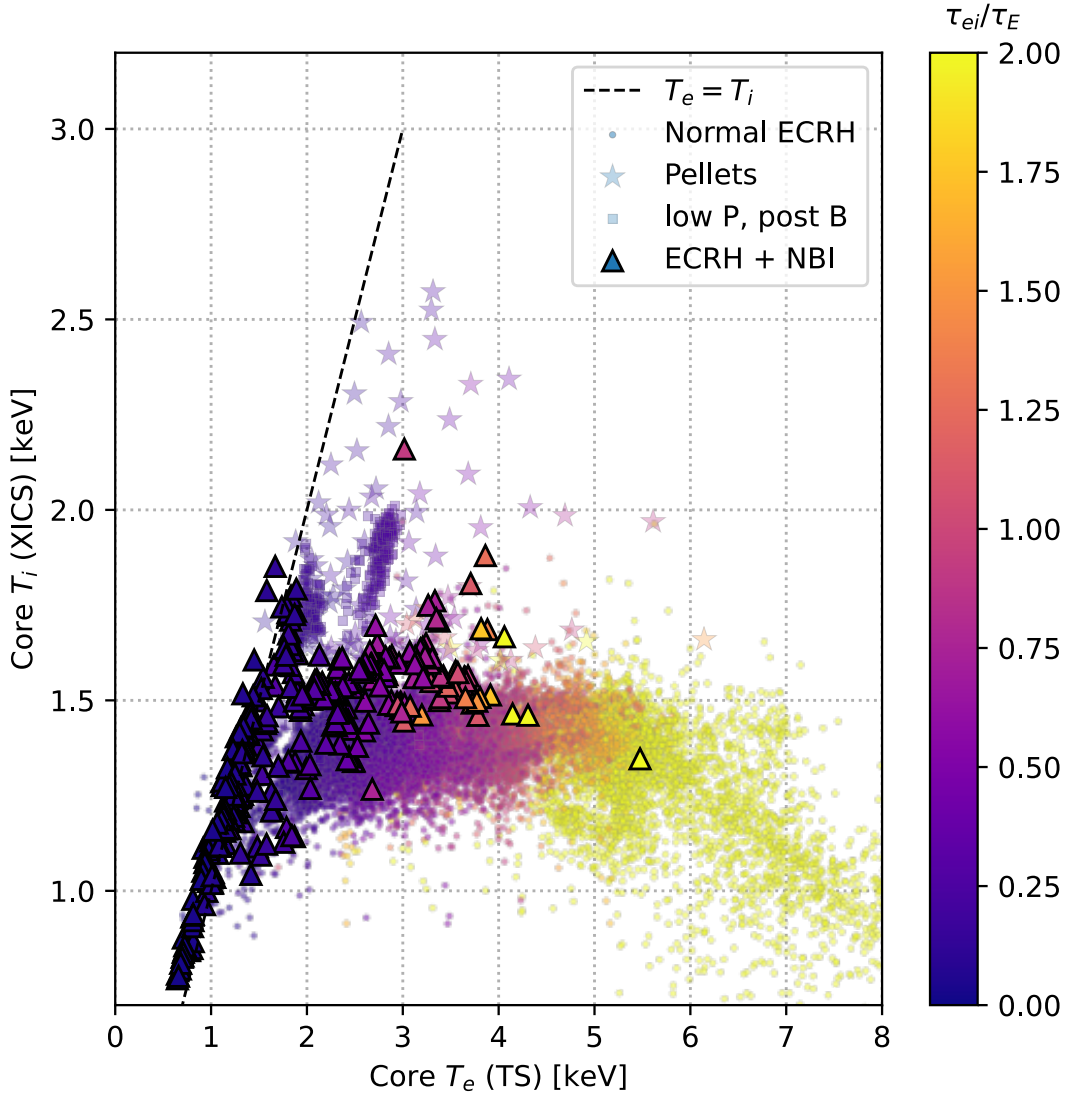


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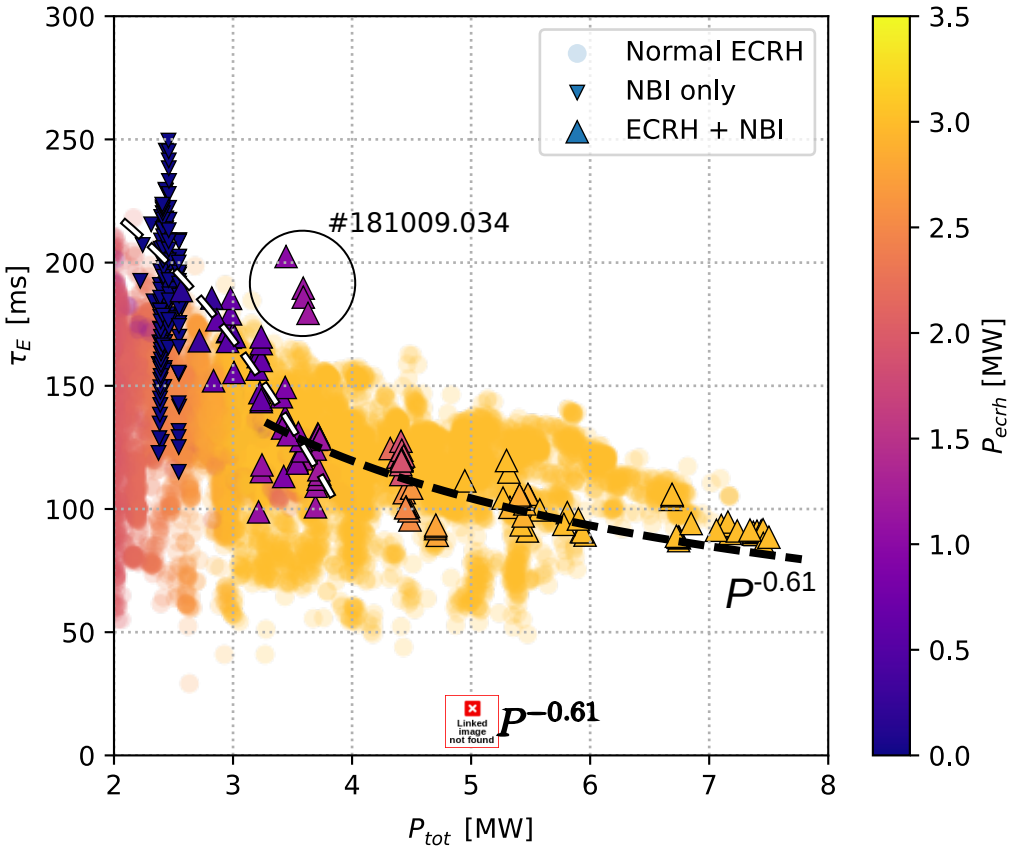
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- Highest $\tau_E$ plasmas at zero or low ECRH power.
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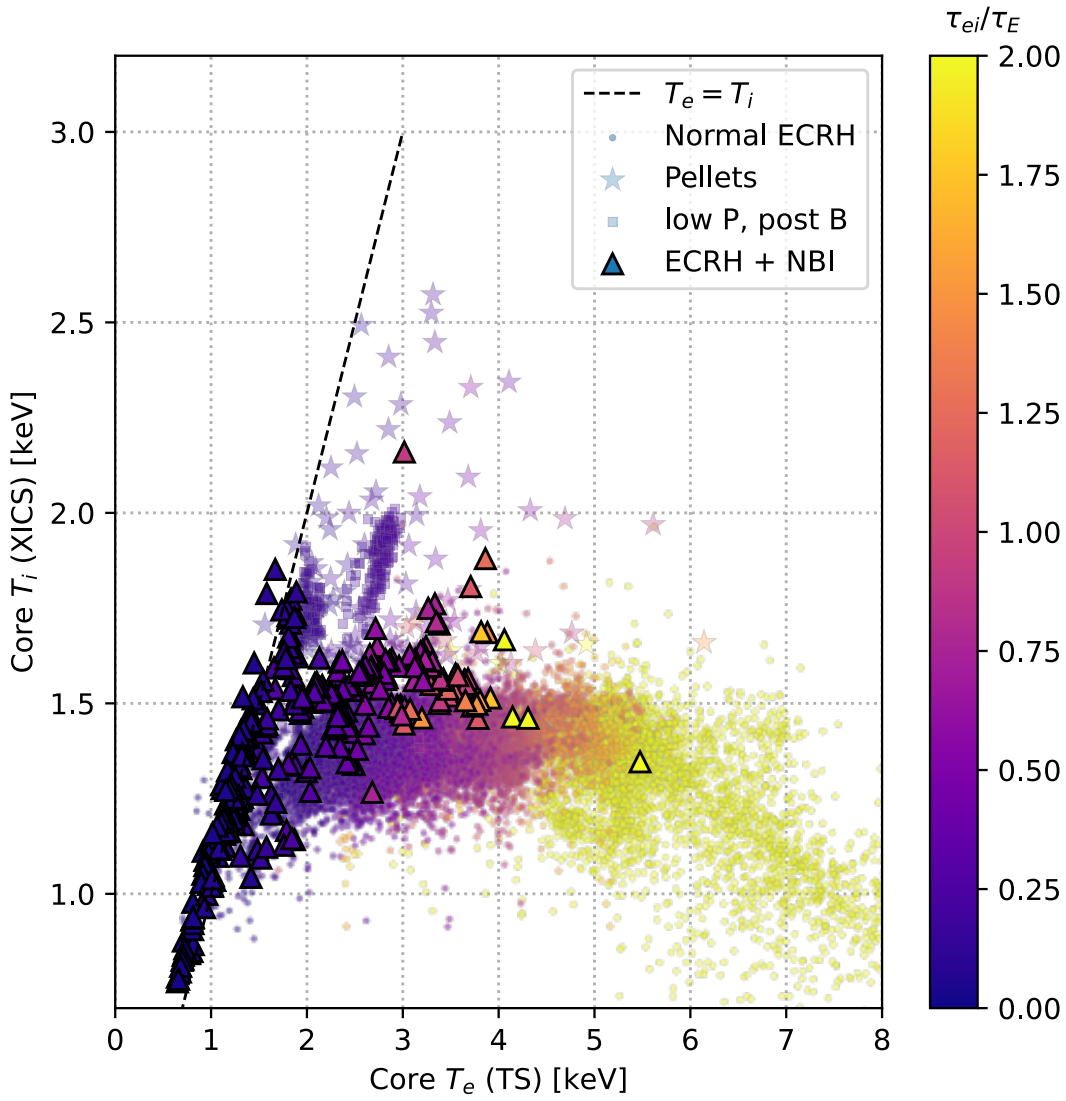


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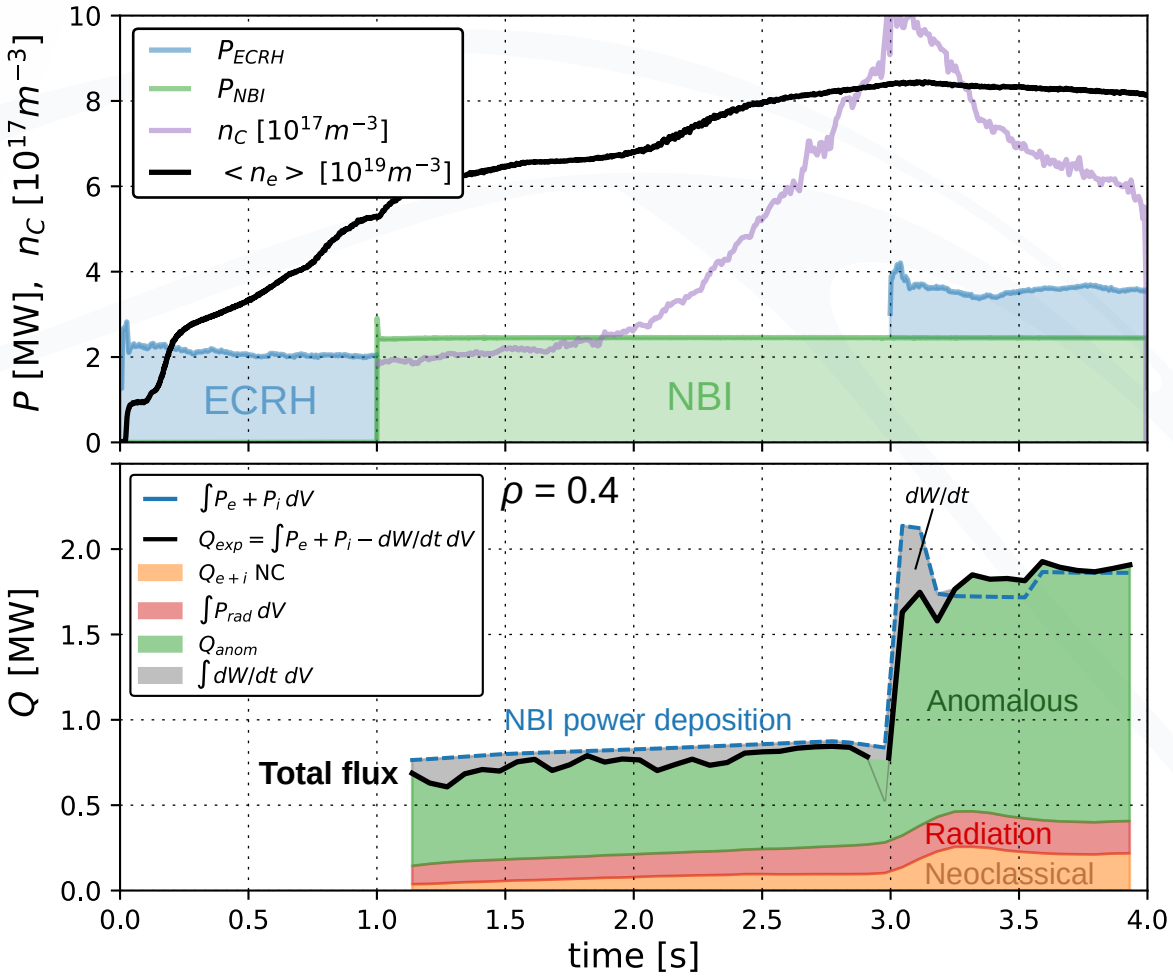



# Energy transport: Total fluxes

- High collisionality leads to large $P_{ei}$ with small $O$(~10eV) differences in $T_e$, $T_i$ profiles.
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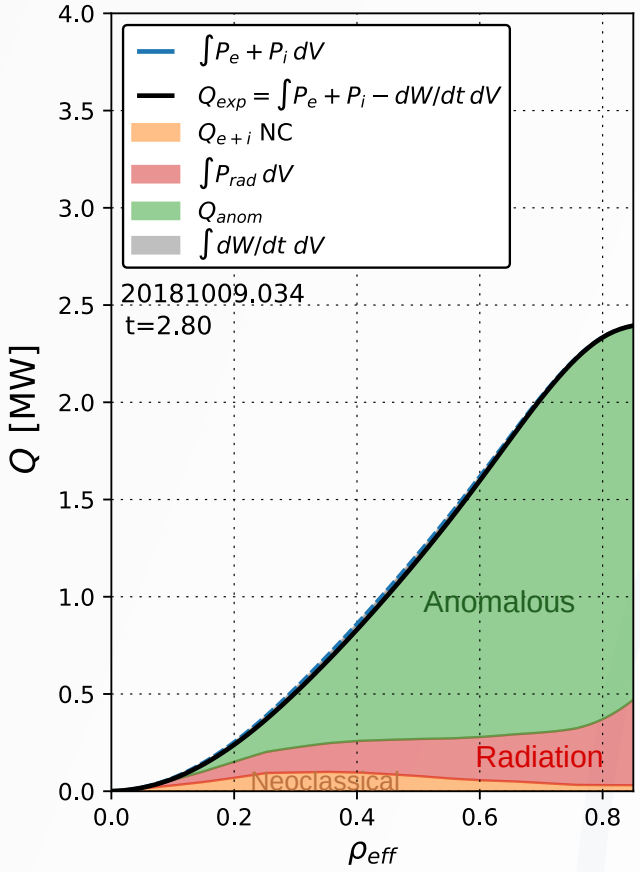
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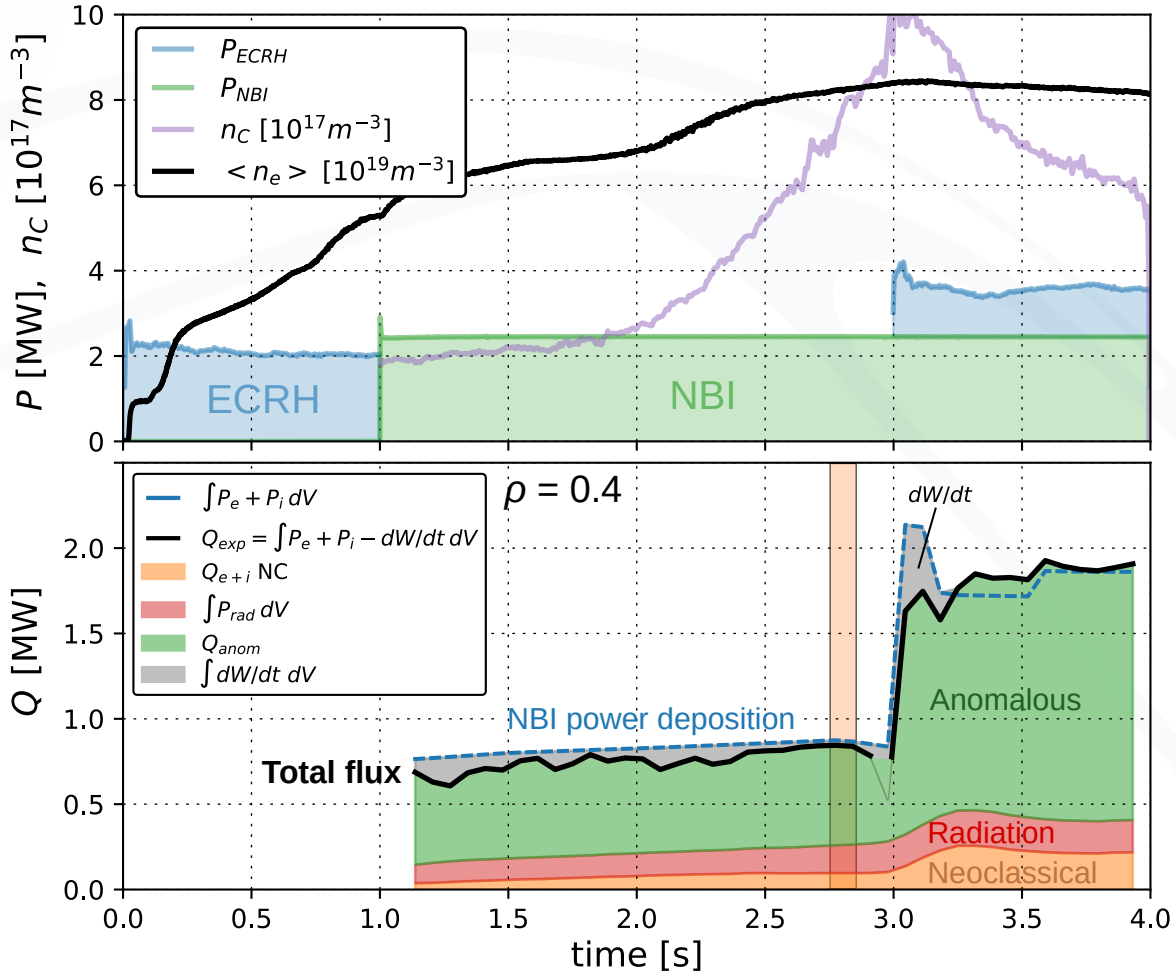
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- Anomalous fluxes increase with ECRH addition.

